

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 and South Beach outfall site, examination of aerial photography and analysis of a high-resolution bathymetric survey. The aerial photographs indicate relatively deep water in the vicinity of the pipeline and wave focusing occurring to the northwest. The bathymetric survey showed a large seabed depression located parallel to, and offset to the southeast, of the pipeline. This depression, caused by current-induced scour around the pipe, appears to spread wave energy leading to reduced wave height within the depression. While wave convergence occurs along the sides of the depression, focusing and height increase along the northwestern side is particularly evident. This latter phenomenon is possibly associated with the depression's oblique orientation to the prevalent swell approach direction. Field results show period to be the primary variable influencing wave focusing, with direction also being important. These results are consistent with findings for natural canyons at La Jolla, California (Shepherd and Inman, 1951). Refraction and diffraction-based numerical modelling also showed period to be a key parameter. However, wave approach direction results differed from the field observations which suggests that wave deformation is not simply a product of localised refraction and diffraction processes.

1. Introduction

Long ocean outfalls and pipelines crossing the nearshore are becoming increasingly common on sandy coastlines. While field studies and numerical modelling (eg. Stadeler et al., 1996; Sumer and Fredsoe 1999; Kit and Nikitin, 2003) have enabled progress to be made in understanding the seabed response to such structures, the relationship between the structure and wave deformation has received little attention. Anecdotal evidence (eg. see Figure 1) suggests that a significant increase in wave height can occur in the vicinity of such structures; a situation with possible consequences for the structure's integrity, shoreline stability and coastal users. This paper aims to investigate any association between such nearshore structures and wave deformation by carrying out a field-based study of a long ocean outfall at Wanganui on the southwest coast of the New Zealand North Island (Figure 2).

In particular, the study will: quantify wave deformation in the vicinity of the South Beach outfall by comparing wave parameter values at a 'control' site (Castlecliff Beach) to the northwest (Figure 2); identify wave-crest deformation and breaking location using aerial photographs; survey the bathymetry at the site, and numerically model wave propagation in the vicinity of the pipeline. The paper begins by describing environmental conditions, and backgrounding the history and characteristics of the outfall. A summary of the field-based research design is outlined in the methods section (3). Results are presented in section 4 and discussed in section 5.



Figure 1: Waves 'peaking' and breaking near the outfall pipeline which is located on the left hand side of the photograph.

2. Background

2.1 Study Site

Wanganui City 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). More recently, this erosion and accretion appears to have reached a state of dynamic equilibrium.

The Wanganui coastline has a northwest - southeast orientation. It is characterized by an ebb tide delta at the Wanganui Rivermouth, the delta is offset toward the southeast. Castlecliff Beach is

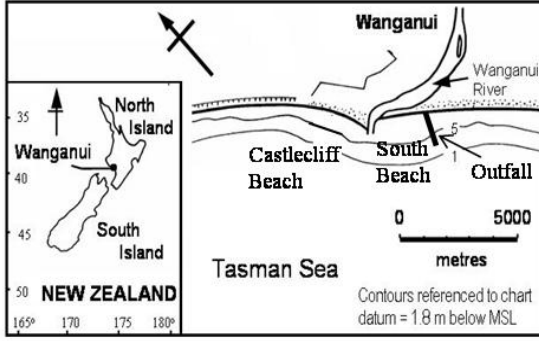


Figure 2: The study site at Wanganui, New Zealand

multi-barred and generally dissipative (Shand, 1999). South Beach is influenced more by the asymmetric river delta and has less pronounced sandbars than at Castlecliff. Sediment size in the vicinity of the outfall is 0.125 mm. The mean significant wave height is 1.3 m and the 5% exceedence 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 the predominant NW to SE longshore drift.

2.2 Outfall Background

The outfall was constructed in 1982 by Downer Construction. The pipe originates from a wastewater treatment station on the western side of the river. It then passes under the rivermouth, through a surge chamber and extends 1800 m out to sea. The pipe crosses the beach 3000 m southeast of the rivermouth and is offset 17° southeast of shore-normal. The pipe 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 on the then seabed. The pipe is supported by a combination of 310 and 760UC piles at 22 and 30 m centres.

3. Field Data

3.1 Wave Measurement

Wave measurements at South Beach were taken offshore from the surge chamber, where the pipe crosses the foreshore. At Castlecliff Beach, the measurement site was 1500 m northwest of the river mouth.

