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Wave Characteristics and Transformations on Sub-Horizontal (Type B)

Shore Platforms on the East Coast of the North Island, New Zealand

Hiroki Ogawa

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy in Geography, The University of Auckland, 2012
Abstract

This study presents the results of the most detailed hydrodynamic experiments conducted on sub-horizontal ‘Type B’ shore platforms to date. The aims of this study were to: provide detailed descriptions of wave transformation processes; identify morphological controls on wave processes; and investigate possible morphological implications. Six platforms with a range of widths (80–270 m) and gradients (0.2–1.3°) were selected from Gisborne and Auckland, North Island, New Zealand. Synchronised high frequency sea-surface records were obtained using electronic wave gauges. The Gisborne experiments were conducted under fair-weather swell conditions to characterise temporal and spatial characteristics of wave transformation. The Auckland experiments were conducted under storm conditions to explore the interaction of storm waves with the platform surface. Results showed that breaking was forced on the platform edge when the relative water depth (depth/significant wave height) at the edge was less than 2.5; whereas waves shoaled onto the platform surface under lower energy conditions. Gravity-wave height was depth limited on the inner platform surface and independent of incident wave conditions. The maximum wave height on very flat (< 0.23°) platform surfaces was limited to 55% of platform water depth, but this limit increased with increasing platform gradient. Platform width was an important control on wave attenuation at low tide due to increased frictional energy loss: the attenuation rate of gravity waves was 1.5 times higher at low than high tide. In general, gravity waves progressively attenuated across platforms, but infragravity-wave energy increased toward the cliff toe. The relative importance of infragravity waves at the cliff toe increased with increasing platform width and decreasing water depth. The proportional increase in infragravity-wave height at the cliff toe was found to be a function of the platform
energy window index ($\psi$) and it was proposed that Type B platforms may be characterised as ‘gravity-wave’ and ‘infragravity-wave’ dominated platforms. Collectively, the results presented within this thesis demonstrate the importance of platform water depths (hence elevation), width and gradient in controlling wave energy characteristics across shore platforms. Existing models of platform morphodynamics and evolution present a ‘black box’ in respect to wave processes. The quantitative field data on wave processes presented here provide an opportunity to reconsider some of the basic assumptions in existing models.
Acknowledgements

Throughout the course this study I have received advice, support and encouragement from a number of people, to whom I would like express my sincere thanks.

I would like to thank Paul Kench and Mark Dickson for their time, knowledge, advice, constructive comments and criticism and encouragement over the last four years. In particular, I would like to thank Paul for being always supportive and patient and providing very sharp comments on chapter drafts and article manuscripts, and Mark for a number of discussion sessions on rock coast processes both in the field and office. I could not possibly have better supervisors.

A number of people assisted me in the field. I would like to thank Tom Stephens, Claire Gregory, David Wackrow, Patrick Senior, Eddie Beetham, Rachael Pentney, Farah Lodhawalla, Aaron Napier and Shona Dey and GEOG 746 students (2009) for their assistance in the field.

I would like to say a big thank you to the following people, who, in their spare time have kindly proofread draft articles and thesis chapters. Those are: Claire Gregory, Emma Ryan, and Nicole Sutton. I would also like to thank Alexis Robinson for a number of interesting discussions on wave processes on shore platforms.

When I started this PhD I had no background in wave analysis, signal processing and programming. I would like to acknowledge Mark Dickson, Richard Gorman and Karen Bryan for their assistance in data processing and programming during the first several months of the study.

I originally came to Auckland as a PhD student in tsunami sedimentology. Although I have changed my PhD topic, I had a great time working on the tsunami topic thanks to Scott Nichol, who I had a number of exciting discussions in the field, in the office and, most importantly, at the pub. Thanks also to Amy Dougherty, who introduced me to ground penetrating radar (GPR) and more importantly, Double Brown, the cheapest beer in the country. Several other people helped me in the field, especially on Great Barrier Island, including Daniel Atkin, Tom Stephens, Andrew Lorrey, Peter Crossly, David Wackrow and Sam Morgan. I would particularly like to thank Tom
and Dan for waiting patiently while the gear van was extracted from a gravel road by a crane and for their impressive coring effort.

I would also like to thank fellow PhD students, most of whom have already graduated, for their encouragement and all the fun we had together, including: Murray Ford, Amy Dougherty, Keith Adams, Francis Collins, Steven Kelly, Nathaniel Wilson, Eric LaFary, Claire Gregory, Jane Lee, David Bade, Megan Selby, Daniel Atkin, Stephen FitzHerbert, Kyle Morgan, Brendon Blue, Phillip Mandlier, Jamie Steer, Simon Aiken, Helen Reid, Tom Stephens, Claas Damken, Christina Ergler, Amit Kokje, Roger Baars, Chris McDowell, Pippa Mitchell, Alan Chung, Corina Buckenberger, Kathryn Davies, Tara Coleman, Jason Myers, Fraser Morgan, Aaron Cheng, Indra Kularatne, Nicolas Le Corvec and Aleksandra Zawalna-Geer among others. Big and special thanks to Claire Gregory, Stephen FitzHerbert and Helen Reid for so many cups of coffee and food, and keeping me reasonably alive.

The best and the biggest learning experience I have had during the course of my PhD came from my involvement in teaching undergraduate and postgraduate courses at the University of Auckland. First and foremost, I would like all my students who studied GEOG 105, 201, 207, 250, 330, 351, 746 and Marine 202. I have had such great opportunities to work with some excellent and inspirational students including Midi Summers, Tracy and Rod Turner, Eddie Beetham, Nava Fedaef, Adam Millar, Jeremy Swanson and Kermath Davies to name a few. Special thanks also go to the people of Motuti Marae for their great hospitality and making us feel warm and welcome every time we visited on the GEOG 207 field trip to Northland.

Over the past several years I have worked with a number of tutors and lecturers at The University of Auckland. I would like to acknowledge Joe Fagan, Mark Dickson, Paul Kench, Susan Owen, Scott Nichol, Nick Lewis, Gretel Boswijk, Gordon Winder, Nick Richards, Gary Brierley, Anthony Fowler, Chris de Freitas, Paul Augustinus, Phil Shane and Dan Hikuroa for the opportunity to work with them and the experience I have gained from them. Thanks are also due to the technical staff at the school who helped me in various aspects of teaching and research, including Dave Jenkinson, Brendan Hall, Dave Wackrow, Peter Crossly, Colin Yong and Russell Clark. I would also like to thank the following tutors I worked with: Steve Piers, Alexis Robinson,

A number of other people in the department helped me directly and indirectly during the course of my PhD, including Barbara May, Dorothy Chung, Angela Koegh, Anna-Marie Simcock, Desmond Huang, Graeme Glen, Igor Drecki, Lyndsay Blue, Marie McEntee, Karen Fisher (who owns the hot red boots), Mel Wall (especially for chocolate), Damian Collins and Barry O’Connor (for beer). Thank you all.

Over the last several years I have lived with a number of people. I would like to thank Darren, Scott, Marcia, Luke, Nat, Cam, Fraser and all other flatmates and landlords. To my current flatmates Matt Ewen and Amy Brown, thank you so much for being such great flatmates and friends.

I would like to thank Susan Owen who has helped me in a number of ways in the past a few years. I could not have gone through some of the most stressful times (including a couple of relationship crises) without her support. Thanks also to Nick Lewis for lending me money when I needed and Nicole Wilde for keeping me in the country by signing a few things.

While doing a PhD I had some great opportunities to work with wonderful people including Peter Hosking and Quinton Smith in very special places such as Parengarenga Harbour. I also had opportunities to work in the field with James Goff, Anni Madsen and Elain Simd which I am grateful.

A number of friends provided great support in the past a few years. Special thanks to Bridgette Rademakers and her family, Joakim Eidenfalk, Nicole Sutton, Joe Fagan, Amy Dougherty, Matt Ewan, Amy Brown, Helen Reid and her parents Ian and Robyn (especially Robyn for tons of ice cream and chocolate she’s given me), Claire Gregory, Ashlee McCormick, Stephen and Erin FitzHerbert, Pam Howard, Yuki Oe, Pedro
Fernandes and friends at Tu Kaha BJJ, David Spares and his family for their support and encouragement.

Thomas Forde is thanked for the countless pints of beer he generously served me free of charge at his bar. I thank him in advance for buying me a few more beers to celebrate the completion of my PhD.

Finally, the biggest thanks go to my family who have supported me during my PhD in many different ways. Mum and Dad, you are the best parents in the world. Without you and your support, I wouldn't have been able to do so many things in my life including this PhD. You have always encouraged me to pursue things I loved, including baseball, athletics, martial arts and intellectual challenges such as a PhD. You never questioned my choices even though I kept changing the directions every a few years and, at times, had some ridiculous dreams and goals. To my sisters, Megumi and Moe, thank you for being such great sisters and friends and being supportive and always encouraging.
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<td>$H$</td>
<td>Wave height</td>
<td>$Q_p$</td>
<td>Spectral peakedness</td>
</tr>
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<td>$H_{m0}$</td>
<td>Significant gravity-wave height</td>
<td>$v$</td>
<td>Spectral width</td>
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<td>Maximum gravity-wave height</td>
<td>$m_n$</td>
<td>$N^\text{th}$ moment of the variance density spectrum</td>
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<td>Significant wave height (ZDC)</td>
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<td>Wave length</td>
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<td>PSD at peak frequency</td>
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<td>Extent of contribution by PhD candidate (%)</td>
<td>95</td>
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### CO-AUTHORS

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<tr>
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<tr>
<td>Paul Kench</td>
<td>Edited and commented on the manuscript.</td>
</tr>
<tr>
<td>Mark Dickson</td>
<td>Edited and commented on the manuscript.</td>
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</tbody>
</table>

### Certification by Co-Authors

The undersigned hereby certify that:

- the above statement correctly reflects the nature and extent of the PhD candidate’s contribution to this work, and the nature of the contribution of each of the co-authors; and
- in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

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<tr>
<td>Paul Kench</td>
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<td>Mark Dickson</td>
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This form is to accompany the submission of any PhD that contains research reported in published or unpublished co-authored work. Please include one copy of this form for each co-authored work. Completed forms should be included in all copies of your thesis submitted for examination and library deposit (including digital deposit), following your thesis Abstract.

Please indicate the chapter/section/pages of this thesis that are extracted from a co-authored work and give the title and publication details or details of submission of the co-authored work.

Ogawa, H., Kench, PS., Dickson, ME., submitted. Hydrodynamic constraints on storm wave transformations on a Type B shore platform. Article currently under review (Chapter 4: Section I)

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Preface

This thesis presents research carried out by the author under the supervision of Associate Professor Paul Kench and Dr. Mark Dickson. The main body of this thesis is based on published and unpublished research articles written by the author during the course of his PhD enrolment. Unless otherwise stated, all experiments and analyses were conducted by the author. The material presented in chapters 3, 4 and 5 consists of five articles, each containing a standalone introduction, methods, results and conclusion. Each of chapters 3 and 4 consists of two case studies (presented in two articles), while chapter 5 presents a meta-analysis of all case studies with two additional datasets. Chapter 5 serves as a discussion and synthesis chapter. These chapters start with a short paragraph explaining how each case study (article) is linked with respect to the overall objectives of the thesis. Inevitably there is some overlap between chapters/sections, especially in introduction and method sections since (part of) each chapter stands as independent research articles. A general introduction, literature review and conclusions are given in chapters 1, 2 and 6. These chapters present the motivation and rationale, overall objectives and the background of the study, and the overall conclusions from all articles. The first two articles presented in this thesis (chapter 3) have been published in recognised peer-reviewed journals. The third article (chapter 4) has been resubmitted to a journal after the initial review process and a revision. The fourth article (chapter 4) has been submitted for publication and currently under review and the last article (chapter 5) is currently in preparation.

Hiroki Ogawa
25/05/2011
Publications/articles


3) **Ogawa, H**, Kench, PS, Dickson, ME, submitted. Hydrodynamic constraints on storm wave transformations on a Type B shore platform. In review. Earth Surface Processes and Landforms (Chapter 4)

4) **Ogawa, H**, submitted. Observation of wave transformation on a sloping Type B shore platform under storm and swell conditions. In review. Geo-Marine Letters (Chapter 4)

5) **Ogawa, H**, in prep. Generalised Observations of Wave Processes on Sub-Horizontal (Type B) Shore Platforms: A Meta-Analysis of Case Studies from the North Island, New Zealand. (Chapter 5)

Conference Papers

The material presented in chapter 4 has also been presented at the following conferences:


CHAPTER 1
Introduction

1.1 Introduction

Rocky coasts are the most common coastal types in the world (Emery and Kuhn, 1982). Rocky coasts can be classified into two major morphologies: plunging cliffs and shore platforms (Fig. 1.1). Two major types of intertidal shore platforms are recognised - sloping shore platforms with no clear seaward boundary and sub-horizontal shore platforms with a distinctive seaward edge (Fig. 1.1). Shore platforms with a steep and well defined seaward edge are commonly found in micro and meso-tidal environments while sloping platforms are often associated with upper meso to mega-tidal environments, although gently sloping platforms can also be found in micro-tidal environments. Sunamura (1992) termed shore platforms that gradually slope into the nearshore without a seaward scarp ‘Type A’ and those with a sharp scarp defining the seaward extent of the platform ‘Type B’ (Fig. 1.1).

Shore platforms are erosional landforms that represent the interface between coastal cliffs (or beaches) and the sea. The erosive force of waves is considered to be a major factor responsible for the formation and subsequent evolution of shore platforms on many coasts, although the rate of formation and resulting morphology of the contemporary shore platforms are greatly influenced by other factors such as local geology and lithology (Kennedy and Dickson, 2006; Cruslock et al., 2010; Kennedy, 2010; Naylor and Stephenson, 2010), biological actions (Healy, 1968b;
Naylor et al., 2012), sub-aerial physiochemical weathering processes (Bartrum, 1926; Trenhaile and Mercan, 1984; Stephenson and Kirk, 2000b) and mass movements (McLean and Davidson, 1968).

**Figure 1.1: Major morphological features on a rocky shore (based on Sunamura, 1992).**

The morphology of shore platforms varies globally and regionally (Healy, 1967; Trenhaile, 1974; Takahashi, 1977; Dickson and Woodroffe, 2005; Kennedy, 2010) and is thought to be controlled by various factors including wave exposure, rock strength, lithology and geology (Trenhaile, 1987; Sunamura, 1992; 1999; Kennedy, 2010; Naylor and Stephenson, 2010). An analysis of 400 survey profiles across the
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islands of Japan by Takahashi (1977) shows that platforms in Japan are generally narrower than 150 m with a modal width around 30 to 50 m, although platforms as wide as 320 m exist. The majority of shore platforms in Japan appear to have a mean gradient below 0.5° with platform elevation between mid-intertidal and higher intertidal zone (Takahashi, 1977). In Gaspe, Canada, shore platform widths vary from 30 to 150 m and gradients between 0° and 1° are typically developed around mid-tide level (Trenhaile, 1978). On the macro-tidal, storm wave dominated coast of Vale of Glamorgan, Wales, platforms range from 100 to 250 m in width and 2° to 3° in gradient. In Bay of Fundy, Canada, where spring tidal range reaches 13.5 m, shore platforms are represented by very steep gradients (up to 7.5°) (Trenhaile and Kanyaya, 2007).

Shore platforms are a distinctive morphological feature on many rocky coasts. Shore platforms provide a hydrodynamically unique environment due to their solid and impermeable surface, with fixed alongshore and across-shore geometry. Unlike clastic sandy beaches where the majority of hydrodynamic and morphodynamic studies have been conducted, shore platforms do not respond to hydrodynamic forcing instantaneously. In particular, the steep seaward edge and the near horizontal surface that characterise Type B platforms create a unique hydrodynamic regime. Key definitions used to describe Type B shore platforms and shore platform wave processes are summarised in Table 1.1 and Figure 1.2. Some of the key references are also cited.
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Figure 1.2: Key definitions used to describe Type B platform morphology.

Table 1.1: Key definitions used in shore platform wave processes and hydrodynamics.

<table>
<thead>
<tr>
<th>Key Terminologies</th>
<th>Definitions</th>
<th>Hydrodynamic importance</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Approach slope</td>
<td>Nearshore slope in front of, or leading to, a shore platform.</td>
<td>Important control on wave transformation (i.e. shoaling and breaking). Reported to affect the wave breaking behaviour over the seaward edge.</td>
<td>(Goda and Morinobu, 1998; Stephenson and Kirk, 2000b)</td>
</tr>
<tr>
<td>Front depth</td>
<td>Water depth directly off the seaward edge of a platform. Only relevant for sub-horizontal (Type B) platforms.</td>
<td>Often used as an indicator of platform wave exposure. Some studies show positive linear correlation between front depth and platform elevation.</td>
<td>(Sunamura, 1991; Dickson, 2006)</td>
</tr>
<tr>
<td>Seaward edge (low tide cliff / seaward scarp)</td>
<td>Seaward extent of a shore platform. For sloping shore platforms (Type A), it can be defined as either the mean spring low water level (MSLW) or the mean sea-level (MSL). Some Type B platforms have a rampart (raised platform surface) on the seaward edge.</td>
<td>Important control on wave energy dissipation on Type B platforms. Under high energy conditions, waves are forced to break as they cross this boundary due to a sudden change in water depth. Wave breaking against the edge or over the edge may generate large impact force.</td>
<td>(Sunamura, 1992; Trenhaile and Kanyaya, 2007)</td>
</tr>
<tr>
<td>Platform water depth</td>
<td>Water depth on shore platform. May vary significantly depending on platform geometry.</td>
<td>Exerts controls on wave height on the platform surface.</td>
<td>(Farrell et al., 2009)</td>
</tr>
<tr>
<td>Platform width and slope</td>
<td>Width and gradient of the platform surface between the seaward edge and the cliff toe. Generally, platforms with mean gradient &gt; 1° are considered as sloping platforms.</td>
<td>Thought to directly affect wave energy delivery to the cliff toe. Numerical models use these two attributes as key morphological controls on wave energy dissipation. They may be an important control on platform wave height.</td>
<td>(Stephenson and Kirk, 2000a; Trenhaile, 2000; Trenhaile and Kanyaya, 2007; Marshall and Stephenson, 2011)</td>
</tr>
<tr>
<td>Elevation</td>
<td>Elevation of a shore platform in relation to the local mean sea-level or Chart Datum.</td>
<td>Key attribute that determines platform water depths.</td>
<td>(Trenhaile and Kanyaya, 2007)</td>
</tr>
</tbody>
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As well as being an agent of direct erosion of rock substrate, wave processes are responsible for mechanical actions such as abrasion and attrition through sediment entrainment and transport (Robinson, 1977; Woodroffe, 2002) and erosion and transport of large clasts on high energy rocky shores (Süssmilch, 1912; Mastronuzzi and Sansò, 2004; Noormets et al., 2004; Williams and Hall, 2004). Despite the acknowledged importance of wave processes on shore platforms, these processes are still poorly understood. This lack of understanding is due to a general lack of quantitative process studies on shore platforms with regards to wave processes and wave induced geomorphic changes (Stephenson, 2000; Trenhaile, 2002b). Conducting instrumented field research on shore platforms can be difficult, as shore platforms are often located in exposed and dangerous environments which may not be readily accessible (Trenhaile, 2002). Furthermore, the emphasis of modern coastal research on clastic depositional coasts (Trenhaile, 2002) and the belief that fundamental questions about shore platform evolution have been addressed already (Stephenson, 2000) can also be attributed to the general lack quantitative studies on shore platforms.

Significant advances in process research have been made in several fields of shore platform and rocky coast geomorphology in the past decade. First, several studies on the physical impact of incident oceanic waves on coastal rock substrate have been reported in the past decade (Adams et al., 2002; Adams et al., 2005; Lim et al., 2011; Young et al., 2011; Dickson and Pentney, 2012). These studies utilised seismometers to monitor and quantify wave-induced cliff motions. Collectively, the studies on wave induced micro-seismic motions identified hydrodynamic and hydrostatic
loading of shore platforms and coastal cliffs can cause shaking and swaying of the cliffs: processes that may have significant geomorphic implications as wave induced cliff motions can cause strain within the rock substrate (Adams et al., 2005; Young et al., 2011; Dickson and Pentney, 2012). Second, a large number of studies have been carried out to understand coastal boulder transport and mechanics, as large boulders on shore platforms can be utilised to identify the types and magnitude of waves responsible for their deposition. Such studies are motivated by the need to better understand the risk posed by high energy coastal inundation events such as tsunamis and extreme storms. In particular, a significant effort has been made to distinguish tsunami boulders from storm boulders (Nott and Bryant, 2003; Noormets et al., 2004; Nott, 2004; Morton et al., 2008; Goto et al., 2010; Paris et al., 2011) and hydrodynamic boulder transport equations for tsunami and storm waves have been developed (Nott, 2003; Lorang, 2011). Third, a series of numerical models have been developed in the past decade to simulate the evolution of rocky coasts. As the evolution of shore platforms generally occurs over the geological timescale, numerical models have been utilised to explore the evolution of shore platforms (Trenhaile, 2000; Trenhaile, 2008a), the role of waves and weathering processes (Trenhaile, 2001; Trenhaile, 2008b), late quaternary sea-level change (Trenhaile, 2010a) and the impact of future change in sea-level (Walkden and Dickson, 2008; Trenhaile, 2010b; Trenhaile, 2011). Fourth, the adaptation of a morphodynamic approach in rocky coast and shore platform evolution has been advocated (Stephenson and Thornton, 2005; Naylor et al., 2010) and a new morphodynamic model proposed specifically for rock coasts (Naylor et al., 2012).
However, to date, few studies have undertaken detailed investigations of wave hydrodynamics and transformation on shore platforms. While there are several studies available (e.g. Stephenson and Kirk, 2000a; Stephenson and Thornton, 2005; Trenhaile and Kanyaya, 2007; Farrell et al., 2009), differences in focus and methods used, and relatively coarse temporal and spatial resolution of those studies mean that there exists a significant gap in knowledge with regard to wave processes on shore platforms (see chapter 2 for a detailed review). In addition, the majority of wave studies on shore platform conducted to date used a time-domain analysis and only described gravity waves. While micro-seismic studies on coastal cliffs provide proxies for understanding wave energy delivery, direct measurements are required to better characterise wave transformations on shore platforms and resolve their geomorphic significance. Furthermore, a lack of quantitative wave data on shore platforms means both conceptual and numerical models developed for shore platforms are something of a “black box” in terms of the treatment of wave hydrodynamics. Current models of shore platform morphodynamics and evolution are largely based on theoretical assumptions (e.g. Trenhaile, 2000; Trenhaile, 2003). Underpinning such assumptions with empirical data is important, as shore platforms act as a buffer between the oceanic waves and the coastal cliffs (or beaches). The efficiency of shore platforms as a buffer is expected to change with projected rise in sea-level (Meehl, 2007; Walkden and Dickson, 2008). Improved resolution of shore platform hydrodynamics is required for coastal engineering and management applications. Furthermore, morphodynamics of platform-cliff systems are still poorly understood. In coastal morphodynamics, fluid motions (i.e. waves, currents and tides) play an integral role in modifying landforms and initiating a
feedback loop within the system (Wright and Thom, 1977). It is crucial that wave processes on shore platforms are adequately described and understood in the field in order to develop a robust morphodynamic model.

A lack of wave studies on shore platforms is also considered responsible for several important research problems that are yet to be fully resolved. Such problems include the century-long “weathering vs. wave erosion” debate (Trenhaile, 2002b; Kennedy et al., 2011) on platform evolution and the dynamic vs. static equilibrium models of profile adjustment (de Lange and Moon, 2005; Stephenson, 2008). The “weathering vs. wave erosion” debate has focused on the relative dominance of physical processes responsible for the formation and the evolution of shore platforms. Although recent studies recognise the importance of both processes more or less equally, or suggest that the relative importance of weathering and wave processes change spatially and temporally (Trenhaile, 2002b; Dickson, 2006; Trenhaile and Kanyaya, 2007; Trenhaile and Porter, 2007; Trenhaile, 2008a; Kennedy et al., 2011), opinions have often been divided, with some attributing the formation of shore platforms almost entirely to wave induced erosion (e.g. Dana, 1849; Bartrum, 1926; Edwards, 1941; Edwards, 1958; Takahashi, 1977; Sunamura, 1978b), while others consider sub-aerial weathering to be dominant (Bartrum, 1916; Wentworth, 1938; Wentworth, 1939; Hills, 1949; Hills, 1972). A consensus view on the relative importance of these processes has yet to be reached (Stephenson, 2000).

The dynamic vs. static equilibrium model problem refers to the debate concerning the mode of platform profile evolution. The dynamic equilibrium model assumes that platform profile evolves with “self-parallel” retreat (Challinor, 1949), while the static equilibrium model assumes that the position of the seaward edge does not
change over the course of shore platform evolution (Sunamura, 1992). This debate has important implications for shore platform evolution. If the platform edge does not retreat, it is inferred that a platform will eventually become too wide and horizontal erosion of the cliff will cease as waves will be attenuated completely (Johnson, 1919; Sunamura, 1992). The debate hinges upon the understanding of rock strength and the erosive force of waves, as well as the importance of sub-aerial weathering processes and determining how the platform profile may adjust over time in response to physical processes. In this context, it is crucial that morphological feedbacks on wave processes are adequately understood, as changes in platform morphology will likely affect wave processes on the platform surface. This issue has recently been debated in the literature (de Lange and Moon, 2005; Moon and de Lange, 2008; Stephenson, 2008), highlighting the lack of process understanding on shore platforms including wave processes.

1.2 Research Aims and Objectives

The aim of this research is to describe and characterise wave transformation processes across Type B shore platforms and examine the morphological controls on wave transformations. The specific objectives are:

a) To describe and quantify wave-energy transmission and dissipation from the seaward edge to the cliff toe.
b) To characterise spatial variations in wave energy characteristics across the platform surface from the seaward edge to the cliff toe.

c) To characterise temporal variations in wave characteristics on platforms.

d) To investigate and assess tidal controls on wave transformations.

e) To investigate how platform wave processes are affected by the variations in incident wave conditions and tide conditions.

f) To identify morphological controls on wave transformations by comparing the results obtained from each platform.

g) To discuss the significance of wave processes in the context of shore platform morphodynamics.

The study aims to present the most detailed field studies of wave characteristics on shore platforms available and to provide a benchmark dataset on wave processes on Type B shore platforms.

1.3 Research Design

To address the objectives, Type B platforms with different widths were selected from two coastal regions of the North Island, New Zealand, which have contrasting oceanographic regimes and are characterised by abundant shore platforms. The
regions included the northeast coast of Auckland and the coastline of Gisborne (Fig. 1.3). The two regions were selected as the shore platforms in these regions were relatively accessible and offered a range of platform morphological characteristics. In particular, the coastline of Gisborne offered a range of platform widths including very wide platforms (> 250 m) and consistent swell waves that provided a level of assurance for obtaining wave measurements, while the east coast of Auckland allowed rapid deployment of instruments and provided logistical ease for otherwise challenging field instrumentation in rock coast environments under high energy conditions.

Wave energy delivery across the platform surface and to the cliff toe is often considered to be a direct function of incident wave conditions and the width of shore platforms (Sunamura, 1992; Trenhaile, 2000). Shore platform width has been considered the most important morphological attribute controlling wave energy dissipation and delivery to cliffs (Johnson, 1919). Consequently, platform width has been incorporated into conceptual and numerical models as a proxy for wave transformation (Sunamura, 1992; Trenhaile, 2000). To evaluate the assumption that platform width is a fundamental control on wave processes, the study selected platforms that possess different platform widths. The following sections present the study site characteristics for the experiments and an overview of the research and analytical methods.
1.3.1 Study Regions

The northeast coast of Auckland and the coastline of the Gisborne Region, North Island, New Zealand (Fig. 1.3) offer different oceanographic environments in terms of wave exposure and tidal conditions. The northeast coast of Auckland experiences a semi-diurnal, meso-tidal regime with a spring tidal range of approximately 3 m. The coastline is considered a leeward, low energy environment (Brookes and Green,
The wave climate is characterised by locally generated short-period waves and low-amplitude swell due to the fetch limitations of the Hauraki Gulf (Fig. 1.3b) (Brookes and Green, 2001). Waves generally arrive from the north-northeast sector (Gorman et al., 2003). This low energy wave condition is punctuated by episodic storm events several times per year. The mean offshore wave height for Auckland is 1.2 m with only 3% and 0.35% of waves exceeding 3 m and 7 m respectively (Gorman et al., 2003).

The oceanographic regime on the Gisborne coast is characterised by semi-diurnal, micro-tidal conditions with a mean spring tide range of 1.7 m. The average wave height for this coastline is 0.8 to 0.9 m with wave periods of 9-10 s (Smith, 1988). The coastline is considered as a leeward coast but it is exposed to persistent swell waves generated in the Southern Ocean (Yuliastuti and Hashim, 2011). During storm events wave heights reach > 3 m on the coast (Dunn, 2010). The mean offshore wave height for Gisborne is 1.6 m with only 5% and 0.34% of waves exceeding 3 m and 5 m respectively (Gorman et al., 2003).

1.3.2 Selection of Study Sites

To examine the influence of platform width on wave processes, the six platforms selected ranged in width from 80 to 270 m. Platform gradient ranged from 0.2° to 1.3°, allowing the role of platform gradient in dissipating wave energy to be investigated. The platforms were selected after the initial reconnaissance visits to the two regions, based on morphological characteristics, accessibility and safety of
the field sites and instrument security. The Gisborne experiments were conducted under fair-weather swell conditions with little variation in incident wave conditions in order to characterise swell wave transformations across the platforms. All experiments in the Gisborne region were conducted under similar incident wave height and period conditions to control for wave exposure. In contrast, the two experiments in the Auckland region were conducted under storm conditions in order to characterise high energy wave interactions with platforms and to explore the importance of incident wave energy characteristics on platform wave processes. The close proximity to the study sites from the University of Auckland allowed for a rapid deployment of wave gauges prior to a storm event.

It should be noted that shore platforms with high elevation were excluded from this study because:

a) the purpose of this study is to examine wave transformation processes on shore platforms. High platforms (above MSL) are not suitable for hydrodynamic experiments as the temporal window within which the platform surface is inundated is very short.

b) the effect of platform elevation on wave processes is relative to tidal range. Therefore it can be substituted by sampling across the spectrum of low to high tide conditions on lower elevation platforms.

Lithological and geological characteristics of shore platforms were not considered upon selecting study site, as these factors affect platform morphology over engineering ($1 \times 10^1 \sim 10^2$ yrs) to geological ($> 1 \times 10^{100}$ yrs) time scales and are not relevant for instantaneous process-based hydrodynamic studies. Large topographic
irregularities on the platform surface, such as large dykes, islands and channels, may introduce significant hydrodynamic noise and complicate wave signals. Therefore, platforms with relatively smooth surface morphology were selected for this study.

1.3.3 A Comparison of Field Sites with Global and Regional Platform Characteristics

In New Zealand and Australia, shore platforms typically have a gradient less than 1° (Trenhaile, 1987), although there are steeper platforms present (Stephenson and Kirk, 2000a; Thornton and Stephenson, 2006). Widths of platforms in New Zealand vary significantly from less than 10 m to over 350 m, although platforms wider than 150 m are relatively uncommon. However, along the coastline of Gisborne, New Zealand, shore platforms are unusually wide, with some platforms reaching 350 m in width (Gill, 1950). The mean platform elevation in this region also varies significantly, but the majority of the contemporary shore platforms are located within 2 m either side of local MSL.

Figure 1.4 presents a global and regional summary of morphological characteristics of shore platforms. Of note, the widths of the six study platforms (80 – 270m) are generally comparable to shore platforms in Wales, Canada and Japan. The gradients of the study platforms are generally comparable to shore platforms in micro and meso-tidal environments, although one of the six sites has a slightly steeper gradient than the range commonly observed on meso-tidal coasts (Fig. 1.4a). The study
platforms represent the lower and the wider end of the platform width and elevation range observed in New Zealand and Australia (Fig. 1.4b).

Figure 1.4: Global and regional characteristics of shore platforms: a) global characteristics of platform gradient and tidal range (modified from Trenhaile (1999)) and; b) platform
elevation and width in New Zealand and Australia. Auckland and Gisborne data are based on the profiles surveyed as part of this study and data for other sites are compiled from Dickson (2006), Thornton and Stephenson (2006), Kennedy and Dickson (2006), Kennedy (2010), Stephenson and Kirk (1996), and Kennedy (2010). The platforms investigated in the present study are plotted in red.

1.3.4 Descriptions of Experiment Profiles

Experiments were conducted at Tatapouri and Pouawa, north of Gisborne; Oraka (two sites), Mahia Peninsula, south of Gisborne, and; Rothesay Bay and Red Beach on the northeast coast of Auckland (Fig. 1.5; 1.6). Geological settings of each study site and detailed descriptions of the study transects are presented in Chapters 3 and 4. A brief description of the six study transects is provided below. Morphological characteristics of the study platforms are summarised in Table 1.2.

**Tatapouri**: shore platforms around Tatapouri, Gisborne are characterised by a wide, low gradient and low elevation surface (Fig. 1.6a). The study transect at Tatapouri is 250-m-wide, with a mean elevation and surface gradient of -0.7 m (MSL) and 0.3° respectively. It represents one of the widest and the flattest shore platforms in the study.

**Oraka**: shore platforms at Oraka are characterised by a low gradient surface with a steep but irregular seaward edge. There are a number of rock shoals present in the nearshore. Two transects are selected for this study. The first transect (Oraka 1 – the short profile) is 140 m long, with a mean elevation and surface gradient of -0.4 m (MSL) and 0.4° respectively (Fig. 1.6b). The platform has a comparable width and gradient with the Rothesay Bay platform. It also has comparable morphological characteristics to the Tatapouri platform, except for the narrower width. The second transect (Oraka 2 – the long profile) is located east of the short transect on the same
platform. The profile is 270 m long, with a mean elevation and surface gradient of -0.9 (MSL) and 0.35° respectively (Fig. 1.6c). The morphology of the transect is comparable to that of Tatapouri.

**Pouawa Beach:** the experiment transect at Pouawa represents the narrowest and the steepest among the Gisborne sites (Fig. 1.6d). The shore platform at Pouawa is characterised by a relatively irregular platform surface truncated by several intertidal channels. The seaward edge of the platform is well defined but irregular in terms of elevation and lateral continuity. The study transect was selected on the least irregular part of the platform. It is 90-m-wide with a mean gradient and surface elevation of 0.7° and -0.4 m (MSL) respectively.

**Rothesay Bay:** the study transect at Rothesay Bay is 140-m-wide, with a mean gradient of 0.4° and elevation of -0.9 m (MSL). The platform has a near-horizontal surface gradient on the seaward side and a low angle with a concave cliff-toe slope (Fig. 1.6e), which is the most common platform type on the east coast of Auckland (Healy, 1968a).

**Red Beach:** the study transect at Red Beach is 80-m-wide, with a mean gradient of 1.3° and elevation of -0.6 m (MSL). This platform represents the narrowest and the steepest shore platform among the six shore platforms studied (Fig. 1.6f).
Figure 1.5: Photos of the study platforms

a. Tatapouri

b. Oraka

c. Pouawa Beach

d. Rothesay Bay

e. Red Beach
Chapter 1: Introduction

Figure 1.6: Platform topographical profiles and wave gauge deployment locations. Triangles indicate locations of wave gauges. VE=1:25

Table 1.2: Summary table of platform morphological characteristics at the study sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Width</th>
<th>Mean Elevation (MSL)</th>
<th>Slope</th>
<th>Type</th>
<th>Nearshore characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatapouri, Gisborne</td>
<td>253 m</td>
<td>-0.7 m</td>
<td>0.25°</td>
<td>Type B</td>
<td>Front depth 1.5 m+ off the edge of the platform.</td>
</tr>
<tr>
<td>Oraka, Mahia Peninsula, Gisborne</td>
<td>143 m</td>
<td>-0.3 m</td>
<td>0.4°</td>
<td>Type B</td>
<td>Front depth 0.5 m off the edge. A large rock shoal offshore.</td>
</tr>
<tr>
<td>Oraka, Mahia Peninsula, Gisborne</td>
<td>266 m</td>
<td>-0.9 m</td>
<td>0.35°</td>
<td>Type B</td>
<td>Front depth 2.5 m. Some offshore rock shoals and outcrops.</td>
</tr>
<tr>
<td>Pouawa, Gisborne</td>
<td>91 m</td>
<td>-0.4 m</td>
<td>0.7°</td>
<td>Type B</td>
<td>Front depth 1 m directly off the study profile. It varies significantly along shore. Sandy nearshore slope. Depth 1.5 ~ 2 m off platform edge. Smooth.</td>
</tr>
<tr>
<td>Rothesay Bay, Auckland</td>
<td>136 m</td>
<td>-1.1 m</td>
<td>0.3°</td>
<td>Type B with concave slope</td>
<td>Depth 0.5 m off the edge. Gradual increase in depth offshore.</td>
</tr>
<tr>
<td>Red Beach, Auckland</td>
<td>81 m</td>
<td>-0.6 m</td>
<td>1.3°</td>
<td>Type B with straight surface.</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Site</th>
<th>Width</th>
<th>Mean Elevation (MSL)</th>
<th>Slope</th>
<th>Type</th>
<th>Nearshore characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatapouri, Gisborne</td>
<td>253 m</td>
<td>-0.7 m</td>
<td>0.25°</td>
<td>Type B</td>
<td>Front depth 1.5 m+ off the edge of the platform.</td>
</tr>
<tr>
<td>Oraka, Mahia Peninsula, Gisborne</td>
<td>143 m</td>
<td>-0.3 m</td>
<td>0.4°</td>
<td>Type B</td>
<td>Front depth 0.5 m off the edge. A large rock shoal offshore.</td>
</tr>
<tr>
<td>Oraka, Mahia Peninsula, Gisborne</td>
<td>266 m</td>
<td>-0.9 m</td>
<td>0.35°</td>
<td>Type B</td>
<td>Front depth 2.5 m. Some offshore rock shoals and outcrops.</td>
</tr>
<tr>
<td>Pouawa, Gisborne</td>
<td>91 m</td>
<td>-0.4 m</td>
<td>0.7°</td>
<td>Type B</td>
<td>Front depth 1 m directly off the study profile. It varies significantly along shore. Sandy nearshore slope. Depth 1.5 ~ 2 m off platform edge. Smooth.</td>
</tr>
<tr>
<td>Rothesay Bay, Auckland</td>
<td>136 m</td>
<td>-1.1 m</td>
<td>0.3°</td>
<td>Type B with concave slope</td>
<td>Depth 0.5 m off the edge. Gradual increase in depth offshore.</td>
</tr>
<tr>
<td>Red Beach, Auckland</td>
<td>81 m</td>
<td>-0.6 m</td>
<td>1.3°</td>
<td>Type B with straight surface.</td>
<td></td>
</tr>
</tbody>
</table>
1.3.5  Field Methods

In order to maintain consistency across all study sites, pressure gauges were used in all experiments to measure high frequency variations in water level. Three types of pressure wave gauges were used in this study, including RBR-2050TWR, KPSI 550/551 Water Level Monitor and InterOcean S4DW (Fig. 1.7). Prior to deployment sensors were tested for accuracy and linearity in the laboratory. During the field experiments, wave gauges were either directly mounted on the platform surface or deployed on 20 kg metal plates which were placed on the platform surface or on the sea-bed in the nearshore (Fig. 1.7a, c). A S4DW bi-directional wave and current meter was deployed during the Oraka experiment. The S4DW is equipped with a pressure gauge which records the vertical motion of water, and magnetic sensors that record currents around the instrument in two directions. It was deployed with a metal frame which was anchored on the study platform (Fig. 1.7b). Barometric pressure was recorded using a KPSI 556 barometric gauge.