Measured wave parameters were based on observational methods developed by the Beach Protection Authority of Queensland (Patterson and Blair, 1983). These measurements include wave direction, wave period (T), travel time across the surf zone and maximum wave height, $(H_{los})_{max}$. The latter was determined using the line-of-sight (los) method which is based on a graduated staff being placed at approximately still-water-level (Fig 3).

This measurement could then be converted to a significant wave height at the breakpoint, $(H_b)_{sig}$ using corrections for wave set-up, the earth's curvature and an empirical adjustment from maximum to significant wave heights.

Wave 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) and the wavelength at breakpoint (L_b).

In addition, the relative difference in corresponding wave height at Castlecliff (H_{Cas}), and South Beach, (H_{Sth}) was determined using Equation (1). This property gives a measure of wave deformation.

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

Errors involved in the wave measurement were not considered crucial since these data were used for comparative purposes and the same level of error occurred at each site.

3.2 Aerial photography

Aerial photographs are well suited for identifying wave deformation as variation in wave-crest orientation can be detected. Oblique 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.

The oblique photographs were rectified to map coordinates and the output image further enhanced to show wave-crests more clearly.

3.3 Bathymetric Survey

The Wanganui Port Company carried out a high resolution bathymetric survey of the study area. Thesounding equipment consisted of a Hydrotrack sounder with both digital and analogue (trace) outputs. Elevation accuracy, after allowing for errors in reducing the data, was estimated at ± 0.3 m. Position fixing was achieved using a Ashtech differential GPS system (accuracy ± 0.2 m) which was integrated with depth measurements.

Once the onboard computer had recorded depths along each run, the data was tide-adjusted, reduced to chart datum and presented as a digital terrain model.

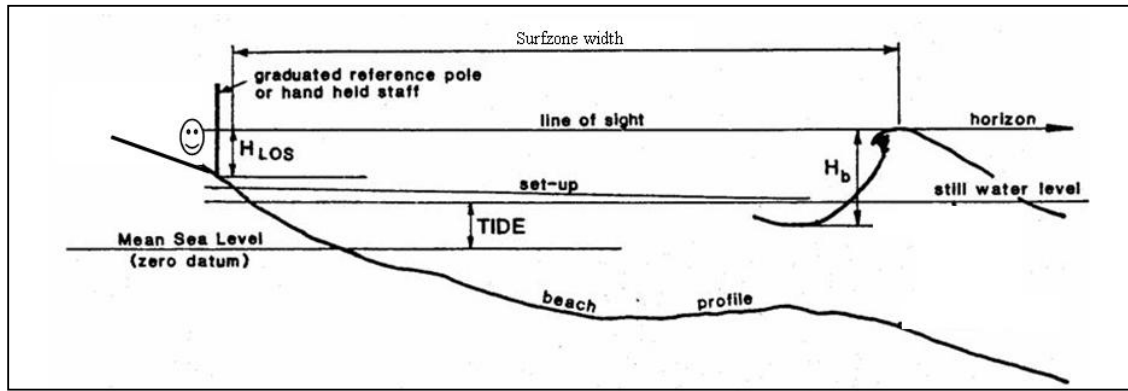


Figure 3: Illustration of components used for the line-of-sight (los) method of measuring breaking wave height. Method described in detail in Patterson and Blair (1983).

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. Wave period ranged between 8.1 and 17.0 sec.

The relationship between different variables was investigated using Pearson (linear) correlation analysis (Shaw and Wheeler, 1985). For 10 observations ($n=10$), the correlation becomes significant at the 5% level when r is greater than 0.632. Wave period had a strong association with the level of wave deformation at the outfall, i.e. wave height increase between Castlecliff and South Beach, with $r = 0.917$. However, the best-fit curve for these data is exponential with $r^2 = 0.932$ (Figure 4). 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 ($r = 0.717$). A notably weak association occurred between the inter-site wave height difference and wave height at Castlecliff ($r = -0.113$). Wave direction was not included in the correlation as not enough variation occurred during the study to enable its effect to be statistically assessed.

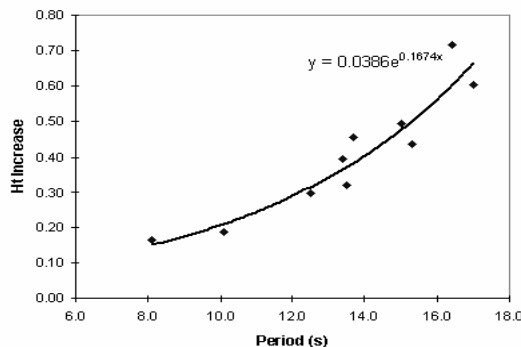


Figure 4: Best-fit relationship between wave period and wave height increase at South Beach relative to the wave height at Castlecliff.