Figure 1.7: Sensor deployment methods and sensors used in this study. (a) a RBR deployed on a steel plate, (b) a S4DW being deployed on the platform at Oraka, and (c) a KPSI 551 mounted directly on the platform surface.
Details of the sensor deployments for each of the experiments are summarised in Tables 1.3 and 1.4. Sensor types and sampling intervals and durations differed between study sites on the basis of equipment availability (Table 1.3).

**Table 1.3: Summary of sensor deployment and sampling strategies on each of the six platforms.**

<table>
<thead>
<tr>
<th>Location</th>
<th>Sensor ID</th>
<th>Sensor Type</th>
<th>Sampling Strategy</th>
<th>Wave Condition</th>
<th>Tidal Condition</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatapouri</td>
<td>T1 – T4</td>
<td>RBR 2050</td>
<td>2Hz</td>
<td>17.1 min every 30 min over 24 h</td>
<td>Fair weather</td>
<td>Spring</td>
</tr>
<tr>
<td>Oraka 1</td>
<td>M0</td>
<td>RBR 2050</td>
<td>2Hz</td>
<td>17.1 min every 1 h over 24 h</td>
<td>Fair weather</td>
<td>Spring</td>
</tr>
<tr>
<td></td>
<td>M2, M1, M3, M4</td>
<td>S4DW, KPSI 551/550</td>
<td>2Hz, 2Hz, 2Hz</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oraka 2</td>
<td>N0, N1, N3, N4</td>
<td>RBR 250</td>
<td>2 Hz</td>
<td>17.1 min every 30 min over 24 h</td>
<td>Fair weather</td>
<td>Spring</td>
</tr>
<tr>
<td>Pouawa</td>
<td>P1, P4</td>
<td>RBR 250</td>
<td>2Hz</td>
<td>17.1 min every 30 min over 24 h</td>
<td>Fair weather</td>
<td>Spring</td>
</tr>
<tr>
<td>Rothesay Bay</td>
<td>R00 – R3</td>
<td>RBR 2050</td>
<td>2 Hz</td>
<td>17.1 min every 30 min over 3 days</td>
<td>Storm</td>
<td>Spring</td>
</tr>
<tr>
<td>Red Beach</td>
<td>RB00 – RB3</td>
<td>RBR 2050</td>
<td>2Hz</td>
<td>17.1 min every 30 min over 24 h</td>
<td>Storm -&gt; Swell</td>
<td>Neap</td>
</tr>
</tbody>
</table>

Note that the labelling (IDs) of the sensors in this table and Fig. 1.6 may differ from the published material presented in Chapters 3 and 4.

**Table 1.4: Details of sensor deployment locations on shore platforms**

<table>
<thead>
<tr>
<th>Study Site</th>
<th>Nearshore Distance (elev)</th>
<th>Off edge Distance (elev)</th>
<th>Seaward edge Distance (elev)</th>
<th>Centre 1 Distance (elev)</th>
<th>Centre 2 Distance (elev)</th>
<th>Cliff toe Distance (elev)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tatapouri</td>
<td>-</td>
<td>-</td>
<td>1.8 m (-1.0 m)</td>
<td>103 m (-1.0 m)</td>
<td>174 m (-0.3 m)</td>
<td>245 m (-0.3 m)</td>
</tr>
<tr>
<td>Oraka 1</td>
<td>-</td>
<td>-4 m (-2.1 m)</td>
<td>2.0 m (-1.0 m)</td>
<td>50 m (-0.6 m)</td>
<td>104 m (-0.1 m)</td>
<td>141 m (0.1 m)</td>
</tr>
<tr>
<td>Oraka 2*</td>
<td>-</td>
<td>-1 m (-1.9 m)</td>
<td>0 m (-0.9 m)</td>
<td>121 m (-0.6 m)</td>
<td>203 m (-0.1 m)</td>
<td>255 m (0.5 m)</td>
</tr>
<tr>
<td>Pouawa</td>
<td>-</td>
<td>0 m (-0.8 m)</td>
<td>35 m (-0.3 m)</td>
<td>62 m (-0.3 m)</td>
<td>87 m (0.2 m)</td>
<td></td>
</tr>
<tr>
<td>Rothesay Bay</td>
<td>-20 m (-)</td>
<td>-5.2 m (-2.6 m)</td>
<td>0 m (-1.1 m)</td>
<td>69 m (-1.0 m)</td>
<td>128 m (-0.4 m)</td>
<td></td>
</tr>
<tr>
<td>Red Beach</td>
<td>-35 m (-2.9 m)</td>
<td>-2 m (-2.5 m)</td>
<td>2.0 m (-2.5 m)</td>
<td>39 m (-0.6 m)</td>
<td>80 m (0.1 m)</td>
<td></td>
</tr>
</tbody>
</table>

Values represent the distance from the seaward edge. Values in brackets represent platform surface elevation in relation to local MSL.

*values based on Beetham and Kench (2011).
Generally sensors were deployed at three to four locations on a shore perpendicular transect in order to record wave transformation across the platform surface (Fig. 1.6; Table 1.4). One or two additional sensors were deployed off the seaward edge of the platforms to measure incident wave conditions, except for the Tatapouri and Pouawa experiments where sensor availability and the conditions during the deployment did not allow an additional sensor to be deployed. A standard high-frequency short-duration sampling strategy often used in waves studies in process geomorphology (e.g. Ivany and Kench, 2006; Jago et al., 2007) was adopted in order to balance between the data resolution and quality and data size. During the Red Beach, Tatapouri and Rothesay Bay experiments, sensors were programmed to sample at 2 Hz for 17.1 minutes every 30 minutes or segments of 17.1 minutes were extracted from the record if data were logged continuously. For the Oraka experiments, all sensors were programmed to sample at 2 Hz for 17.1 minutes every hour due to memory limitations of some of the wave gauges used. In general, experiments were conducted over a 24-hour period due to logistical reasons including site access, equipment availability and equipment security. The one exception to this was the Rothesay Bay experiment during which sensors were deployed over three days in order to capture wave data during the duration of a wind-storm event.

1.3.6 Analytical Methods

All analysis was carried out in a MATLAB environment. A series of MATLAB routines were developed for processing multiple bursts of sea-surface elevation time-series which were used to extract information on wave characteristics and behaviour.
The analytical procedure used in this study is summarised in Figure 1.8. Measured pressure time-series were post-corrected for barometric pressure in order to determine mean burst-water depth. The barometric pressure was linear averaged over 17.1 minutes and subtracted from the pressure data recorded by each of the instruments. The pressure data were linearly detrended in order to remove the tidal component. Due to depth recording offsets, the water depth records for the Oraka and the Tatapouri experiments were reduced to the tide level recorded by one sensor, by subtracting the difference in platform elevation between the sensor sites. After initial processing, each time-series was plotted and inspected visually for data quality. Time-series data containing unrealistic record or obvious sensor exposure were discarded at this stage.
Pressure signals generated by sea-surface motion attenuate with increasing water depth. Attenuation of pressure signals is a function of wave length (hence the frequency) and water depth (Tucker and Pitt, 2001). Higher frequency waves, which have shorter wave lengths for a given water depth, are more susceptible for depth induced pressure attenuation. The amount of signal attenuation increases with increasing water depth. Pressure signals were corrected using a linear transfer function, assuming the sea-surface time-series to be a product of a linear superimposition of Airy waves of different periods, via:
\[ A(f, z) = \frac{\cosh(k(h - z))}{\cosh(kh)} \quad \text{Eq. 1.1} \]

where \( f \) is the frequency (Hz), \( z \) is the sensor depth (m), \( h \) is the depth of water column and \( k \) is the wave number (Tucker and Pitt, 2001; Gibbons et al., 2005).

Attenuation correction was applied in the frequency domain via Fast Fourier Transform (FFT). Sea-surface time-series were then reconstructed via inverse Fast Fourier Transform (IFFT). In general pressure signals were corrected for depth attenuation where the maximum water depth during an experiment reached 2 m or greater, or where high frequency signals were considered important. Consequently, the treatment of pressure data differed between study sites and sensor locations. Nevertheless, differences in wave height values calculated from pressure corrected and uncorrected data were small (< 10%) on the study platforms. Detailed descriptions of the application of pressure attenuation correction and cut-off frequencies used are provided in chapters 3 and 4.

Processed sea-surface time-series were filtered in the frequency domain to separate gravity and infragravity-wave (or high and low frequency) components. Time-series data were then analysed in the frequency domain (spectral analysis) and the time-domain (zero downcrossing analysis). A wave spectrum describes the distribution of energy with frequency. The concept of a wave spectrum is based on the assumption that waves in a random sea can be described as a linear superposition of sinusoidal periodic motions of different wave lengths (Tucker and Pitt, 2001). The total variance of the sea-surface elevation therefore equals the sum of the variance of such components. The average wave energy per unit area of the sea surface is proportional to the variance. Hence the total energy contained in a given wave
system is the sum of the energy associated with each of the periodic components within the system (Tucker and Pitt, 2001).

Waves with different periodic components (or frequencies) often have different generation mechanisms and origins. Examination of the wave spectra allows identification of the variance associated with each of the periodic components and hence the relative importance of waves in different frequency bands.

In this study spectral analysis was performed using Welch’s averaged modified periodogram method (Welch, 1967). All analyses were performed on contiguous records of 2048 samples using a 256-point Hanning window with 50% overlap, providing 16 degrees of freedom (DOF). Wave energy was then portioned into several frequency bands representing different generation mechanisms as used by Brander et al. (2004), including: infragravity (<0.05 Hz), swell (0.05 – 0.125 Hz) and wind (> 0.33 Hz) wave bands. All data were then checked for spectral energy “blow-up” (see Chapter 4, Section 2), which is an indication of noise amplification in the high-frequency region.

Wave statistics were expressed in terms of the spectral moments (Holthuijsen 2006). The definition of the moments of the measured spectrum is:

\[ m_n = \int_{l_0}^{h_i} f^n E(f) df \]  \hspace{1cm} \text{Eq. 1.2}

where \( m_n \) is the \( n \)th moment of variance density spectrum \( E(f) \), \( l_0 \) is low frequency cut-off and \( h_i \) is high frequency cut-off. Descriptive statistics of wave parameters including mean wave period \( (T_1 = m_0/m_1) \) and significant wave height \( (H_{m0} = \)
4\sqrt{m_0} \) were estimated from the spectral moments. Note that the values of \( H_{m0} \) do not necessarily correspond with the values of significant wave height calculated in the time domain \( (H_{1/3} = \text{average of the highest 33\% of waves}) \) derived from the same data. A detail description of this issue and an empirical method to relate those two parameters are described in Vandever et al. (2008). The moment definitions of those parameters can be found in Tucker and Pitt (2001: pp.39 – 41).

Zero downcrossing (ZDC) analysis is a time-domain method that calculates wave height and period by measuring individual waves in a given time-series data (also called the wave-by-wave method). The ZDC was used mainly to determine maximum wave height values \( (H_{max}) \) in this study, although a suite of descriptive statistics were calculated using this method, including significant wave height \( (H_s \text{ or } H_{1/3}) \) and significant wave period \( (T_s \text{ or } T_{1/3}) \).

### 1.4 Thesis Outline

Figure 1.9 presents the structure of the thesis. A description of field sites and site selection rationale, and field and analytical methods used in this study are presented in chapter 1. Chapter 2 presents a concise review of the relevant literature regarding the wave processes and hydrodynamics on shore platforms. Following chapters present the results of the field investigations. In Chapters 3 and 4, results from selected individual experiments are presented in order to provide in-depth descriptions and analyses of wave processes on each of the platforms.
Chapter 3 presents the results of two hydrodynamic experiments conducted under non-storm swell conditions on platforms of different widths at Tatapouri and Oraka. The two case studies focus on temporal and spatial variations in wave characteristics and wave transformation under swell conditions. The first study (published as Ogawa et al., 2011) presents detailed analyses of wave transformation on the 250-m-wide shore platform at Tatapouri. A particular focus is given to gravity-wave processes and energy characteristics, although infragravity-wave energy is also described. The second case study describes wave characteristics on the 150-m-wide platform at Oraka, Mahia Peninsula, south of Gisborne (Ogawa et al., 2012). It examines gravity and infragravity-wave energy transmission across the
platform. The Oraka study also presents the first measurement of directional wave data on shore platforms.

In Chapter 4, results of the wave transformation experiments conducted on two platforms on the meso-tidal northeast coast of Auckland are presented. The two experiments were conducted under storm conditions with varying incident energy conditions (Ogawa et al, submitted; Ogawa, submitted). These case studies focus on the interaction of storm waves with the platform surface and explore how variations in incident wave conditions affect inner platform wave characteristics. First, an experiment conducted on the 150-m-wide shore platform at Rothesay Bay is described. Various hydrodynamic threshold values concerning wave propagation are examined using the variation in wave conditions experienced during the experiment. The second study describes and compares wave characteristics during the passage of a storm on the 90 m shore platform at Red Beach. During the experiment, incident wave conditions shifted from high energy storm conditions to post-storm swell conditions. Inner platform wave characteristics under storm and post-storm swell conditions are compared.

Chapter 5 presents a meta-analysis of all case studies reported in chapters 3 and 4. Two additional datasets obtained on the 90-m-wide shore platform at Pouawa Beach and the 270-m-wide platform at Oraka are also incorporated in order to complement the dataset and enable broader comparisons and analyses. Hydrodynamic data collected on each of the platforms are compared. Morphological controls on wave processes on Type B shore platforms, including platform width, elevation and slope, are explored. This chapter serves as a discussion and synthesis
Chapter. Chapter 6 summarises the results and discussion presented in chapters 3 to 5.
CHAPTER 2
Literature Review

2.1 Introduction
This chapter reviews the existing literature concerning wave transformations on rock shore platforms. A short review of shore platform morphodynamics is presented, followed by a review of the theoretical assumptions on wave transformations that have been applied in shore platform studies. Field observations of wave processes on shore platforms are then reviewed and current understanding of wave transformation across platform surfaces to cliffs is examined. Throughout the chapter, relevant literature concerning wave transformations and hydrodynamics from analogues coastal landforms such as coral reef platforms, and also sandy beaches, are reviewed, as only a few studies of waves on shore platforms are currently available.

2.2 Shore Platform Morphodynamics and Importance of Wave Processes
The importance of waves in shaping rock coasts was recognized as early as in the 19th century. Charles Darwin recognised the importance of wave processes in eroding cliffs around St Helena (Darwin, 1846). In ‘Principle of Geology’, Charles Lyell described low angle shoals or ledges found on many volcanic islands and attributed the formation of such features to the effect of “aqueous denudation” (Lyell, 1850). Dana (1849) coined the term "wave-cut platform" in recognition of the importance of wave processes in
forming shore platforms. The wave cut hypothesis of shore platform evolution has subsequently been supported by a number of researchers including Edwards (1941; 1958), Takahashi (1977) and Sunamura (1978b). Earlier researchers also recognised the importance of shore platforms in controlling wave energy reaching the cliff toe and performing geomorphic work. Darwin (1846) suggested that waves eroded coastal cliffs to sea-level. He further suggested that, for waves to continue eroding the cliff, subsidence would be required so that waves can reach the cliff face without being attenuated. Johnson (1919) also identified platform width as an important control on wave energy attenuation and suggested that cliff-toe erosion would eventually cease as platforms widen, due to increased wave energy attenuation across the platform surface. Significantly, this theoretical assumption has underpinned shore platform geomorphology for more than a century (see for example, Sunamura, 1992; Trenhaile, 2000; de Lange and Moon 2005). However, it is yet to be validated thorough field measurements.

Recognising the importance of shore platforms in modulating wave energy that reaches the cliff toe and promotes erosion, Carter et al. (1987) suggested that coastal cliffs and platforms should be treated as one morphodynamic system. More recently, Stephenson and Thornton (2005) advocated the benefit of a morphodynamic approach in framing shore platform research and pointed out the need to understand wave characteristics on shore platforms and how these vary between platforms with different morphological characteristics. Empirical relationships between the platform types and the balance between the erosive force of waves and the rock strength reported by Sunamura (1992)
and Tsujimoto (1987), and the correlation between platform gradient and tidal range identified by Trenhaile (1974; 1999) both indicate that there are morphodynamic linkages between hydrodynamic processes, resulting morphology and the morphological feedbacks on wave processes (Fig. 2.1). Most recently Naylor et al. (2012) proposed a morphodynamic model for rock coasts that includes a complex feedback loop between wave induced erosion and the resisting force of rock substrate which is a function of rock material properties and rock mass properties (Fig. 2.2).

Figure 2.1: Relationship between shore platform morphology and tide and wave forces. a) relationship between tidal range and platform gradient (after Trenhaile, 1999) and b) relationship between substrate resistance force, wave force and resulting morphology (after Sunamura, 1992).
Figure 2.2: Morphodynamics of rocky coasts including shore platforms (source: Naylor et al. 2012: p.28).
The morphodynamic concept is yet to be fully explored in rock coast and shore platform geomorphology. The morphodynamic model proposed by Naylor et al. (2012) does not recognise the importance of morphological feedback on wave processes which ultimately controls the amount of erosive force of waves exerted at the erosion front (i.e. platform surface and cliff toe). As seen in Figure 2.2, the treatment of wave processes is simplistic, as it indicates a linear wave input that promotes erosion. The model does not reflect different wave types that can occur or feedbacks where morphology influences wave processes. Such feedback processes have been recognised in other coastal systems such as clastic sandy beach (Wright and Short, 1984; Masselink and Short, 1993) and coral reef environments (Kench and Brander, 2006; Kench, 2011), and are an integral part of the coastal morphodynamic concept. Furthermore, the model does not consider time-scales over which different processes operate and morphological adjustments occur. It is likely that different components within a shore platform system respond to various processes at different rates. For example, at or near the seaward edge of a shore platform, erosion may occur instantaneously by dynamic pressure exerted on the substrate by breaking waves, while erosion at an inner platform location may be caused by mechanical wave actions at a much slower rate. Significantly, the timescales of responsiveness of the entire platform-cliff morphodynamic system are many orders of magnitude greater than for unconsolidated depositional coastal landforms.

Recent micro-seismic studies on rocky coasts provide further evidence that shore platforms are important morphological features that affect wave energy delivery to
cliffs. Adams et al. (2005) recognised the importance of nearshore wave transformation processes on wave energy delivery to the cliff face. Wave energy delivery to the cliff was tidally modulated, and wave energy dissipation across the submerged shore platform fronting the cliffs exerted an important control on micro-seismic signals generated (Adams et al., 2002).

More recently Lim et al. (2011) utilised a seismometer and terrestrial laser scanner to monitor the effects of micro-seismic impacts on the cliff face on the North Yorkshire coast of the U.K. They found that wave energy delivery to the cliff was strongly modulated by the tide, with a bimodal distribution of micro-seismic events that occurred at water depth 1 m below and above high tide and low tide respectively. The elevational dependency for micro-seismic events was found to be approximately 1 m above the cliff base, but a minor step (0.2 m) on the platform also caused an increase in the number of micro-seismic events towards low tide (Lim et al., 2011), indicating that tide and platform morphology have important controls on wave energy expenditure. However, these studies lacked synchronous across-shore measurements of wave characteristics. Consequently the pattern of wave energy dissipation and transformation can only be speculated from the proxy micro-seismic signals and, in some studies, wave record from a single offshore wave gauge. Recently, Dickson and Pentney (2012) measured wave induced cliff shaking and wave transformations on a shore platform on the east coast of the North Island, New Zealand, using an extensive array of seismometers and wave gauges. They found that the majority of wave energy was dissipated at the seaward edge of the platform at all tidal stages. The intensity of
cliff motions was found to be correlated to incident wave conditions and became greater at low tide due to greater intensity of wave breaking across the seaward edge (Dickson and Pentney, 2012). Results presented by Dickson and Pentney (2011) demonstrate the importance of platform morphology, in particular, platform elevation, in attenuating and transmitting wave energy to the rock substrate. However, specific conditions under which wave breaking takes place at the seaward edge and subsequent transformation of waves across the platform surface is yet be investigated in detail.