4.2 Aerial Photographs

An example of a rectified aerial photograph illustrating wave-crest patterns in the vicinity of the South Beach outfall is shown in Figure 5. The wave deformation and irregular breaking indicate uneven seabed topography. Waves can be seen peaking and changing direction as they approach the central part (within ellipse) of photo A. In B, an area of deep water is inferred at the right of the pipeline (dashed line), with unbroken wave fronts (marked in C) bending into it.

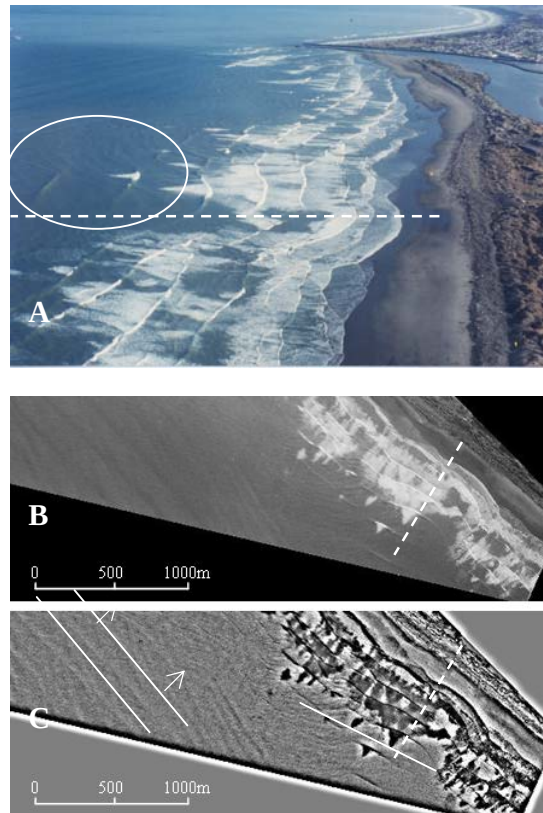


Figure 5: Oblique aerial photograph of outfall area (A) with the rectified image in B and enhanced output in C. Marked features described within text.

On the rectified images, waves can be seen breaking several hundred metres out to sea on the northwestern side (rivermouth side) of the pipeline, but no wave breaking occurs for ~300 m on the southeastern side. This indicates the presence of a seabed depression centred just to the southeast of the pipe.

4.3 Bathymetric Survey

The bathymetric map shows a depression ~300-400 m wide in the vicinity of the outfall pipe (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. Closer the pipe the slope increases to ~0.03. The pipe is located at the base of the depression which is asymmetric in cross-section and tails off toward the southeast. This topography is consistent with the breaking wave pattern evident from land-based observation and aerial photographs.

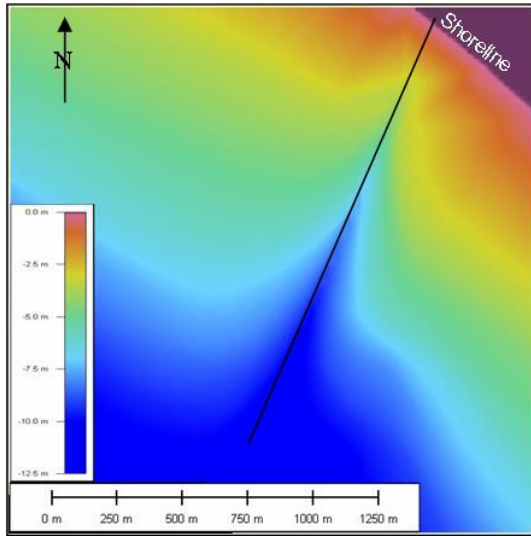


Figure 6: Bathymetry of the South Beach depression with pipeline depicted by black line.

5. Discussion

The dominant variable associated with level of wave deformation, as measured using the relative height difference between the study and control sites, was wave period. This can be explained by longer period waves interacting with the seabed at greater depth and therefore undergoing greater deformation over the irregular topography of the outfall area.