2.3 Theoretical Assumptions on Shore Platform Wave Processes

The development of shore platforms has commonly been considered a balance between the erosive force of waves and the strength of substrate rock, which is controlled by lithology and the degree of weathering (Sunamura, 1992). In its simplest term, the horizontal extension of shore platforms \( (x) \) can be described as a function of the assailing force of waves \( (F_w) \), rock resistance \( (F_r) \) and time \( (t) \):

\[
x = f(F_w, F_r, t)
\]

Eq. 2.1

Sunamura (1992). In this context, understanding wave transformations on shore platforms is critical in determining wave energy delivery to cliffs. Although wave transformations from deep, intermediate to shallow water are explained in the two major rock coast textbooks by Trenhaile (1987) and Sunamura (1992), wave transformation processes on the shore platform surface have been assumed to be relatively simple and there are comparatively few detailed studies available. On Type B
platforms waves typically break at the seaward edge due to the sudden change in water depth. To date, broken waves have been considered to dissipate progressively across the platform surface (Sunamura, 1992; Trenhaile, 2000) and modelled with a exponential decay function within the surf zone (Sunamura, 1992) regardless of the location of the initial breaker line (i.e. offshore or at the seaward edge). This model of wave transformation and energy reduction is illustrated in Figure 2.3. In most cases, it is assumed that waves break on, or in front of, the seaward edge of sub-horizontal 'Type B' shore platforms (Trenhaile 2008a).

In attempting to model erosion of cliffs and evolution of shore platforms, Trenhaile (2000) developed a wave transformation model which uses an exponential decay function:

\[
S_f = 0.5 p_w (H_b/0.78)e^{kW_s}
\]

Eq. 2.2

where \( S_f \) is surface force, \( p_w \) is water density, \( H_b \) is breaker height, \( k \) is wave decay constant and \( W_s \) is surf width which is calculated as:

\[
W_s = h/\beta
\]

Eq. 2.3

where \( h \) is water depth and \( \beta \) is surface gradient.
Figure 2.3: Theoretical assumptions of wave transformation on shore platforms as presented in literature. a) wave propagation towards the cliff (after Sunamura. 1992) and b) wave energy attenuation model used in Trenhaile (2000)'s numerical model.

In the absence of acceptable wave theories and field data on shore platforms, Trenhaile (2000; 2008a) used a single $k$ value to model the wave attenuation rate. Several $k$ values were used for different model runs (Fig. 2.3b). Of note, Equation 2.2 indicates
that, with this parameterisation, wave energy on shore platforms is a direct function of the initial breaker height and the width of the surf zone.

The assumptions made in these expressions for wave transformations on shore platforms have subsequently been incorporated into a number of numerical models that simulate the role of subaerial weathering (Trenhaile, 2008b), the effect of Holocene sea level change (Trenhaile, 2010a), the development of marine terraces (Trenhaile, 2002a) and the evolution of platforms in micro-tidal environments (Trenhaile, 2008a) without a field verification. As acknowledged by Trenhaile (2000; 2008a) the actual rate of wave attenuation will likely vary depending on breaker types, surface roughness and platform water depth. In addition, the assumption that waves dissipate exponentially across the platform surface has not been validated through detailed field observations.

Equation 2.2 indicates that waves attenuate across the length of the surf zone. As seen in Eq. 2.3, the surf zone on shore platforms is considered to be a direct function of wetted width on the platform surface measured from the breaker line. Consequently, the entire platform surface from the seaward edge to cliff toe becomes the surf zone on a very flat shore platform assuming that waves break at the seaward edge, neglecting the possibility of wave reformation. These assumptions and numerical expressions will be examined using field data in the following chapters.

One of the most important parameters in nearshore and surf zone hydrodynamics is the wave breaking criterion or the breaker index \( \gamma \). In shallow water coastal environments, waves become depth-limited and eventually break (Komar, 1998;
Chapter 2: Literature Review

Masselink and Hughes, 2003). Wave height in depth-limited conditions is generally expressed as:

\[ H = \gamma h \]  \hspace{1cm} \text{Eq. 2.4}

where \( H \) is wave height, \( \gamma \) is the breaking criterion and \( h \) is water depth.

McCowan (1894), and later Munk (1949), derived a value of 0.78 for the wave breaking criterion on the basis of solitary wave theory. This value has been used for determining breaker depths in numerical models and calculating maximum wave height on shore platforms (Stephenson and Kirk, 2000a; Trenhaile, 2000; Trenhaile and Kanyaya, 2007).

In contrast to other studies on shore platforms, Sunamura (1992) assumed that waves break when wave height to water depth ratio became 1:1 (\( \Upsilon=1.0 \)), because “it would be allowable in most cases to assume” this simple relation (Sunamura, 1992: p.174) without presenting any supporting evidence.

These theoretical assumptions may be consistent with standard wave theories during the initial stages of wave energy dissipation (Stephenson and Thornton, 2005), but they are yet to be underpinned by field observations on shore platforms. In those expressions (Eq. 2.2 and 2.3), morphological controls on wave transformation are reduced to a simple function of platform width and dissipation rate determined simply from the incident wave height. However, it has been demonstrated on coral reef platforms that reef platform geometries play important roles in modulating wave processes on the inner reef platform surface (Kench and Brander, 2006). Furthermore, the wave breaking criterion currently used on shore platform research appears to be
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overly simplistic and outdated as identified in other coastal settings (Thornton and Guza, 1982; Nelson, 1985). For example, Dally et al. (1985) showed that the 0.78 criterion is only marginally accurate for a bottom gradient of 1/30 ($\beta = 0.033$).

The lack of wave studies on shore platforms and rocky coasts in general partly explains the omission of morphological feedbacks on wave processes in the shore platform morphodynamic model.

2.4 Field Studies of Wave Characteristics on Shore Platforms
There has been a recent increase in field studies of waves on shore platforms. To date six field studies of waves on shore platforms containing wave data on 11 platforms have been published (Table 2.1). The published studies are limited geographically and morphologically as seen in Table 2.1. It is evident that most studies have been conducted in micro and lower meso-tidal environments. The majority of the studies were also on Type B platforms. In terms of platform geometry, most studies have occurred on low gradient platforms with platform widths ranging between 60 m and 150 m.
Table 2.1: Summary of wave experiments on shore platforms.

<table>
<thead>
<tr>
<th>Study</th>
<th>Location</th>
<th>TR (m)</th>
<th>Morphology</th>
<th>Focus of study</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stephenson and Kirk (2000a)</td>
<td>Kaikoura, South Island, New Zealand</td>
<td>2.6</td>
<td>A</td>
<td>160*</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2.6</td>
<td>B</td>
<td>80*</td>
</tr>
<tr>
<td>Stephenson and Thornton (2005)</td>
<td>Otway Coast, Victoria, Australia</td>
<td>B</td>
<td>35</td>
<td></td>
</tr>
<tr>
<td>Trenhaile and Kanyaya (2006)</td>
<td>Scots Bay, Bay of Fundy, Canada</td>
<td>13.5</td>
<td>A</td>
<td>100*</td>
</tr>
<tr>
<td></td>
<td>Mont Louis, Gaspe, Quebec, Canada</td>
<td>3</td>
<td>B</td>
<td>170*</td>
</tr>
<tr>
<td>Farrel et al. (2009)</td>
<td>Belinho, Portugal</td>
<td>2.5</td>
<td>B</td>
<td>90*</td>
</tr>
<tr>
<td>Beatham and Kench (2011)</td>
<td>Rothesay Bay, Auckland, North Island, New Zealand</td>
<td>3</td>
<td>B</td>
<td>130</td>
</tr>
<tr>
<td></td>
<td>Oraka, Mahia Peninsula, North Island, New Zealand</td>
<td>1.7</td>
<td>B</td>
<td>270</td>
</tr>
<tr>
<td>Martial and Stephenson (2011)</td>
<td>Kaikoura, South Island, New Zealand</td>
<td>1.4</td>
<td>B</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Kaikoura, South Island, New Zealand</td>
<td>1.4</td>
<td>A</td>
<td>140</td>
</tr>
<tr>
<td></td>
<td>Hayley Point, Marengo, Victoria, Australia</td>
<td>1.1</td>
<td>B</td>
<td>60</td>
</tr>
<tr>
<td></td>
<td>Browns Creek, Apollo Bay, Victoria, Australia</td>
<td>1.1</td>
<td>A</td>
<td>65</td>
</tr>
</tbody>
</table>

Morphology: Type: A = sloping platform, B = sub-horizontal platform, W = width, G= gradient.

TR = spring tidal range (note that the definition of spring tidal range differs among countries and the values given here are guide only).

*estimated from the cross-sections presented in the publications. None of the three publications defined mean platform elevation and width.

** estimated from the cross-sections presented in the original publications.
Field studies of waves on shore platforms have focussed on three areas: wave height measurements across the platform surface; erosion potential of waves; and wave transformation processes. Stephenson and Kirk (2000a) and Trenhaile and Kanyaya (2007) investigated whether waves had the potential to erode substrate on contemporary shore platforms. Of note, Stephenson and Kirk (2000a) were the first to measure wave height attenuation from offshore to nearshore and across two shore platforms on Kaikoura Peninsula, New Zealand.

Stephenson and Kirk (2000b) reported over 90% of wave energy was dissipated across the platform surface. Given the limited amount of data available due to the number of sensors deployed and a sensor failure, Stephenson and Kirk (2000a) used the solitary wave theory criterion of 0.78 (McCowan, 1894; Munk, 1949) to estimate the wave height limit on the platforms. They concluded that wave erosion is inactive on the platform surface and at the cliff toe, as almost all wave energy was dissipated in the nearshore and upon breaking at the seaward edge. Trenhaile and Kanyaya (2007) recorded wave height and period (using a video camera and wave poles) and estimated the erosive capacity of waves at two study sites in Canada: the micro-tidal coast of Gaspe, and; the micro-tidal coast of Bay of Fundy. Trenhaile and Kanyaya (2007) concluded that waves are important agents of erosion on Type A platforms as the steeper gradient of the platform allows larger waves to propagate towards the cliff, but less effective on Type B platforms due to shallow water depths and forced breaking at the seaward edge.

Stephenson and Thornton (2005) and Farrell et al. (2009) investigated wave height transformations on sub-horizontal shore platforms in micro-tidal environments. Stephenson and Thornton (2005) measured wave height on a Type B platform on
Otway Coast, Victoria, Australia, and identified a relatively low rate of attenuation (10 to 23%) between the seaward and the cliff toe. Importantly Stephenson and Thornton (2005) were the first to demonstrate that waves can reach the inner platform surface without being significantly attenuated and thereby presenting field evidence to support the assertion that waves are active agents of platform erosion. Furthermore, Stephenson and Thornton (2005) argued that the pattern of wave energy dissipation may differ between different platform types, suggesting that Type A platforms may be similar to dissipative beaches while Type B platforms are akin to reflective beaches. Farrell et al. (2009) investigated the wave breaking criterion on a sub-horizontal platform in Belinho, Portugal, and reported that the root-mean-squared wave height ($H_{rms}$) was limited to 42% of the platform water depths. This value is similar to the value reported by Thornton and Guza (1982) for inner surf zone stable wave height on sandy beaches.

The most recent studies on wave processes on shore platforms have utilised an array of multiple wave gauges across the platform surface to describe wave characteristics and transformation in detail. Spectral analysis was performed on wave data collected on shore platforms for the first time and detailed descriptions of wave transformation across shore platforms have become available (Beetham and Kench, 2011; Marshall and Stephenson, 2011). Beetham and Kench (2011) described several important controls on infragravity-wave energy amplification including incident wave height, platform width and cliff-toe water depth. In another study, Marshall and Stephenson (2011) measured wave height and characteristics on four different shore platforms in Otway, Victoria, Australia, and Kaikoura, South Island, New Zealand. Marshall and Stephenson (2011) identified platform gradient
and water depth as two primary controls on wave energy dissipation. Furthermore, Marshall and Stephenson (2011) reported infragravity waves to be the most important wave energy component on three out of four platforms they investigated.

Collectively field studies of waves on shore platforms have provided several new insights into wave characteristics and transformation processes on rocky shores, including the presence of infragravity waves. Interestingly, however, field data collected in those studies have not been utilised to test and/or verify theoretical assumptions and model parameters. In some studies (Stephenson and Kirk, 2000a; Trenhaile and Kanyaya 2007) field data were extrapolated or interpreted by using the same theories (e.g. the solitary wave theory breaking criterion) in order to further assess the ability of waves to perform geomorphic work. Furthermore such discussions of detailed wave processes are not found in recent review articles (Naylor et al., 2010; Dasgupta, 2011) concerning shore platforms and rocky coast geomorphology.

2.5 Wave Transformations on Shore Platforms

2.5.1 Wave attenuation and the role of the seaward edge

On shore platforms, attenuation of incident waves may occur in three spatially distinct zones: 1) the nearshore to the platform edge; 2) across the seaward platform boundary/edge, and; 3) across the platform surface. Waves may dissipate before reaching the platform if nearshore water depth is sufficiently shallow or by nearshore structures such as rocky reefs. For example, Stephenson and Kirk (2000a) reported that over 90% of offshore wave energy dissipated before reaching the platform edge during their experiment in Kaikoura, New Zealand, due to the energy
loss associated with shoaling and refraction in the nearshore. In contrast, wave energy dissipation is considered to be minimal where shore platforms are fronted by deep water (e.g. Dickson and Woodroffe, 2005; Dickson and Pentney, 2012). Sunamura (1991) suggested that the “front depth” is an important control on shore platform wave exposure. Although a direct relationship among front depth, wave exposure and platform geometry is yet to be established, a statistically significant, positive correlation between platform elevation and front depth have been reported by Sunamura (1991) in the laboratory and Dickson (2006) in the field. Furthermore, neashore slope (approach slope) is considered to be an important factor that affects the breaking behaviour across the seaward edge and hence wave attenuation (Goda and Morinobu, 1997; Goda and Morinobu, 1998).

Wave dissipation across the seaward boundary of shore platforms is most relevant on Type B forms which are characterised by a sharp seaward break in slope. Due to a sudden change in water depth across the seaward edge, waves are forced to rapidly transform and break. Threshold conditions for wave energy dissipation across the seaward edge of Type B platforms are yet to be determined. On coral reef platforms, which are morphologically analogous to shore platforms, reef edge water depth has been identified as an important control on wave energy attenuation (Brander et al., 2004). Gourlay (1994) reported that the minimum relative water depth \( h/H_s \) of 2.5 at the reef edge is required to induce wave breaking. The actual amount and the rate of energy dissipation across the reef edge are a function of breaker types and breaking intensity (Gourlay, 1994). It has been reported that up to 95 % of wave energy can be dissipated across the seaward edge on coral reefs (Roberts et al., 1975; Gourlay, 1994; Lugo-Fernández et al., 1994), although the
amount of energy dissipation also depends on incident conditions and morphological characteristics of reef flats (Kench and Brander, 2006). Nevertheless, given the similarities in morphological characteristics between type B platforms and coral reef platforms, it is likely that the threshold relative water depth at the seaward edge reported by Gourlay (1994) is applicable to shore platforms.

As demonstrated by Beetham and Kench (2011), not all wave energy is dissipated through the initial breaking processes at the seaward edge. It is this residual wave energy that is crucial for geomorphic work on the platform surface and at the cliff toe. The attenuation of wave height (or energy) across the platform surface is tidally modulated (Beetham and Kench, 2011; Marshall and Stephenson, 2011). The amount of wave attenuation between the seaward edge and cliff toe reported in the literature vary from 10% to over 90% (Stephenson and Kirk, 2000a; Stephenson and Thornton, 2005; Beetham and Kench, 2011). Results from the previous studies show that, in general, wave energy attenuation is greater at low tide due to shallow water depths (Beetham and Kench, 2011; Marshall and Stephenson, 2011). Marshall and Stephenson (2011) suggested that there is a water depth threshold for wave propagation on shore platforms which is yet to be quantified. Depth-limited wave conditions and wave height limit on shore platforms are discussed in the following section.

2.5.2 Constraints on wave height on shore platforms

Wave height is the most important physical property of waves as wave energy and wave velocity, the two important physical parameters in nearshore processes, are a
direct function of wave height. Wave energy and velocity are important on shore platforms in determining the ability of waves to perform various geomorphic work and transport sediments and large clasts (Nott, 1997; Dickson et al., 2007).

Waves have two forms of energy associated with vertical fluctuations in water surface (potential energy) and orbital motions (kinematic energy) (Komar, 1998; Masselink and Hughes, 2003). In Airy wave theory, those two forms of energy are equal and the total wave energy ($E$) can be calculated as:

$$E = \frac{1}{8} \rho g H^2$$  \hspace{1cm} Eq. 2.5

Where $\rho$ is density of water, $g$ is gravitational acceleration and $H$ is wave height. Similarly, the first order approximation of wave velocity ($c$) is a function of wave height as:

$$c = \sqrt{gH}$$  \hspace{1cm} Eq. 2.6

As noted earlier wave height in shallow water coastal environment is known to be depth-limited (Komar, 1998). This limit is often expressed through the depth-limited breaking criterion ($\gamma$ – Eq. 2.4). The significance of depth-limited breaking criterion is that wave height in the surf zone can be described without having to consider the details of wave energy dissipation processes and energy fluxes (Sallenger and Holman, 1985; Kamphuis, 2000). As a result this parameter is widely used in engineering and modelling applications.

The depth limited condition occurs due to spectral energy saturation in shallow water. Under energy saturated conditions, wave height becomes a direct function of water depth (Thornton and Guza, 1982; Sallenger and Holman, 1985). Similarly, the
height of reformed oscillatory waves are depth limited (Hardy and Young, 1996). To date, few studies have examined wave height limit on shore platforms, with the exception of Farrel et al. (2009) who reported wave height limits on a shore platform to be 42% of platform water depth.

Although spatial and temporal variations in wave height characteristics on shore platforms are yet to be investigated in detail, there is a wealth of knowledge about wave height limits and the breaking criterion in cognate fields (e.g. beach hydrodynamics and coastal engineering).

The breaking criterion has been found to vary significantly (0.3 to >1.0) from the breaker line, the outer surf zone and to the inner surf zone (Komar, 1998). However as waves propagate from the breaker zone to the inner surf zone, wave height becomes stable for a given water depth (Fig. 2.4a). Studies of wave breaking on a uniform slope show the wave height to water depth ratio decays asymptotically and eventually become stable at $0.5h$ (Horikawa and Kuo, 1966; Dally et al., 1985). Dally et al. (1985) proposed a wave energy flux model to account for wave transformation in the surf zone. As illustrated in Figure 2.4b, the wave height to water depth ratio gradually decreases as waves propagate through the surf zone stabilising at values of 0.35 to 0.40 (Dally et al., 1985). On a sloping surface, wave energy dissipation is proportional to the difference between the local energy flux and the stable energy flux for a given water depth (Dally et al., 1985). It is this stable wave height limit that is most relevant to wide Type B shore platforms as waves are expected to attain a stable wave height on the near-horizontal platform surface after the initial breaking at the seaward edge.
Figure 2.4. Wave energy flux in the surf zone and formation of stable waves: a) conceptual diagram illustrating wave height transformation in the surf zone with horizontal bottom, and b) ϒ value as a function of dimensionless distance (distance/wave height) inside the breaker zone. The equation in the figure demonstrates the changes in wave energy flux in the surf zone. a) and b) are based on Fig 2 and 3 from Dally et al. (1985) respectively (ECn)in = incoming “incident” wave energy flux. (ECn)out = outgoing “stable” wave flux.

On coral reef platforms, which are analogous to shore platforms, the value of the significant wave height breaking criterion (ϒs) is reported to stabilise at 0.4 and the maximum wave breaking criterion (ϒmax) at 0.6 (Hardy et al., 1990; Hardy and Young, 1996). Both physical experiments and theoretical analyses suggest that, on very flat
surfaces, the maximum wave height is unlikely to exceed 55% of local water depths (Nelson, 1985; Gourlay, 1994; Nelson, 1994; Massel, 1996; Massel, 1998). Nelson (1985; 1994) reported, based on extensive laboratory data, that the maximum wave height to water depth ratio on a flat surface is a function of the non-linearity parameter $F_c$ (Swart and Loubser, 1979), which is essentially a wave shape parameter, and proposed the following expression.

$$\gamma_{max} = F_c / (22 + 1.82F_c) \quad \text{Eq. 2.7}$$

where

$$F_c = (H/h)^2(T\sqrt{g/h})^{5/2} \quad \text{Eq. 2.8}$$

However, such an equation is transcendental, as $F_c$ also depends on $H$ and $h$ (Massel, 1996). Massel (1996) suggested that $F_c$ should be replaced by an independent variable. The following relation was proposed (Massel, 1996; Massel and Gourlay, 2000):

$$\gamma_{max} = [1 + 0.001504(h/gT^2)^{-2.5}] / 0.1654 (h/gT^2)^{-1.25} \quad \text{Eq. 2.9}$$

The actual value of $\gamma_{stable}$ is known to vary according to a number of factors including the surf similarity parameter (Masselink, 1993), bottom slope (Sallenger and Holman, 1985; Masselink, 1993; Camenen and Larson, 2007), in-shore wave steepness (Price and Ruessink, 2008) and in very shallow water depths (< 0.5 m), local water depth itself (Sénéchal et al., 2004; Dehouck et al., 2009). Raubenheimer et al. (1996) and Sallenger and Holman (1985) demonstrated $\gamma$ in the inner surf zone is independent of offshore wave steepness. Raubenheimer et al. (1996) and Sénéchal et al. (2001) reported that $\gamma$ values increased with increasing bottom slope.
and decreased with normalised slope. Nelson (1987) and Kamphuis (1991a; 1996; 2000) conducted extensive laboratory experiments and proposed empirical equations for predicting $\gamma$ values on sloping surfaces (Fig. 2.5). Of particular relevance to shore platform hydrodynamics is Nelson (1987) who investigated wave height transformation on flat and very mildly sloping surfaces. According to Nelson (1987), the maximum wave-height to water-depth ratio ($\gamma_{\text{max}}$) for a given slope can be estimated using the following expression:

$$\gamma_{\text{max}} = 0.55 + 0.88 \exp(-0.012 \cot \beta) \quad \text{for } \beta \leq 0.1 \quad \text{Eq. 2.10}$$

Nelson (1987) reported that, at $\beta = 0.004$ (0.2°) wave mechanics appeared to change and the $\gamma$ value increased dramatically beyond this threshold (Fig. 2.5). Given that the Eq. 2.10 is designed especially for very gently sloping near-horizontal surfaces, it may be applicable on shore platforms.

![Figure 2.5: Examples of dependence of the wave breaking criterion on bottom slope.](image)
It is likely that differences in platform slope control the breaking criterion is very important on shore platforms. If wave height on very horizontal platform platforms does not exceed 55% to 60% of local water depth as demonstrated in physical modelling and on coral reefs, the current practice of using the solitary wave criterion ($Y = 0.78$) is likely to significantly overestimate the wave height limit on sub-horizontal shore platforms. Furthermore, if there is a clear boundary between ‘horizontal’ and ‘sloping’ surfaces where the breaking criterion changes as predicted by Nelson (1987), it may be possible to classify hydrodynamic characteristics of near-horizontal shore platforms based on the differences in the wave breaking criterion. The dependence of gravity-wave height on platform slope and the applicability of Eq. 2.10 are examined in chapters 4 and 5.

### 2.5.3 Bottom roughness and frictional controls on platform wave height

Wave height on the inner platform surface may also be limited by frictional energy loss caused by the interaction of wave orbital motion with the platform surface. Two frictional mechanisms are considered important: the roughness of the bottom surface and the gradient of the bed (Kurian and Baba, 1987). On shore platforms, frictional energy loss most likely occurs due to the attenuation caused by surface roughness given the relatively small surface gradient of most platforms. Energy loss due to surface friction is an important part of the wave transformation component in numerical models for shore platform evolution. However frictional attenuation on shore platforms is yet to be investigated and appropriate values of frictional or roughness coefficient determined. In the absence of field measurements, a range of values that is “large enough” (Trenhaile, 2000: 165) to simulate low to high
roughness conditions are used in numerical models to account for frictional attenuation on shore platforms.

Given that the surface morphology of shore platforms varies significantly according to lithological and structural controls (Trenhaile, 1987; Sunamura, 1992), even within a region (Healy, 1968b), the role of bottom friction is likely to vary significantly as hydraulic roughness increases with surface roughness. Previously Kamphuis (1991b) demonstrated that the frictional energy loss due to the presence of bedforms on sandy beaches to be minimal regardless of bed form dimensions, suggesting that the effect of bottom friction is likely to be small on shore platforms with smooth surface or with minor topographic variations. Indeed, wave attenuation due to friction is considered to be negligible in the surf zone for most conditions (Kamphuis, 1975; Dally et al., 1985). In contrast, studies on frictional attenuation on coral reef platforms show some discrepancies in the friction coefficient (Lugo-Fernández et al., 1994; Nelson, 1996; Zhu et al., 2004) and indicate that the effect of bottom friction is site specific. Previously, Brander et al. (2004) demonstrated that the maximum wave-height to water-depth ratio is rarely approached on the inner reef platform on the Warraber reef in Torres Strait, Australia. Brander et al. (2004) suggested that the large reef width and rapid attenuation at the seaward edge and topographic effects are responsible, indicating that frictional energy loss plays an important role in wave height attenuation on wide reef platforms. Consequently, it is likely that the effect of bottom friction is more significant on wide shore platforms with very a rough platform surface, especially at low tidal stages as frictional effects are also reported to be depth-dependent (Jago, 2005). Increased wave energy attenuation at low tide reported on shore platforms by Marshall and Stephenson
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(2011) indicates that frictional attenuation may be an important process at low tide. However, as dissipation rates on shore platforms are often calculated from incident wave height, it is impossible to determine whether the tidal modulation of incident wave conditions or increased frictional loss is responsible for the observed increase in dissipation rate at low tide. In order to confirm the role of surface friction (or roughness) in wave energy dissipation on shore platforms, the existing data needs to be re-analysed or new experiments conducted. Tidal modulation and water depth control on wave attenuation will be evaluated in chapter 5.

2.5.4 Importance of wave frequencies

Waves can be described in terms of wave frequencies, which can be linked to different wave generation mechanisms. Waves of different origins such as swell waves, locally generated wind waves, and infragravity waves generated by gravity-wave interactions are characterised by different wave frequencies (Masselink and Hughes, 2003). Brander et al. (2004) categorised waves into five different frequency bands including far infragravity waves (< 0.01Hz, > 100 s) infragravity waves (<0.05 Hz, > 20 s), swell waves (0.05 – 0.125 Hz, 8 – 20 s), locally generated wind waves (0.125 – 0.33Hz, 3 – 8 s) and short-period capillary waves (> 0.33Hz, < 3 s). In many other studies, wave frequencies are simply categorised into the infragravity waves (< 0.05Hz) and gravity waves (> 0.05 Hz).

Recent advances in quantitative process studies on rocky coasts show that waves of different frequencies load shore platforms and cliffs differently. Young et al. (2011) found that high frequency cliff shaking was caused by incident waves while gravitational loading-induced swaying and slow swaying were caused by swell
waves and infragravity waves respectively. In accordance with the previous studies on cliff shaking, wave energy delivery was tidally modulated, and, at low tide, cliff motions were only forced by oceanic waves at infragravity frequencies (Young et al., 2011). The presence and the importance of different waves frequencies are well recognised in other coastal systems (Ivamy and Kench, 2006; Kench and Brander, 2006; Masselink et al., 2006), but are yet to be fully examined on shore platforms. Few studies described wave spectra and different wave types on shore platforms to date, with two notable exceptions: Beetham and Kench (2011) and Marshall and Stephenson (2011).

In shallow water coastal environments, including shore platforms, transformation of waves involve a number of complex processes including shoaling and local wind energy input that lead to an increase in wave energy, non-linear triad and quadruplet energy transfer to harmonic and sub-harmonic frequencies that change wave energy distribution within the wave field and energy loss due to breaking and friction (Fig. 2.6) (Holthuijsen, 2007).

![Figure 2.6: Generalised conceptual diagram of wave energy and frequency transformation in shallow water coastal environments (modified from Holthuijsen, 2007).](image)
Previously Beetham and Kench (2011) showed that the relative importance of waves at incident gravity and infragravity frequencies varied spatially and temporally on shore platforms. They showed that energy at infragravity frequencies increased towards the cliff toe while energy at gravity frequencies was significantly attenuated at the seaward edge. Marshall and Stephenson (2011) reported that infragravity-wave energy dominated the wave spectra on shore platforms on the micro-tidal coast of New Zealand and Australia. They showed that waves at wind-wave frequencies were more susceptible to attenuation across the platform surface and consequently waves at swell and infragravity frequencies were more important at inner platform locations. Studies on coral reef platforms also identified temporal and spatial variations in wave frequencies across the reef surface. Brander et al. (2004) demonstrated that, on a coral reef platform, transformation of waves across the seaward edge, onto the platform surface and to the beach toe involved a major change in wave frequency and energy characteristics. In particular, they showed that incident swell waves were most dominant on the outer rim of the reef platform, while infragravity waves (<0.05 Hz) and locally generated short-period waves (>0.33 Hz) were more dominant on the inner reef platform surface. Given the small number of studies of wave frequency and energy characteristics available on shore platforms, the patterns of wave energy transformation observed by Beetham and Kench (2011) and Marshall and Stephenson (2011) needs to be verified at other study sites.
2.5.5 Infragravity wave motions on shore platforms

As noted above, the presence of infragravity waves has been reported on shore platforms (Beetham and Kench, 2011; Marshall and Stephenson, 2011), although their geomorphic significance is yet to be determined. Infragravity waves are generated by temporal and spatial variations in radiation-stress gradients in the wave field generated by wave groups (i.e. the group bound wave theory, Longuet-Higgins and Stewart, 1962) or temporal variations in break points (i.e. the break point variation theory, Symonds et al., 1982) or both (List, 1992; Schaffer et al., 1993). Infragravity-wave energy is known to increase towards the shore and with increasing offshore incident wave height (Holman, 1981; Elgar et al., 1992). On sandy beaches, horizontal and vertical excursions of swash at infragravity frequencies are known to increase with increasing incident wave height while swash at gravity frequencies are independent of offshore wave conditions (Guza and Thornton, 1982). Hence infragravity waves are very energetic on the inner shore of dissipative and intermediate sandy beaches and coral reef platforms (Wright et al., 1982; Elgar et al., 1992; Brander et al., 2004). They are considered to be an important agent of beach erosion and sediment transport during storm events as gravity waves tend to break further offshore (Russell, 1993).

Beetham and Kench (2011) reported that infragravity-wave energy reached the maximum at the cliff toe of shore platforms due to shoaling. Furthermore, they showed that cliff-toe infragravity-wave height is linearly correlated to nearshore significant wave height. In general, results reported by Beetham and Kench are in accordance with the studies on dissipative and intermediate sandy beaches and coral reef platforms (Lee and Black, 1978; Wright et al., 1982; Wright and Short,
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1984; Kench and Brander, 2006). Consequently, infragravity waves may be an important geomorphic agent on shore platforms, especially in the presence of sandy beaches or talus slope at the cliff toe.

Although Marshall and Stephenson (2011) and Beetham and Kench (2011) demonstrated the importance and the dominance of infragravity waves on some shore platforms, several aspects of wave frequency characteristics on shore platforms remain to be determined. In particular, it is unclear when and where infragravity waves become dominant on shore platforms. Beetham and Kench (2011) noted that infragravity waves were reflected by the steep seaward edge of Type B platforms during low tide, indicating that there is a water depth threshold below which infragravity waves cannot propagate onto the platform surface. Previously Kench and Brander (2006) reported the presence of water depth thresholds beyond which gravity waves became more dominant on coral reef platforms. Results reported by Marshall and Stephenson (2011) and Beetham and Kench (2011) indicate there may be different hydrodynamic zones present that are associated with different wave types (i.e. gravity and infragravity waves). The presence of different hydrodynamic zones with different wave characteristics across the platform surface is yet to be identified. The presence and the characteristics of different hydrodynamic zones will be addressed in chapter 3.

Transformation of infragravity waves across the platform surface to the cliff toe remains to be described in detail. While Beetham and Kench (2011) identified incident wave conditions and platform geometry as important controls on infragravity wave shoaling, no correlation can be found in the results reported from the two study sites in their study. Transformation of infragravity waves is known to
be complex and their response to the changes in incident wave energy may not be linear and instantaneous. For example, while infragravity-wave energy at the shore is known to be positively correlated to incident wave height, the amount of across-shore increase in infragravity-wave energy is reported to decrease with wave breaking criterion at the breaker line (Ruessink, 1998a; Ruessink, 1998b). Cetin et al. (2005) reported that the maximum infragravity-wave energy on a barred beach was not observed during the peak storm period but under the post-storm swell conditions. These studies demonstrate that further studies are required to understand the behaviour of infragravity waves on shore platforms. These issues are examined in two case studies presented in chapter 4.

2.6 Morphological controls on wave transformation

Field based studies of wave characteristics on shore platforms, although limited in terms of the scope and number, demonstrate the importance of platform morphology in modifying wave energy characteristics. However as demonstrated in other coastal environments (e.g. Wright and Short, 1984; Kench and Brander, 2006; Dehouck et al., 2009), wave processes on a number of platforms with different morphological types need to be investigated and compared before general relationships between wave and morphological characteristics can be established.

Morphological feedbacks on wave transformation on shore platforms are yet to be adequately described. Wave transformation in the nearshore and the surf zone is known to be significantly affected by the morphology of the sea bed. Nearshore features such as inter-tidal bars are known to affect wave processes on sandy
beaches (Masselink et al., 2006). The morphological effects on wave transformation on shore platforms reported in the available literature vary considerably. Trenhaile and Kanyaya (2007) concluded that wave erosion was more important on the sloping platform because a steeper slope (hence deeper water) allowed waves to reach inner platform areas without dissipation. Stephenson and Thornton (2005) considered Type A platforms to be more dissipative and Type B platforms to be more reflective. In contrast, Marshall and Stephenson (2011) concluded that a steeper platform gradient results in greater wave attenuation. Furthermore, Marshall and Stephenson (2011) recognised platform water depth as an important control on platform wave energy gradients. Interestingly, they suggested that platform width is the least important control on wave energy dissipation (Marshall and Stephenson, 2011: 30). In another study, Beetham and Kench (2011) considered platform width, water depth and cliff-toe gradient as important controls on wave processes, especially for the transformation of infragravity waves.

The aforementioned studies on waves on shore platforms attempted to compare morphological effects on wave energy transformation without providing adequate controls for incident wave energy conditions. Although the importance of incident wave conditions in wave energy dissipation and infragravity-wave height have been recognised by Marshall and Stephenson (2011) and Beetham and Kench (2011), there is no threshold value for gravity and infragravity wave transmission reported in those studies. While attempts were made to compare wave-height attenuation and infragravity-wave shoaling, a lack of normalisation in these studies means it is difficult to make inter-site comparisons. Furthermore, the most energetic infragravity-wave frequencies are not isolated in the studies conducted on shore
platforms to date to calculate significant wave height. As infragravity waves and gravity wave behave differently in the inner surf zone, it is essential that higher and lower frequency components are isolated before wave height and dissipation rate are calculated (Sénéchal et al., 2001).

While Marshall and Stephenson (2011) argued that platform width was not the most important control on wave energy attenuation, platform width can be important for other wave processes. For example, waves are known to reform after travelling two to three wave lengths after the initial breaking at the edge of coral reef platforms (Gourlay, 1994). Gourlay (1994) presented an empirical equation for predicting surf zone width on coral reef platforms. Reorganisation of Eq. 7 in Gourlay (1994) gives the width of the surf zone \( W_s \) as:

\[
W_s = \left(2 + 1.1 \frac{H_i}{h_e}\right)/T(gh_e)^{0.5} \tag{2.11}
\]

where \( H_i \) is incident wave height and \( h_e \) is water depth at the reef edge. Once reformed, the rate of wave energy attenuation becomes negligible (Gourlay, 1994; Hardy and Young, 1996), unless a large amount of wave energy is dissipated due to frictional loss, or a change in water depth forces waves to break again. As the distance waves can travel on shore platforms is limited by the platform width, there should be multiple hydrodynamic zones present on wide platforms (e.g. surf zone, reformation zone etc.) while narrower platforms may only have a surf zone.

Taking into account platform width and water depth (and hence the elevation), Kench and Brander (2006) proposed the reef energy window index \( \psi \) to describe wave energy characteristics on coral reef platforms (Fig. 2.7). According to Kench
and Brander (2006), the occurrence of gravity-wave energy on reef flats can be estimated as:

\[
\text{Percent dominance of gravity waves} = 13.4 \ln(\psi) + 117.5 \quad \text{Eq. 2.12}
\]

where

\[
\psi = \frac{h_{sp}}{W} \quad \text{Eq. 2.13}
\]

and \( h_{sp} \) is mean depth at spring high tide and \( W \) is reef width.

Wide reef platforms with a high platform elevation will have a small value of \( \psi \), indicating that gravity waves will be dissipated before reaching the beach toe. In contrast, narrow reef platforms with a low platform elevation (or high water depth) will experience a greater amount of gravity waves as more wave energy can be transmitted across the reef flat (Fig. 2.7). Given the similarity in morphological characteristics between Type B platforms and coral reef platforms, there is a
possibility that the reef energy window index may be a useful parameter on Type B platforms. If found to be applicable, the reef energy window index has important implications on shore platform wave processes under rising sea-level, as rising sea-level has the potential to increase the water depth on shore platforms and therefore increase the energy widow. However, the application of such a parameter may require some modifications as the reef energy window index does not take into account changes in incident conditions and morphological factors such as platform slope.

Morphological controls on wave-energy transmission and the importance of incident wave energy conditions have been investigated extensively on submerged breakwaters. Studies of wave transmission over submerged breakwaters have identified a number of important controls on wave-energy transmission, including: relative wave height (wave height / depth), relative crest submergence or free board (depth / wave height), dimensionless crest widths (crest width/ wave height) and relative width (crest width / wave length) (e.g. Blenkinsopp and Chaplin, 2008; Cappietti, 2011; Yuliastuti and Hashim, 2011). Parameters such as the dimensionless crest width that do not take into account water depth are unlikely to be important on wide platforms (most shore platforms are considerably wider than breakwaters). However, as shown in wave studies on reef platforms, parameters such as relative wave height, relative crest submergence and relative width are likely to be important controls on wave transformations on shore platforms. In addition, field studies on waves on shore platforms may provide useful comparisons to the studies on breaker waters and other submerged structures as the majority of such studies are conducted in wave tanks.
2.7 **Cliff-toe wave processes and associated hydrodynamic phenomenon**

The cliff-platform junction (i.e. cliff toe) is the most geomorphologically important and active part of a shore platform – cliff system where the cliff is eroded and a platform created. Cliff-toe geomorphic processes are activated by residual wave energy arriving at the cliff toe as a result of wave transformations across the platform surface. As discussed throughout the chapter, morphological controls on wave transformations on shore platform are yet to be fully understood.

In addition to first order wave transformation processes across the shore platform surface, cliff-toe wave characteristics can be complicated by a number of associated hydrodynamic processes including wave setup, wave induced currents, infragravity wave motions and wave reflection from the cliff face. Field observations of wave processes on shore platforms confirm that waves are being reflected by the cliff face at high tide (Marshall and Stephenson, 2011). Stephenson and Thornton (2005) suggested that the relatively small amount of wave attenuation across a 35 m Type B platform on the Otway Coast might be due to the narrow platform width and wave reflection from the cliff. However the effect and the amount of wave reflection on shore platforms are yet to be quantified.