The longest period waves recorded during this study were 17 seconds. The observed exponential relationship noted earlier, suggests that large increases in wave height could be expected for these particularly long period waves. Waves at South Beach could be almost twice the size of those at Castlecliff during such events. The particularly

weak association between level of wave deformation and wave height at Castlecliff ($r = -0.113$) indicates wave height does not play a significant role in the level of wave focusing.

While wave direction was not included in the correlation analysis, on two occasions (15/01/03 and 17/04/03) measurements were made of waves with a notably greater southerly component and relatively low periods (8 and 11 seconds). Not only was there was no wave height increase observed at South Beach, 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 pipeline, behave quite differently to waves approaching at an angle to the pipe.

From aerial photographs, waves were observed to refract and bend near the outfall. This can be qualitatively explained in terms of simple wave refraction. Wave velocity (c), is expressed in terms of the Airy Wave Theory formula in Equation (2).

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

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. This refractive phenomenon is well understood under such variable seabed topography (see Figure 7). Wave refraction, together with the associated diffraction, causes energy to be transferred along the wave crest, leading to localised energy concentrations and areas of increased wave height.

However, the observed difference in wave height between Castlecliff and South Beach, i.e. the basis of measuring the wave deformation, may not be entirely due to the depression. These beaches have different orientations and nearshore geometry. Effects on wave refraction due to these differences have not been assessed in this study.

A comparative example of wave deformation in the vicinity of seabed depressions also occurs with the canyons at La Jolla, California. Incoming waves refract and defocus over the canyons leading to increased wave height along the margins (Shepherd and Inman, 1951). The northern canyon presents an oblique orientation to incoming wave-crests, as does the South Beach depression to the predominant southwest swell. As with South Beach, a significant increase in wave height occurs at this La Jolla canyon. By contrast, the southern canyon at La Jolla presents a more perpendicular

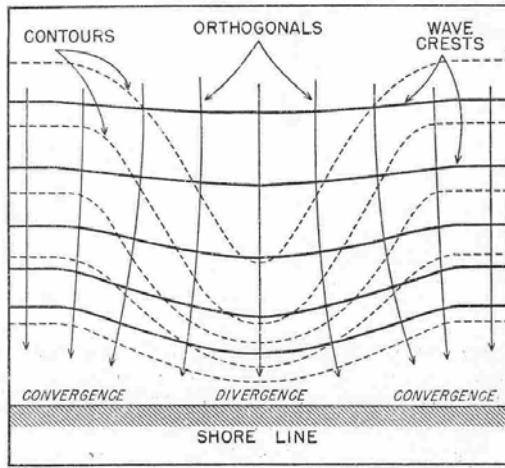


Figure 7: Theoretical wave refraction as waves propagate over a seabed depression. Wave orthogonals diverge over the depression and converge to either side. (Source: Munk and Traylor, 1947)

orientation to incident wave-crests and less wave height increase occurs; again this is similar to the South Beach observation. Furthermore, the South Beach observations of more intense focusing being associated with longer period waves was also reported at La Jolla (Munk and Traylor, 1947).

Numerical modelling was undertaken using the combined refraction/diffraction model REF/DIF 1, V2.5 (Kirby and Dalrymple, 1994). This model uses a mild slope equation to model monochromatic wave movement over irregular bathymetry. Mild

Table 1: Wave parameters used for numerical model simulations with resultant wave height increase.

Model run	Incident wave height (m)	Incident wave period (s)	Incident wave direction ($^{\circ}$) ¹	Ht Diff ²
1	2.0 ³	14.0	30	1.58
2	4.0	14.0	30	1.26
3	6.0	14.0	30	1.16
4	4.0	10.0	30	1.26
5	4.0	14.0	30	1.26
6	4.0	16.0	30	1.32
7	4.0	18.0	30	1.41
8	4.0	14.0	70	1.08
9	4.0	14.0	55	1.32
10	4.0	14.0	40	1.26
11	4.0	14.0	25	1.29
12	4.0	14.0	10	1.28
13	4.0	14.0	0	1.42

1. Wave direction relative to depression axis (i.e. wave approaching with crest perpendicular to depression axis has a direction of 0°)
2. Ht Diff is relative height difference between incident wave and breaking wave height
3. Parameter shown in bold indicates variable being tested.

slopes are theoretically defined as having a gradient of less than 1:3. The South Beach depression satisfies this requirement. The computational grid of 2 km by 2 km was used with a 20 m resolution.

Wave heights ranging from 2 to 6 m, periods ranging from 10 to 18 s and directions from west through south were modelled. An example of the model output is shown in Figure 8. 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 (Table 1).