As discussed earlier, infragravity waves are known to be dominant at the cliff toe of several shore platforms (Beetham and Kench, 2011; Marshall and Stephenson, 2011). Results reported by Beetham and Kench (2011) indicate that there is a consistent pattern of gravity wave attenuation and infragravity wave shoaling, albeit differences in magnitude between study sites. Infragravity waves can modulate inner shore water depths significantly. It is possible that the temporal increase in
cliff-toe water depth caused by infragravity waves may allow gravity waves access the cliff toe (Beetham and Kench, 2011).

Wave setup on shore platforms is yet to be described. Wave setup is a result of wave breaking, causing across shore variations in the mean water level (Bowen et al., 1968; Guza and Thornton, 1981; Holman and Sallenger, 1985). This occurs due to the pressure gradients in the wave field balancing the cross-shore component of the momentum flux (radiation stress) of propagating waves (Longuet-Higgins and Stewart, 1962). Field and theoretical studies on coral reef platforms (Tait, 1972; Jago et al., 2007) suggest that cliff-toe water depths on shore platforms may be super-elevated due to wave setup. Studies on sandy beaches show that wave setup can be up to 17% of incident wave height (Guza and Thornton, 1981). However, given the inherent variability of shore platform surface morphology, including the presence of channels, wave setup on shore platforms may not be as significant as those on beaches and reef platforms, as the elevated water can escape through channels and topographically lower points, and thereby reducing the effect of wave setup (Gourlay, 2011). Nevertheless, wave setup will, if present on shore platforms, increase the effective water depth for wave propagation on the platform surface and therefore has potential to enhance cliff-toe wave-energy delivery.

The combined effect of wave setup, infragravity waves and wave reflection on wave characteristics at the cliff toe is unknown. However, previous studies on seawalls indicate that wave height at the toe of a nearshore structure can be higher than expected due to the presence of those processes. For example, Kamphuis (1996) demonstrated that the combined effect of wave setup, incoming and outgoing bound and free long waves and the presence of the antinode of reflected waves at a toe of a
structure results in an increase in effective water depth and hence the wave height in front of the structure. Kamphuis (1996) found that such effects on effective water depth and wave height are directly proportional to incoming incident wave heights (approximately 10% of incident wave height). The hydrodynamic effect of infragravity waves and wave setup may be more pronounced under storm conditions, as both processes are known to be positively correlated to incident wave height. It is therefore possible that wave height at the cliff toe on shore platforms may be higher than the wave height on the platform surface for a given platform geometry, especially under high energy conditions. Temporal increase in cliff toe water depth caused by infragravity waves and wave setup, if present, will allow gravity waves to access the cliff face. In chapters 3 (Oraka) and 4 (Rothesay Bay), attempts are made to describe wave reflection and setup on shore platforms and the amount of water depth modulation caused by infragravity waves are reported also reported and discussed.

2.8 Summary
Intertidal shore platforms present a unique hydrodynamic regime due to their fixed geometry, impermeable surface and, in the case of Type B platforms, near horizontal slope that terminates abruptly at the seaward edge. Although waves have been considered as an important geomorphic forcing on shore platforms, comparatively little research has been conducted on wave transformations on shore platforms until recently. Consequently, conceptual understanding of wave processes on shore platforms is simplistic and has not considered types and transformation of wave energy that take place across the platform surface to the cliff toe. As a result, both
conceptual and numerical models of shore platform morphodynamics and evolution have been developed based on several theoretical assumptions which are yet be underpinned by field observations.

A small number of field based studies of wave characteristics and transformation have become available in the past decade. However, the differences in focus, objectives and methods used mean that a direct comparison of such studies is difficult. Furthermore, field studies of wave processes on shore platforms are geographically limited and platform morphology and incident conditions sampled vary. Consequently, the universality of the results presented in those studies needs to be confirmed.

A large body of knowledge about wave characteristics in other coastal environments such as coral reef and sandy beaches exist. Wave transformation and hydrodynamics have also been described in coastal engineering and physical oceanography literature. However the applicability of such studies needs to be tested on shore platforms.

Shore platforms provide a buffer that protects coastal cliffs from wave induced erosion. The efficacy of this buffer is expected to change with projected increases in sea level rise globally (Meehl, 2007; Grinsted et al., 2010) with the potential to increase cliff erosion (Walkden and Dickson, 2008). It is therefore important to underpin the morphological controls on wave processes and associated hydrodynamic phenomenon on shore platforms. Systematic studies that describe wave transformation from the seaward edge to the cliff toe are required. It is only
then morphological effects on wave processes can be assessed and a robust morphodynamics model constructed.
CHAPTER 3

Wave Transformations on Type B Shore Platforms under Fair-Weather Swell Conditions

Case Studies from the Coast of Gisborne Region, New Zealand

3.1 Introduction

This chapter presents two published case studies of wave transformation experiments conducted in the Gisborne region of the North Island of New Zealand, under fair-weather, swell-wave and spring tide conditions. The case studies focus on the following objectives as stated in chapter 1 section 1.3:

Objective (a): To describe and quantify wave-energy transmission and dissipation from the seaward edge to the cliff toe.

Objective (b): To characterise spatial variations in wave-energy characteristics across the platform surface from the seaward edge to the cliff toe.

Objective (c): To characterise temporal variations in wave characteristics on platforms.

Objective (d): To investigate and assess tidal controls on wave transformations.
Chapter 3: Wave Transformations under Swell Conditions

The case studies presented in the following section are reproduction of Ogawa et al. (2011) and Ogawa et al. (2012). These studies represent two of the first detailed descriptions of wave transformations on shore platforms to be published. As such, experiments were conducted under persistent swell conditions without a significant change in incident wave height. Temporal and spatial characteristics of waves on the platforms and transformation of swell waves from the seaward edge to the cliff toe are described. Both studies were conducted under similar incident wave conditions with high tide significant wave heights of 0.5 m observed at the seaward edge of the platforms during the experiments to control for incident wave energy entering the platform systems.

The first section (section 3.2) presents the results of a field experiment conducted on the 250 m shore platform at Tatapouri, north of Gisborne. This study describes wave energy and height transformation across the platform surface, with a particular focus on gravity-wave attenuation. The study provides the most detailed analysis of wave-energy spectra on shore platforms. An attempt is made to quantify the maximum and significant wave breaking criterion. The study also describes spatial and temporal variations in wave characteristics and identifies the presence of three hydrodynamic zones.

The second case study (section 3.3) focuses on wave-energy transmission across the platform surface to the cliff toe on the 140 m platform at Oraka. Across-shore transmission of gravity-wave height and infragravity-wave height are quantified and compared. The first measurements of directional wave data are also presented and discussed in order to quantify the amount of gravity and infragravity-wave reflection.
The platforms have comparable gradients but different widths, allowing the effect of platform width to be isolated. A comparison of the results reported in these two cases studies are made in the discussion section of each study (i.e. the articles are cross-referenced). However, detailed descriptions and comparisons of the results of the two studies are provided in this chapter as these are presented in chapter 5.
3.2 Case Study 1

Wave transformation on a sub-horizontal shore platform, Tatapouri, North Island, New Zealand

3.2.1 Introduction

Shore platforms are near-horizontal or low-gradient rock surfaces that occur within or close to the intertidal zone, usually in front of sea cliffs (Trenhaile, 1987). They are a distinctive morphological feature of many rock coasts. Trenhaile (1987) distinguishes two generalised shore platform morphologies; (a) gently sloping platforms (gradient between 1° and 5°) extending into the sub-tidal zone without any breaks of slope (sometimes labelled Type A), and (b) sub-horizontal platforms with a sharp seaward boundary (Type B). This second type is the subject of the current study. Unlike sandy beaches where the majority of nearshore and surf-zone hydrodynamic studies have been conducted, shore platforms provide a hydrodynamically unique environment due to their solid and impermeable surface, with a fixed alongshore and cross-shore geometry, that does not instantaneously adjust to the hydrodynamic forcing. The near-horizontal surface and the presence of a steep and abrupt seaward boundary that characterize sub-horizontal platforms generate a unique hydrodynamic regime.

Wave induced erosion is generally considered to be one of the most important processes driving morphological change on rocky coasts. However, there has been considerable historical debate over the relative dominance of two processes; sub-
aerial weathering and wave erosion in shore platform evolution. For example, while Dana (1849), Bartrum (1926), Edwards, (1941; 1958), Takahashi (1977) and Sunamura (1978) considered wave erosion to be the primary process, Bartrum (1916), Wentworth (1938; 1939), Hills (1949; 1971) and Stephenson and Kirk (2000a, b) attributed the formation of platforms to sub-aerial weathering, with wave action merely afforded a role in removing weathered rock. A number of studies have recognised that the processes operate together and that their roles may change over time (Trenhaile, 2002; 2008; Dickson, 2006). However, a consensus view on the relative importance of these processes has yet to be reached, which is in part attributable to a lack of detailed hydrodynamic studies of wave action in rocky coast environments (Stephenson, 2000). In addition to understanding the role of waves as an agent of shore platform development, improved resolution of nearshore hydrodynamic processes on rocky coasts is necessary to underpin coastal management and engineering applications. Located between coastal cliffs and the sea, shore platforms act as a buffer that protects cliffs from wave action. The efficacy of this buffer is expected to change with projected increases in sea level rise (Meehl et al., 2007) with the potential to increase cliff erosion (Walkden and Dickson, 2008). A recent study by Trenhaile (2010a; 2010b) is notable in this respect, as it implies that many sub-horizontal shore platforms may have been partly formed during an earlier mid-Holocene high sea level. If found to be correct the study has important implications for current and future potential rise in sea-level and its impact on shore platform erosion and cliff recession. Furthermore, numerical models suggest that rising sea level will result in an increased cliff recession rate, both on soft and hard rock coasts (Trenhaile, 20010a; 2010b; 2011).
In order to understand and model these complicated effects there is a need for field data on the hydrodynamic processes operating on shore platforms. However, there has been a paucity of research on hydrodynamic processes and interactions of waves with shore platforms (Naylor et al., 2010). There are a few notable exceptions. Stephenson and Kirk (2000a) examined the total amount of wave energy impacting the cliff toe on a sub-horizontal platform and a gently sloping platform at Kaikoura Peninsula, New Zealand. Based on the data collected by two pressure sensors, they found that only 6.8% of wave energy incident at the platform edge reached the cliff toe. On this basis they concluded that hydraulic forces generated by waves do not play a direct role in platform formation at Kaikoura. They also observed that incident waves were forced to break at the outer platform edge of the sub-horizontal platform. On the gently sloping platform the wave field was dominated by bores and no direct breaking occurred against the platform surface and the cliff. In contrast to the Kaikoura study, Stephenson and Thornton (2005) reported that waves on a platform at Marengo, Australia only reduced in height by up to 33% between the seaward edge and the cliff toe. The platforms studied by those authors differ in morphology (i.e. slope and width). Such differences in dissipative wave properties between the platforms with different geometries led Stephenson and Thornton (2005) to suggest that shore platforms may have dissipative and reflective morphological types much like sandy beaches. Trenhaile and Kanyaya (2007) used a video camera and a series of poles mounted across shore platforms to measure wave characteristics, on a sloping platform at Scots Bay in mega-tidal Bay of Fundy and a sub-horizontal platform at Mont Louis in Gaspe, Quebec, where lower meso-tidal conditions prevail. They concluded that waves measured on the sub-horizontal platform were generally not capable of eroding the platform, in part due to breaking
and energy dissipation at the edge of the platform. However they also noted that, given sufficient water depths, waves may reach the cliff-platform junction and attack the cliff toe. On the sloping platform, greater wave energy was able to reach the platform-cliff junction due to greater water depths associated with the steep platform gradient and the much higher tidal range. In another study, Farrel et al. (2009) examined the wave breaking relationship on a 90 m-wide shore platform at Belinho, Portugal, using a cross-shore array of pressure sensors. They found the breaking criterion of $0.42h$ for inner surf zone root-mean-squared wave height ($H_{\text{rms}}$), as proposed by Thornton and Guza (1982), to be valid on the study platform. More recently, Ogawa et al. (2012) investigated the wave transformation processes, directional wave properties and infragravity waves on a sub-horizontal shore platform on the Mahia Peninsula, New Zealand. They found that waves were strongly dissipated before reaching the seaward edge of the platform due to the presence of an offshore rock shoal. On the platform surface, waves in the gravity-wave band were further dissipated. Wave reflection from the cliff was limited due to the dissipative nature of the platform surface.

Collectively, existing studies of platform hydrodynamics have focused on wave-height attenuation across a shore platform and the potential role of waves as erosive agents. Large gaps exist in understanding the interaction of waves with shore platforms including: the interaction of incident waves with the outer platform edge; the spatial variations in wave energy and wave transformation across platform surfaces and; identification and behaviour of secondary motions (e.g. infragravity motion, currents and wave setup). This study examines the temporal and spatial characteristics of waves on a sub-horizontal shore platform. The specific objective is
to describe and characterise the first order wave transformation processes on a 250-m-wide sub-horizontal platform on the coast of Gisborne, North Island, New Zealand. In particular, wave height and spectral transformation of gravity waves are described in detail. Results are discussed with consideration of the potential geomorphic implications for shore platform development.

### 3.2.2 Field site

Tatapouri headland is located north of Gisborne on the east coast of the North Island, New Zealand (a). The area is part of the active Hikurangi subduction margin where the Pacific plate subducts under the Australian plate. Consequently the area is tectonically active and has an average uplift rate of 2.2–2.3 m/ka (Berryman and Hull, 2003). The coastal geology of the Tatapouri area is dominated by the Miocene Tuaheni Point Formation of the Mangatu Group sedimentary rocks (Neef and Bottrill, 1992). The formation is largely composed of Bouma sequences (McLean and Davidson, 1968), with crumbly and loose siltstone units interbedded with slightly to moderately weathered sandstone (Te Aho, 2007).

![Figure 3.1: (a) Study site location; (b) photo of the study platform taken at mid-tide; and (c) platform cross-section and sensor sites.](image-url)
The coastline in the study area is characterised by very wide sub-horizontal shore platforms (up to 400 m) with a sharp seaward edge (Gill, 1950). Platform development is considered to be controlled by sub-aerial weathering of the weak sedimentary rock in the cliff face, which results in mass-moments. Wave action is believed to play an important role in removing debris (Gill, 1950 and McLean and Davidson, 1968). There are two distinct platform morphologies around Tatapouri headland. On the southern side of the headland the platform is characterised by a large fault-controlled structural rampart at the seaward edge while on the northern side the platform has a classic sub-horizontal profile with a very steep seaward scarp (Gill, 1950).

The oceanographic regime is characterised by semi-diurnal micro-tidal conditions with a mean spring tide range of 1.7 m. Incident swell waves approach the platform from the southeast (a). Average wave heights for this coastline are 0.8–0.9 m with wave periods of 9–10 s (Smith, 1988). During storm events wave height reach >3 m and the highest recorded wave height on the coast is 5.5 m recorded 6th June 1978 (Dunn, 2010). On average the coastline experiences three to nine storm events annually with peak storm activity in June (Dunn, 2010).

The experiment location is located north of Tatpouri headland, where no structural rampart exists (Fig. 3.1b). The platform is 250-m-wide (Fig. 3.1c) with an average gradient of 0.27° and a mean elevation of 0.68 m below mean sea level (MSL). The surveyed topography of the platform (c) shows four distinct geomorphic units: first, a marked break in slope at the seaward edge, where the platform drops sharply into
Chapter 3: Wave Transformations under Swell Conditions

water approximately 2–3 m deep; second, the outer platform surface which has a gradient of 0.2° and a mean elevation of 1.0 m below MSL; third, the central platform surface which has a higher elevation (0.6 m below MSL) and a steeper gradient (0.8°, Fig. 3.1c); and fourth, the inner part of the platform has a mean gradient of 0.06° with a mean elevation of 0.2 m below MSL. The cliff toe–platform junction at the study transect is protected by a seawall.

3.2.3 Methods

Four wave gauges were deployed along a shore-normal transect (Fig. 3.1c). The platform and instrument positions were surveyed using a total station, with all elevations reduced to mean sea level. The wave sensors were all RBR-2050 pressure transducers, which were mounted on weighted plates and deployed on the platform surface (denoted as T1 to T4) with near-equal spacing between sensors (Table 3.1).

<table>
<thead>
<tr>
<th>Location</th>
<th>Distance from the seaward edge (m)</th>
<th>Elevation (m above platform edge)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Most landward (T1)</td>
<td>245</td>
<td>0.75</td>
</tr>
<tr>
<td>Inner platform 1 (T2)</td>
<td>174</td>
<td>0.69</td>
</tr>
<tr>
<td>Inner platform 2 (T3)</td>
<td>103</td>
<td>0.1</td>
</tr>
<tr>
<td>Most seaward (T4)</td>
<td>2</td>
<td>0</td>
</tr>
</tbody>
</table>

The experiment was conducted over a 24-h period on February 22nd and 23rd 2009. The experiment period included two high tides (15:00 on 22nd, 4:00 on 23rd) and one low tide (23:30 on 22nd). All instruments sampled at 2 Hz for 17.1 min (2048
samples per burst) at 30 min intervals between bursts. The experiment was undertaken during fair-weather swell conditions with a mean wave height of 0.4–0.5 m and period of 7 s.

Pressure time-series were post-corrected for barometric pressure in order to calculate mean burst water depth, and the pressure data were high-pass filtered at 0.001 Hz with tidal components removed using linear detrending. Pressure attenuation correction was not required due to very shallow water depths (<2 m).

Spectral analysis was performed using Welch’s averaged modified periodogram method (Welch, 1967). The analysis was performed on contiguous records of 2048 samples using a 256-point Hanning window with 50% overlap, providing 16 degrees of freedom (DOF) and a frequency resolution of 0.0078 Hz. Wave energy was partitioned into four frequency bands that reflect different wave generation mechanisms (Kench et al., 2009): infragravity waves (<0.05 Hz); swell waves (0.05–0.125 Hz); wind waves (0.125–0.33 Hz); and capillary waves (>0.33 Hz). The proportion of energy in each frequency band was determined by dividing the variance associated with that band by the total variance in the given time-series.

Significant wave height ($H_{m0}$) and mean wave period ($T_1$) were calculated from the spectra as:

$$H_{m0} = 4\sqrt{m_0} \quad \text{Eq. 3.1}$$

$$T_1 = m_0/m_1 \quad \text{Eq. 3.2}$$

where $m_n$ represents the nth moment of the variance density and determined as (Tucker and Pitt, 2001):
\[ m_n = \sum n \int S(f) df \]  \hspace{2cm} \text{Eq. 3.3}

The maximum wave height \((H_{\text{max}})\) was determined for each burst using a zero downcrossing technique. In order to determine gravity-wave height and period accurately, low frequency signals were filtered at 0.05 Hz using Fourier analysis (Sénéchal \textit{et al.}, 2001).

### 3.2.4 Results

#### 3.2.4.1 Temporal changes in cross-platform wave characteristics

At all tidal stages the water depth was greatest at the seaward edge of the platform (T4) and decreased toward the sensor near the cliff toe (T1), although changes in water depth between T1 and T2 were small (Fig. 3.2a). The seaward sensors (T4 and T3) were submerged throughout the experiment, whereas the landward sensors were submerged about 70% of the time, and exposed during low tide. At T4 the maximum high-tide water depth was 1.57 m, whereas the minimum water depth at low tide was 0.61 m (0.96 m tidal range). Maximum high-tide water depth at other sensors was 1.52 m (T3), 0.88 m (T2) and 0.82 m (T1). Summary data show consistent across-platform trends in wave height and period during the experiment (Fig. 3.2, Table 3.2). In general, wave height (both \(H_{m0}\) and \(H_{\text{max}}\)) was tidally modulated and increased with increasing water depth on all sections of the platform (Fig. 3.2b and c). Maximum \(H_{m0}\) values were observed within 1 h of high tide at all sites and ranged from 0.5 m at the platform edge (T4) to 0.24 m at the cliff toe (T1). High tide \(H_{\text{max}}\) values ranged from 0.9 to 0.5 m at the platform edge and cliff toe respectively. At all tidal stages, the highest wave heights were recorded at the
platform edge (T4). Mean wave period (T1) was also tidally modulated (Fig. 3.2d, Table 3.2) with mean period increasing with water depth over the platform at all but the inner sensor location. Spatial changes in mean wave period were also observed between T4 and T3, where wave period changed from 7.8 to 5.6 s and from 7.4 and 4.1 s between the sensors at high tide and the initial stages of flooding, respectively.

Figure 3.2: Temporal variations of: (a) water level; (b) significant wave height; (c) maximum wave height; and (d) wave period.
Table 3.2. Summary of temporal change in wave height and period. Wave height (Hm0 and Hmax in metres) and wave period (T1 in seconds).

<table>
<thead>
<tr>
<th>Sensor site</th>
<th>Low tide</th>
<th>Low +2.5 h</th>
<th>Low +4 h</th>
<th>High tide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hm0</td>
<td>Hmax</td>
<td>T1</td>
<td>Hm0</td>
</tr>
<tr>
<td>T4</td>
<td>0.32</td>
<td>0.51</td>
<td>5.7</td>
<td>0.38</td>
</tr>
<tr>
<td>T3</td>
<td>0.06</td>
<td>0.10</td>
<td>3.9</td>
<td>0.15</td>
</tr>
<tr>
<td>T2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.10</td>
</tr>
<tr>
<td>T1</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.03</td>
</tr>
</tbody>
</table>

At all tidal stages wave heights at the platform edge were generally double the height of waves at all other sites (Fig. 3.2b and c). Similarly wave period recorded at T4 was consistently longer than wave period recorded at all other sites (Fig. 3.2d). Significant changes in wave height and period occurred across the seaward part of the platform between T4 and T3, despite similar water depths observed at these two sites.

### 3.2.4.2 Across-platform changes in wave characteristics

Across-shore water elevation records and wave-energy spectra from all sensors at high tide and the initial stage of tidal inundation are presented in Fig. 3.3 and Fig. 3.4. Results show that waves incident at the outer platform were dominated by energy at gravity-wave frequencies at both tidal stages, with a peak frequency consistently at 0.08–0.09 Hz (12.5–11.1 s) and a small secondary peak at 0.16–0.17 Hz (Figs. 3.3b and 4b). During the initial stage of tidal flooding (Fig. 3.3a), wave height (Hm0) at the most seaward sensor was 0.38 m (T1=7.4 s). Wave height was reduced by 60% between T4 and T3, with mean period also reduced by 3.3 s (T1=4.1 s), and further
reduced towards the inner part of platform (Fig. 3.3c, e and g). Both the primary and secondary spectral peaks observed at T4 were significantly attenuated between T4 and T3 (Fig. 3.3b and d) and were further attenuated landwards. At the most landward part of the platform wave height was attenuated by 92%. The high frequency water level record shows that the characteristics of the wave field also changed across the platform surface. During the initial stage of tidal flooding, the wave regime at T4 was characterised by breaking waves (asymmetric forms) and bores (steep wave face and a long tail) travelling in groups. At central parts of the platform the wave field was dominated by small-amplitude short-period waves with a mixture of breaking, broken and reformed waves, and decomposition of wave groups was also evident (Fig. 3.3c).
Figure 3.3: Selected 5 min water level time series (a, c, e and g) and wave-energy spectra (b, d, f and h) at a lower water stage (low tide+2.5 h). Water depth represents the lowest tide when all instruments were inundated across the shore platform. From top to bottom the most seaward sensor T4 (a and b), T3 (c and d), T2 (d and f) and the most landward sensor T1 (g and f).
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Figure 3.4: Selected 5 min water level time series (a, c, e and g) and spectra (b, d, f and h) at high tide. From top to bottom the most seaward sensor T4 (a and b), T3 (c and d), T2 (e and f) and the most landward sensor T1 (g and h).

At high tide, there was a reduction in wave height between T4 and T3 of 41% and wave period reduced by 2.2 s (Fig. 3.4a and c). The spectra at T3 show considerable reduction in energy at swell and the first harmonic frequencies, but little change in energy within the infragravity band (Fig. 3.4a and d). In contrast, a slight increase in energy density is observed between 0.21 and 0.26 Hz. Landward of central platform (T3), the wave height at high tide remained relatively constant (0.3 m). However, the
energy density spectra at T2 (Fig. 3.4f) show a significant loss in swell energy which resulted in the shift of peak frequency to the wind wave band at 0.15 Hz (6.6 s). At the most landward wave gauge (T1), waves exhibit a clear tri-modal energy distribution with the primary peak at 0.01 Hz (100 s), secondary peak at 0.14 Hz (7 s) and the third peak 0.24 Hz (4 s, Fig. 3.4h). Of note, there is a marked increase in spectral peaks between T2 and T1 (Fig. 3.4f and h) which is represented by a shorter wave period observed at T1.

High tide water level records at the seaward sensor (T4) show the incident wave field was dominated by non-breaking and breaking waves, travelling in groups of 6 to 10 waves (Fig. 3.4a). The wave field at the central part of the platform (T3 and T2) contained breaking and non-breaking waves and wave groups were absent due to initial breaking (Fig. 3.4c and e). Wave spectra at the cliff toe show long-period fluctuations at infragravity frequencies, with the peak frequency at 0.01 Hz (Fig. 3.4h).

3.2.4.3 Spectral energy characteristics

Temporal and spatial transformations in wave-energy density across the shore platform are summarised in Fig. 3.5 for the entire experimental period. The data show a clear spatial shift in wave frequencies across the platform surface. At the most seaward part of the platform, wave energy is consistently contained in frequencies between 0.07 and 0.12 Hz at all tidal stages with a peak frequency at 0.09 Hz (11 s, Fig. 3.5a). The secondary peak at 0.17–0.18 Hz, though much weaker, is also consistent at all tide levels. These primary and the secondary peaks present at
the seaward sensor are also apparent on the central platform (T3 and T2) during higher tidal stages (Fig. 3.5a, b and c). It is also apparent that gravity-wave energy is more broadly distributed across the wind wave band (0.125–0.33 Hz) at inner platform locations (T3 and T2). At the landward part of the platform, there is a distinct increase in energy (~240% at high tide) contained in the infragravity frequency band at 0.02 Hz. Indeed, the cliff toe is dominated by waves at infragravity frequencies. Of note, the spectra at T1 show a consistent tri-modal distribution of wave energy at mid and higher tidal stages when water depth is greater than 0.3 m.

Figure 3.5: Spectral energy density transformations at T4 (a), T3 (b), T2 (c) and T1 (d). Note the difference in scale for T1 and the rest. The colour scale is exponential.
The summary data also clearly reveal a temporal window in which wave energy can access the platform surface. In general, this window of wave activity diminishes toward the cliff toe.

Examination of the percentage of total wave energy made up by the different wave frequency bands clearly shows the dominance of swell waves at the edge of the platform (T4) and the importance of energy at wind wave frequencies on the platform (T3–T1) especially during higher tidal stages (Fig. 3.6a–d). The proportion of wind wave energy remains similar at all tidal stages at T4. On the central platform wind wave energy dominates spectra at high and mid-tide levels. However, the proportion of wind wave energy drops sharply approximately 2 h before low tide, and infragravity energy becomes dominant. This pattern can also be seen at inner platform locations but the temporal window in which wind wave energy dominates the wave field diminishes landwards. It should be noted that the landward progression of the transition between the wind waves and infragravity waves is not simply due to the change in local water depth, as the elevation difference between sites T2 and T1 is negligible.

In summary, there is a marked shift in the peak frequency across the platform surface, from consistent energy input at the swell band (Fig. 3.5a) at the platform edge, to the infragravity band at the inner platform (Fig. 3.5d). The growth of infragravity energy across the platform surface is particularly evident at high tide. It is also apparent that the temporal window within which waves can access the platform surface becomes narrower towards the inner part of the platform (Fig. 3.5). The temporal window for the occurrence of infragravity-wave energy at the cliff toe is larger than other wave frequencies (Figs. 3.5d and 3.6d).
Figure 3.6: Temporal variations in the percentage of total energy contained in capillary (<3.3 s), wind wave (3.3–8 s), swell (8–20 s) and infragravity (>20 s) frequency bands. From the top, the most seaward sensor T4 (a), T3 (b), T2 (c) and the most landward sensor T1 (d).

3.2.5 Discussion

The results presented from this experiment provide one of the first detailed spectral analyses of wave transformation across a shore platform. It is clear that there are significant modifications to wave height, period and the wave energy, and that these changes are strongly modulated by the tide. Here we examine (a) the rate of wave-
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energy dissipation across the study platform during four different tidal stages, (b) the wave height to water depth relationship (breaking criterion) and (c) infragravity energy and its potential geomorphic implications.

3.2.5.1 Wave-height attenuation

The experiment conducted in this study shows that very rapid attenuation in wave height occurs at the most seaward part of platform at all tidal stages (Fig. 3.7a and b). However, the rate of attenuation at the seaward edge is strongly tidally modulated, with 40% reduction in wave height between T3 and T4 during high tide compared to about 80% during low tide. Rapid energy attenuation is attributable to breaking forced at or near the edge of the platform. Hence, the shore platform edge represents a very important dissipative morphological feature, not unlike the steep seaward edge of coral reefs, which has also been shown to result in very rapid energy attenuation (Young, 1989; Brander et al., 2004).

It has been generally assumed that increasing platform width will result in further wave attenuation (Stephenson and Thornton, 2005). However, in this study there is not a simple linear decay in wave height across the platform. In fact, slight increases in wave height occur over the central part of the platform because of wave shoaling following initial breaking on the seaward edge. Tidal stage exerts an important influence on patterns of wave attenuation across the middle and the landward parts of the platform. At the most landward part of the platform, wave height was reduced by 44% and 93% of the values recorded at the seaward edge at high tide and low tide respectively. This indicates that, depending on the water depth over the
platform surface and the level of incident energy at the edge of the platform, more than 50% of wave height incident at the platform edge may be available for geomorphic work at the toe of the cliff. The amount of wave-height attenuation reported here is comparable to the values reported by Ogawa et al. (2012) of 40–100% on a much narrower shore platform on Mahia Peninsula, New Zealand.

![Figure 3.7: Wave attenuation across the Tatapouri platform at different tidal sages showing: (a) the variation in $H_{m0}$ across the platform and (b) the % wave height at the instrument sites relative to wave height incident at the most seaward part of the platform. (nb: Distance on x-axis is measured from the seaward edge of the platform.)](image)

However the results presented in this study contrast with Stephenson and Kirk's (2000a) observation that almost all wave energy is dissipated before reaching cliff toe. This is likely due to the differences in physical characteristics of the platforms and the incident energy level. The Kaikoura platforms studied by Stephenson and Kirk (2000a) experienced higher incident wave conditions. During their experiment, offshore significant wave height was over 1.5 m although at the seaward edge of the platform significant wave height was reduced to 0.4 m due to dissipation. The Kaikoura platforms were higher in elevation (the cliff toe– platform junction
approximately 1 m above MSL) and were more effective at dissipating wave energy. They also had steeper platform gradient (0.5° and 1.4°).

Notably, the platform at Tatapouri is also 2–3 times wider than the platforms at Kaikoura studied by Stephenson and Kirk (2000a). The comparison highlights the importance of platform geometry as a control on wave dissipation.

The observed changes in wave frequencies, the types of wave processes and the rate of energy dissipation on the study platform (Fig. 3.5 and Fig. 3.7) show there are three distinct hydrodynamic zones (Fig. 3.8). The zones are distinguished by the dominance of different wave processes that occur at different locations on the platform surface: first, the breaking zone at the seaward edge (zone 1) where waves in the incident swell band are forced to break due to abrupt change in water depth. Second, a central platform zone characterised by wave reformation and propagation/shoaling (zone 2). Third, the inner platform zone where broken waves or bores dominate the wave field (zone 3).
Figure 3.8: Conceptual model of the occurrence of different hydrodynamic zones and dominant wave types over a tidal cycle.

An important aspect of Fig. 3.8 is that the relative positions of the three hydrodynamic zones translate landward with increasing tide level. At lower tidal stages, the platform surface is dominated by zone 3 and wave energy is dissipated rapidly at the seaward part of the platform. With increasing water level towards high tide, more wave energy is transmitted landward as zone 3 diminishes and zone 2 widens. As a result the rate of dissipation reduces with increasing water level, creating a temporal window during which a larger amount of wave energy can
access the inner platform. The practical implication of this conceptual model is that, assuming similar incident wave conditions and platform gradient, a narrower shore platform could receive quite different wave types and energy at the cliff toe than a wider platform. However it is not solely a simple function of platform width and elevation as implied in previous work. Rather it is a result of the complex wave transformation processes including breaking, wave reformation and shoaling, which also depend on gross incident wave energy and relative water depth change across the platform surface.

3.2.5.2 Water depth threshold and wave height to water depth ratio

Wave height is limited by water depth in shallow water coastal environments (Nelson and Gonsalves, 1992). The classic study by Thornton and Guza (1982) reported that the upper limit for root-mean-squared wave height (Hrms) on a natural beach is 42% of the local water depth within the surf zone. Previous studies on coral reef platforms have also shown that water depth constrains wave height. Hardy and Young (1996), for example, identified the upper limits of significant and maximum wave heights to be 40% and 60% of the reef-flat water depth. Gourlay (1993) reported that the maximum wave height on horizontal reef surface to be approximately 55% of the local water depth. Farrell et al. (2009) is the only study to date to discuss the control that water depth has on wave height on shore platforms, reporting a similar breaking ratio to the value of Thornton and Guza (1982).

Fig. 3.9 demonstrates the important control of water depth on wave height on the Tatapouri platform. There is a statistically significant relationship between water
depth and wave height (both $H_{\text{max}}$ and $H_{m0}$) at all locations across the study platform, with R-squared ranging from 0.76 to 0.99. At the central and inner platform locations (T3, T2 and T1), the relationship between $H_{m0}$ and $H_{\text{max}}$ with water depth is linear (R$^2$>0.9). Slightly lower R2 values at the edge of the platform (T4) are likely due to wave breaking. Maximum wave height ($H_{\text{max}}$) observed are largely confined within 70% of water depth (0.7 $h$) while significant wave height ($H_{m0}$) is limited to 40% of water depth (0.4 $h$) on the platform (Fig. 3.9e and f). At the seaward edge of the platform, the values for $H_{m0}$ and $H_{\text{max}}$ are much higher when water depth is lower (Fig. 3.9a, e and f). The observed value for $H_{\text{max}}$ is higher than the value reported by Hardy and Young (1996) on a reef platform, while the value for $H_{m0}$ is in a good agreement. The value for $H_{m0}$ reported here is much lower than 0.42 $h$ for $H_{\text{rms}}$ (approximately 0.6 for $H_{m0}$ when converted) reported by Farrell et al. (2009) on a shore platform, although one of the sensor sites in their study recorded a value close to 0.6 $h$ for $H_{\text{rms}}$. The discrepancy between the results reported here and Farrell et al. (2009) may be due to the difference in bottom slope, oceanographic conditions, platform configurations, or differences in analytical method used.
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Figure 3.9: Linear regression relationships between wave height ($H_{m0}$ and $H_{max}$) and water depth at: (a) the most seaward site T4; (b) inner platform site T3; (c) inner platform site T2; (d) the most landward site T1; (e) summary of all four sites for $H_{m0}$; and (f) summary of all four sites for $H_{max}$. The solid line represents maximum wave-height envelope of 0.70 $h$ and the dash line represents significant wave height envelop of 0.40 $h$. 

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While the bulk of wave-height values are limited to the breaking water depths described above, there are several differences in breaking behaviour across the platform. It is notable in Fig. 3.9 that the best fit linear regression lines are more gently sloping at sites closer to the seaward edge. This is probably related to decreasing wave period across the platform surface (Fig. 3.2d), as changes in modal wave period can result in different breaking behaviour through modification in wave length and steepness parameters (Battjes, 1974). A slight difference in wave height to water depth relationship at T2 and T1 (Fig. 3.9c, d) is likely due to the difference in bed slope (0.8° at T2 and 0.06° at T1) and may also be due to wave reflection from the cliff at T1.

It is also apparent that there are significant offsets of the best fit slopes for $H_{\text{max}}$ and $H_{m0}$ at T4 and T3 (Fig. 3.9a and b). The positive offset of the slope seen at T4 indicates that some wave breaking is initiated off the edge of platform, or on the slope between the seaward edge and the sea-bed off the edge of the platform. Given the presence of wave groups at the seaward edge and the amount of offset, it is likely that breaking starts very close to the seaward edge of the platform. The negative offset of the slope observed at T3 indicates that wave height is not limited by local water depths, but rather it is controlled by wave transformation around the edge of the platform. Once broken at the seaward edge, waves reform and propagate towards the shore. Reformed waves break as they reach the breaking limit on the platform and continue propagating as bores (Thornton and Guza, 1982). Another possible explanation for the observed offset is the effect of the platform microtopography, which is complex (Fig. 3.1c). As evident in Fig. 3.1c, the surface of the platform is not perfectly flat. Wave height therefore can be limited by
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topographically higher zones seaward of T3. An elevation difference of 0.1–0.15 m is required to induce the amount of offset observed. These observations demonstrate the importance of platform morphology and geometry on wave behaviour and highlight spatial differences in wave transformation across the platform surface.

3.2.5.3 **Infragravity motions and the geomorphic implications**

The results from this study represent one of the first observations of the presence of infragravity waves on shore platforms. The relative importance of infragravity waves increases landward, because the shore platform very effectively filters energy at gravity-wave frequencies. During higher tidal stages, maximum infragravity energy occur at the most landward part of platform, in accordance with previous studies in sandy beach settings (Huntley, 1976; Huntley *et al.*, 1981; Guza and Thornton, 1982; Masselink, 1995). However, there is a marked difference in spatial transformation of infragravity energy during lower tidal stages. At the initial stage of tidal flooding, with limited water depth on the platform, infragravity energy is maximum at the most seaward location (T4) and attenuates between T4 and T3. From T3 landwards, infragravity energy increases slightly. Such observations are similar to the result reported by Brander *et al.* (2004) on a reef platform, and are probably due to energy loss caused by breaking at the most seaward edge of the platform (Ruessink, 1998b) and the very low water depth.

Infragravity waves are known to be important for sediment transport inside the surf zone (e.g. Wright *et al.*, 1979; Miles *et al.*, 2002; Aagaard and Greenwood, 2008). The presence of infragravity waves indentified in the wave spectra on the study platform
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raises the prospect that these waves may represent a geomorphic agent on shore platforms. Given the small magnitude compared to incident gravity waves, infragravity wave are unlikely be a physical agent of erosion on rocky coasts. However infragravity waves may well contribute to sediment suspension and transport, and once resuspended, sediments can be effective agents of abrasion on shore platforms (Robinson, 1977; Trenhaile, 1987). Infragravity waves may be particularly important on the platforms to remove talus debris from the cliff toe produced by mass-movement.

3.2.6 Conclusion

This study has examined wave transformation processes on a sub-horizontal shore platform under fair-weather swell conditions. It presents the first detailed observations of wave transformation in both time and frequency domains. Waves generally break at the edge of the platform and the amount of residual wave energy present on the platform surface is largely regulated by water depth (tidal stage). On the platform surface, wave height is locally limited by water depth and the pattern of wave attenuation is modulated by the tide. In this regard this study broadly confirms the results from the previous studies by Trenhaile and Kanyaya (2007) and Farrell et al. (2009). However, the study also presents more detailed observations of wave breaking criterion and rate of gravity-wave-energy dissipation across the platform surface. Furthermore, the study identifies the presence of temporal and spatial windows in which different wave processes operate across the platform and highlights the importance of platform geometries (i.e. slope, width and elevation) and hence the morphodynamic feedback on wave processes. Such findings raise the
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prospect of wave related geomorphic activity on shore platforms and potential for platform development. It suggests that narrower and lower platforms may be more susceptible to gravity waves, although waves can also shoal and reach further landward under certain conditions. The practical implication of such findings is that the temporal window for gravity wave action will increase with rising sea-level and the proportion of gravity waves reaching the inner part of a platform will increase spatially and temporally. This also indicates that wave processes on shore platforms are likely to be enhanced by higher water levels caused by wind and wave setups during storm events. The presence of infragravity waves is also identified and we suggest that these may be an important geomorphic agent, particularly for: debris removal; abrasion by activating sediment movement, and; modulating access of gravity-wave energy to the cliff toe at higher water depth.