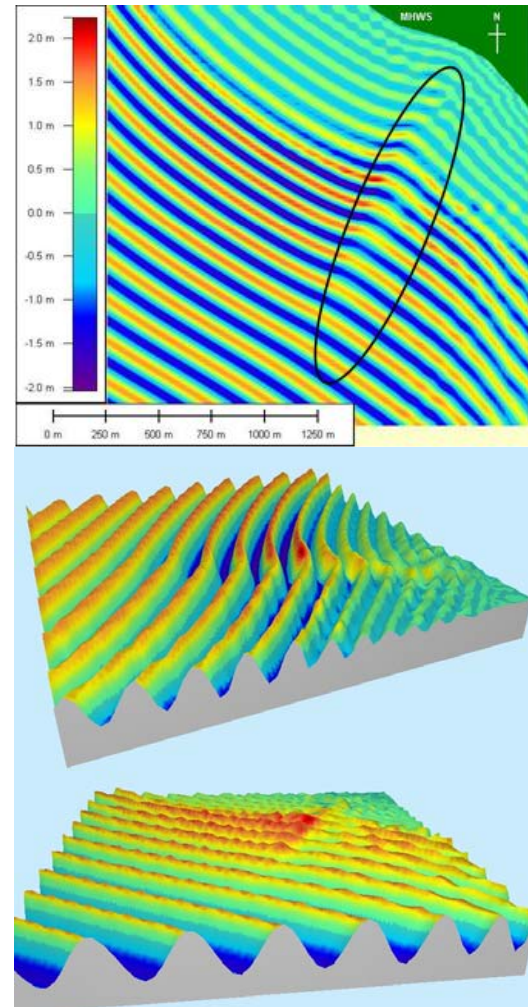


Figure 8 Plan-view (upper image) and oblique perspectives (lower images) of 3 m waves at 14 sec approaching South Beach from the southwest. The waves can be seen deforming over the depression (depicted by ellipse) and focusing along its northwestern margin.

Model outputs show the following relationships:

- Waves of longer period increased in height to a greater extent than shorter period waves;

- Smaller incident waves increased in height to a greater extent than larger waves;
- Waves with crests perpendicular to the pipeline (depression axis) increased in height more than those approaching from an angle.

The relative wave height increase under increasing period is consistent with the most significant result from the field study. However, the greater relative height increase with decreasing incident wave height is more definitive than that from the field data which showed no statistical association. This modelling result may be explained physically by the fact that smaller waves may refract over a greater distance before breaking, i.e. they will break further landward than larger waves. The fact that this was not realized during the field investigation may be attributed to discrepancies between offshore wave height and wave height at the control beach.

Of particular interest, is the relationship between increasing relative wave height and wave approach direction. The modelling result was the opposite of that suggested by field data both at Wanganui and La Jolla, i.e. greater relative height increase occurred when wave approach angles were oblique to the axis of the depression. While the reason for the discrepancy is unclear, the consistency in field observations at both Wanganui and La Jolla, suggest that wave deformation in such situations may be a product of more than just localised refraction and diffraction as derived by standard numerical procedures.

6. Conclusions

This study has shown that substantial wave deformation can occur in the vicinity of the long ocean outfall at Wanganui. This deformation is associated with the trough, or depression, which runs the length of the pipeline. The depression is asymmetric in cross-section, tailing off to the southeast. This seabed configuration probably reflects the predominant southeast-directed longshore current; as such longshore currents are known to drive the scour process (Sumer and Fredsoe, 1999). Aerial photographs show wave-crests bending into the depression, with focusing and associated height increase occurring along the northwestern side.

Field measurements show relative wave height increases of up to 180% under longer period swell conditions. Incident waves crests with an oblique approach direction relative to the pipeline orientation, appear to undergo greater height increase – a result consistent with results from California's La Jolla canyons. While, refraction-diffraction based numerical modelling was able to replicate the wave height increase-period association, the wave approach association was in the opposite direction, i.e. waves approaching directly up the depression underwent greater relative height increase. It is concluded that the

wave deformation may be a product of more than standard wave refraction and diffraction over the local topography.

While wave deformation associated with the Wanganui outfall has relevance for coastal users such as vessel navigators and surfers, and also shoreline response, the increase in wave focusing and dissipation (upon breaking) does not occur over the pipe itself, so the structure's integrity is not at risk.

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