A number of important aspects of wave hydrodynamics on platforms remain to be addressed. In particular, wave processes under high energy storm conditions need to be investigated in detail. Under such conditions, wave and wind setup may increase water depth on a platform, allowing a greater amount of gravity-wave energy to access the inner platform and carry out geomorphic work. The role of infragravity waves may be more significant under high energy conditions as infragravity waves are not depth limited and their magnitude is proportional to incident wave energy (Holman, 1981). Investigations on complex wave interactions such as reflection and refraction on and around a shore platform will also provide further insights into nearshore hydrodynamics and the roles of waves in shaping cliff and platform morphology.
3.3 Case Study 2:

Field Measurements of Wave Characteristics on a Near-Horizontal Shore Platform, Mahia Peninsula, North Island, New Zealand

3.3.1 Introduction

Shore platforms occur at the base of coastal cliffs, often within the intertidal zone. They have been categorised in two major morphological types: Type A platforms have a nearshore gradient (slope); and Type B platforms are characterised by a low-gradient surface and a sharp seaward boundary (Sunamura, 1992) (Fig. 3.10).

Figure 3.10: Conceptual model showing two types of shore platforms.
Waves are considered to be one of the critical controls on shore platform evolution (Trenhaile, 2000; Trenhaile, 2008b). Shore platforms can be conceptualised within a morphodynamic framework (Carter et al., 1987; Stephenson and Thornton, 2005) that comprises distinct components (lithology, physical processes, and weathering processes) which have been identified as important controls on platform development (Trenhaile, 1987; Sunamura, 1992). Morphodynamics describes the co-adjustment of form and processes (Wright and Thom, 1977) which in the case of shore platforms occurs through gradual change in the geometry of the nearshore rock profile, and the feedback that this change has on wave and weathering processes. It is apparent that the timescales of responsiveness of the platform morphodynamic system are many orders of magnitude greater than for unconsolidated coastal landforms. Moreover, whereas for sandy systems waves achieve change through sediment transport, on rock coasts change occurs through substrate response, that is, the physical breakdown of rock and then its transportation. Wave processes on a shore platform are controlled by boundary wave and tidal conditions that determine incident energy conditions and morphological feedback which dictates how waves transform and release energy. The degree to which the substrate responds to wave energy through both mechanical and hydraulic action depends on geological factors such as lithology and structure and the degree of weathering (Kennedy et al., 2011). Depending on the balance between the geological control, the degree of weathering, and wave energy available, waves can either be the primary geomorphic agent responsible for eroding rock material or a secondary process mainly responsible for removing debris produced by sub-aerial processes (Stephenson and Kirk, 2000a; Trenhaile and Kanyaya, 2007). Hence, the role of wave processes on contemporary shore
platforms is likely to vary depending on morphological configurations and the local geological and climatic settings which are important control on sub-aerial weathering processes.

Despite their importance as a control on shore platform development, field observations of wave processes on shore platforms are still rare (Naylor et al., 2010). Stephenson and Kirk (2000a) and Trenhaile and Kanyaya (2007) undertook wave measurements on rock platforms to evaluate the erosion potential of waves, and Farrell et al. (2009) conducted an experiment on a rock platform in Portugal to evaluate the wave breaking criterion. More recently, Ogawa et al. (2011) and Beetham and Kench (2011) undertook wave transformation experiments on Type B platforms in New Zealand. Ogawa et al. (2011) reported that wave height on their 250 m platform was depth limited and identified three hydrodynamic zones that were characterised by different wave processes. Beetham and Kench (2011) investigated the behaviour of infragravity waves on shore platforms and reported a substantial increase in infragravity-wave height towards the cliff toe due to shoaling. Although the aforementioned studies provided valuable insights into wave processes on shore platforms, present understanding of the transformation of wave energy across platform surfaces and relative importance of different wave frequencies on platform surfaces is still poorly resolved. As demonstrated by previous hydrodynamic and morphodynamic studies on beaches and coral reefs (e.g. Wright and Short, 1984; Kench and Brander, 2006), the inherent topographic variability of natural coastal landforms (in this case shore platforms) means it is necessary to compare and contrast wave processes from a number of examples before general relationships can be established. This paper presents measurements
from a study of wave processes across a 140-m-wide shore platform on the east coast of North Island, New Zealand. The originality of this paper lies in the analysis of high-frequency sea-surface elevation data collected using an array of wave sensors including a directional wave gauge and the presentation of across-shore wave-energy spectra and their directional properties. The objectives of the paper are threefold: (1) to present detailed field measurements of gravity and infragravity wave characteristics on the study platform including directional wave data; (2) to describe wave characteristics at different parts of the study platform, and (3) to quantify the rate of wave height and energy transmission across the platform. Results are discussed in the context of shore platform processes and geomorphology.

### 3.3.2 Study site

The study site is located at Mahia Peninsula, on the east coast of the North Island, New Zealand. The geology of Mahia Peninsula is characterised by tuffaceous sandstone and siltstone of the Auroa Formation sedimentary rocks (Te Aho, 2007). The peninsula is in an area of active tectonic uplift and consequently the bedrock is highly deformed with the apparent presence of joints and faults along the cliff face (Berryman, 1993; Te Aho, 2007). The eastern and the Pacific section of the peninsula are predominantly cliffed, with active erosion due to weathering and wave action evident at the cliff toe. The oceanographic regime is characterised by semi-diurnal micro-tidal conditions with a mean spring tidal range of 1.7 m. Average offshore wave heights for this coastline are 0.8 to 0.9 m with wave periods of 9–10 s (Smith, 1988). During storm events wave heights reach >3 m and on average the coastline
experiences three to nine storm events annually with peak storm activities in June (Dunn, 2010).

![Figure 3.11: Location of the study site: (a) North Island, New Zealand and (b) Mahia Peninsula, East Coast, North Island.](image)

The experimental transect is located on the shore platform east of Oraka Beach, Mahia (−39°4′50.23″, +177°54′23.52″; Fig. 3.11). The platform is eroded into sedimentary rocks and characterised by a near-horizontal surface (Type B) with an irregular and steep seaward edge (Fig. 3.12c, d). There are a number of submerged rocky shoals (reefs) occur offshore of the study platform. The study transect is 143-m-wide with an average surface gradient of 0.4° and a mean elevation of −0.4 m relative to mean sea level (MSL, Fig. 3.12d). At the seaward edge there is a sharp break in slope with a steep drop in elevation of approximately 1.0 m. On the
platform studied there are three different morphological zones: (1) the seaward platform surface (0–50 m from seaward edge) is characterised by an irregular surface with a mean elevation of −0.79 m relative to MSL and a gradient of 0.35°; (2) the central platform (50–60 m from the seaward edge) has a relatively steep gradient of 0.81° and an elevation of −0.43 m MSL, and (3) the inner platform surface has a mean gradient of 0.28° and a mean elevation of −0.28 m MSL (Fig. 3.13d). At the toe of the platform the surface is covered by a thick layer of fine sand and fine fragments of mudstone evidently eroded from the cliff (Fig. 3.12a).

Figure 3.12. Study site: (a) view towards the cliff; (b) seaward part of the study platform; (c) planform Global Positioning System map of the platform; and (d) experiment profile and the location of wave gauges. MHWS, mean high water spring; MSL, mean sea level.
3.3.3 Methods

The field experiment was conducted over a 24 h period on the 1st and 2nd April 2009. High-frequency water-surface elevation records were obtained using pressure sensors deployed along a shore-perpendicular transect. Four sensors were deployed on the platform and one off the seaward edge (Fig. 3.12c). Details of the instrumentation and the deployment are summarised in Table 3.3. All sensors logged at 2 Hz for 17.1 min every 1 h. A barometric sensor was used onshore to allow atmospheric pressure correction of water depth data.

Table 3.3. Summary of sensor deployment

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>Sensor Location</th>
<th>Sensor Type</th>
<th>Sampling Rate</th>
<th>Duration</th>
</tr>
</thead>
<tbody>
<tr>
<td>M5 (off edge)</td>
<td>−4 m</td>
<td>RBR 2050</td>
<td></td>
<td>17.1 min every 1 h over 24 h</td>
</tr>
<tr>
<td>M4 (seaward edge)</td>
<td>2 m</td>
<td>InterOceanS4</td>
<td>2 Hz</td>
<td></td>
</tr>
<tr>
<td>M3 (centre 1)</td>
<td>50 m</td>
<td>KPSI 551</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M2 (centre 2)</td>
<td>104 m</td>
<td>KPSI 551</td>
<td></td>
<td></td>
</tr>
<tr>
<td>M1 (cliff toe)</td>
<td>141 m</td>
<td>KPSI 551</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barometric</td>
<td>−</td>
<td>KPSI 560</td>
<td></td>
<td>Continuous</td>
</tr>
</tbody>
</table>

* Elevation values are reduced to mean sea level. Distance values are measured from the seaward edge.

Because of the shallow nature of the platform surface, pressure attenuation was negligible. In addition, pressure fluctuations under a breaking wave are considered to be fully hydrostatic (Lin and Liu, 1998). Therefore, pressure time-series recorded by each instrument on the platform were directly converted to water level records using the barometric pressure record. By contrast, a pressure attenuation correction
was applied to the pressure record obtained off the edge of the platform using the linear transfer function as described in Tucker and Pitt (2001). Spectral analysis was performed on all bursts (2048 contiguous data points) using Welch's averaged modified periodogram method of spectral estimation (Welch, 1967). All spectra were analysed using 16 degrees of freedom. Descriptive values of wave height ($H_{m0}$) and mean wave period ($T_1$) were estimated directly from the spectral moments according to Tucker and Pitt (2001). Gravity-wave height (donated simply as $H_{m0}$) and infragravity-wave height ($H_{m0L}$) were calculated separately by filtering the pressure time-series in the frequency domain using a Fourier technique, with an infragravity cut-off frequency of 0.05 Hz. Similarly, wave period was calculated for gravity waves ($T_1$) and infragravity waves ($T_{1L}$). For descriptive purposes, the gravity wave bands were further subdivided into swell (0.05–0.125 Hz), wind (0.125–0.33 Hz), and short-period capillary wave (>0.33 Hz) bands according to the classification used by Brander et al. (2004). The definitions of those frequency bands are summarised in Table 3.4. Directional wave spectra were computed from the pressure and bidirectional velocity (P-U-V) data obtained by the S4 directional wave and current meter. Directional spectra were estimated using the Iterated Maximum Likelihood Method within the DIWASP analysis tool pack (Johnson, 2002).

Table 3.4. Division of wave frequency bands.

<table>
<thead>
<tr>
<th>Wave Type</th>
<th>Frequencies (Hz)</th>
<th>Periods (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Infragravity</td>
<td>$&lt;0.05$</td>
<td>$&gt;20$</td>
</tr>
<tr>
<td>Gravity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Swell</td>
<td>0.05–0.125</td>
<td>8–20</td>
</tr>
<tr>
<td>Wind</td>
<td>0.125–0.33</td>
<td>3–8</td>
</tr>
<tr>
<td>Capillary</td>
<td>$&gt;0.33$</td>
<td>$&lt;3$</td>
</tr>
</tbody>
</table>
3.3.4 Results

3.3.4.1 Incident wave characteristics

The experiment corresponded with spring tide conditions, and encompassed two high tides and one low tide (Fig. 3.13). Water depth directly off the seaward edge of the platform (M5) varied between 1.2 m and 2.6 m at low tide and high tide respectively. The measured tidal range of 1.4 m during the experiment was much smaller than the mean spring tidal range for the coastline. Waves incident at the platform edge during the experiment were clearly tidally modulated, with the highest gravity waves \(H_{m0} = 0.5–0.6\) m observed during high tide and the lowest during low tide (<0.1 m). Tidal modulation of gravity-wave height is thought to be induced by the presence of a submerged rock shoal located seaward of the platform boundary. Gravity-wave period \(T_1\) varied significantly from 5 to 9 s. During mid to high tide, both peak and mean gravity-wave periods were stable at 6 and 11 s respectively, but increased significantly during the lower tidal stages (Fig. 3.13). During the experiment all sensors on the platform surface were exposed at low tide except for the seaward edge sensor (M4). At the cliff toe, the platform surface was exposed over 60% of the tidal cycle.
Figure 3.13. Incident wave condition measured off the seaward edge of the platform including gravity-wave height ($H_{m0}$), mean period ($T_1$), peak period ($T_{ph}$), and water depth ($h$). The lower panel shows sea-surface data recorded at falling, low, rising, and high tide.

### 3.3.4.2 Wave transformations

Across-platform transformations in wave height and wave-energy spectra at three tidal stages are presented in Figure 3.14. The falling and rising mid-tide stages in Figure 3.14 correspond to the last stage of tidal inundation during falling tide and the initial flooding of the entire platform surface during rising tide. Wave and water depth data during the experiment are summarised in Table 3.5. Highest gravity waves were observed at the edge of the platform (M4) at all tidal stages and peaked at high tide ($H_{m0} \approx 0.6$ m). There was a reduction in $H_{m0}$ values across the platform with lowest values at the cliff toe at all tidal stages. Infragravity-wave height ($H_{m0L}$), on the other hand, increased from the seaward edge to the cliff toe (Fig. 3.14; Table 3.5). The largest increase in infragravity-wave height was observed between the two most landward sensors (M2 and M1), while the change in $H_{m0L}$ was
negligible at the central part of the platform between M3 and M2. At the cliff-toe infragravity-wave height varied from 0.2 m and 0.3 m at the initial stage of tidal flooding and the high tide respectively (Fig. 3.14; Table 3.5).

Across-shore transformation in wave characteristics is clearly seen in the raw surface data and the spectra (Fig. 3.14). At mid to high tidal stages, the wave field at the seaward edge was dominated by gravity waves. The wave spectra show that peak frequency at the seaward edge was at 0.07–0.09 Hz, indicating a dominance of swell waves especially at high tide (Fig. 3.14o). At the landward part of the platform (M2 and M1), oscillations associated with infragravity waves were more evident. At falling and rising mid-tide, long periodic pulses of 1 to 2 min dominated the wave field at the centre-landward and cliff-toe sensor sites (Fig. 3.14c, d, h, i). At the cliff toe the presence of gravity waves was restricted to the crest of the infragravity waves (Fig. 3.14d, i). At high tide, long-period oscillations were still evident at the landward locations, with gravity wave motions superimposed on infragravity waves (Fig. 3.14n). The peak frequency at the cliff toe was consistently in the infragravity band around 0.01 Hz (100 s, Fig. 3.14e, j, o).
Figure 3.14. High-frequency sea-surface records and power spectral density (PSD) across the study platform at falling mid-tide, rising mid-tide and high tide.
### Table 3.5. Summary of gravity and infragravity-wave height and period and water depth observed during the experiment.

<table>
<thead>
<tr>
<th>Burst No.</th>
<th>Tidal Stage</th>
<th>Seaward Edge (M4)</th>
<th>Centre Seaward (M3)</th>
<th>Centre Landward (M2)</th>
<th>Cliff Toe (M1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$H_{m0}$</td>
<td>$T_1$</td>
<td>$H_{m0L}$</td>
<td>$T_{1L}$</td>
</tr>
<tr>
<td>8</td>
<td>H</td>
<td>0.47</td>
<td>6.4</td>
<td>0.17</td>
<td>44.9</td>
</tr>
<tr>
<td>9</td>
<td>MF</td>
<td>0.42</td>
<td>6.1</td>
<td>0.16</td>
<td>44.3</td>
</tr>
<tr>
<td>10</td>
<td>MF</td>
<td>0.36</td>
<td>5.7</td>
<td>0.14</td>
<td>44.3</td>
</tr>
<tr>
<td>11</td>
<td>MF</td>
<td>0.21</td>
<td>5.0</td>
<td>0.14</td>
<td>49.2</td>
</tr>
<tr>
<td>12</td>
<td>MF</td>
<td>0.10</td>
<td>4.8</td>
<td>0.09</td>
<td>54.3</td>
</tr>
<tr>
<td>16</td>
<td>MR</td>
<td>0.12</td>
<td>4.7</td>
<td>0.13</td>
<td>78.7</td>
</tr>
<tr>
<td>17</td>
<td>MR</td>
<td>0.25</td>
<td>5.3</td>
<td>0.13</td>
<td>48.6</td>
</tr>
<tr>
<td>18</td>
<td>MR</td>
<td>0.39</td>
<td>5.4</td>
<td>0.15</td>
<td>54.6</td>
</tr>
<tr>
<td>19</td>
<td>MR</td>
<td>0.45</td>
<td>6.2</td>
<td>0.17</td>
<td>43.3</td>
</tr>
<tr>
<td>20</td>
<td>H</td>
<td>0.54</td>
<td>6.2</td>
<td>0.21</td>
<td>48.2</td>
</tr>
<tr>
<td>21</td>
<td>MF</td>
<td>0.43</td>
<td>6.2</td>
<td>0.15</td>
<td>45.8</td>
</tr>
</tbody>
</table>

The majority of the platform was exposed during low tide (no low tide data). Wave height ($H_{m0}$) and water depth ($h$) values are in metres. Period values ($T_1$) are in seconds. H, high tide; MR, mid tide (rising); MF, mid tide (falling).
### Table 3.6. Percentage of the transmission of gravity and infragravity-wave height and energy from the seaward edge.

<table>
<thead>
<tr>
<th>Burst No.</th>
<th>Tidal Stage</th>
<th>Seaward Edge (M4)</th>
<th>Centre Seaward (M3)</th>
<th>Centre Landward (M2)</th>
<th>Cliff Toe (M1)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$H_{\text{m}0}(E)%$</td>
<td>$H_{\text{m}0L}(E)%$</td>
<td>$H_{\text{m}0}(E)%$</td>
<td>$H_{\text{m}0L}(E)%$</td>
</tr>
<tr>
<td>8</td>
<td>H</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>98 (93)</td>
<td>124 (151)</td>
</tr>
<tr>
<td>9</td>
<td>MF</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>90 (84)</td>
<td>94 (89)</td>
</tr>
<tr>
<td>10</td>
<td>MF</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>83 (68)</td>
<td>114 (142)</td>
</tr>
<tr>
<td>11</td>
<td>MF</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>71 (53)</td>
<td>121 (147)</td>
</tr>
<tr>
<td>12</td>
<td>MF</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>16</td>
<td>MR</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>17</td>
<td>MR</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>84 (72)</td>
<td>123 (153)</td>
</tr>
<tr>
<td>18</td>
<td>MR</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>87 (75)</td>
<td>107 (124)</td>
</tr>
<tr>
<td>19</td>
<td>MR</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>89 (79)</td>
<td>123 (153)</td>
</tr>
<tr>
<td>20</td>
<td>H</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>85 (73)</td>
<td>114 (140)</td>
</tr>
<tr>
<td>21</td>
<td>MF</td>
<td>100 (100)</td>
<td>100 (100)</td>
<td>93 (86)</td>
<td>133 (167)</td>
</tr>
</tbody>
</table>

Values over 100% indicate increase in wave height/energy. Values in brackets reflect the transmission of wave energy $E$. H, high tide; MR, mid tide (rising); MF, mid tide (falling).
To further assess the dominant wave types across the platform surface, measured wave energy was partitioned into infragravity, swell, wind, and short-period capillary-wave bands. Figure 3.15 summaries the proportion of waves within these four bands as well as the percentage change in gravity and infragravity-wave energy (dashed and solid lines respectively) across the platform at three different tidal stages. A consistent pattern in wave-energy distribution was observed at falling, rising, and high tide. At the seaward edge of the platform, energy in swell and wind-wave frequencies dominated the wave field. At the central seaward location (50 m from the seaward edge), wave energy was more broadly distributed across the four different bands. The percentage of swell and wind wave energy became progressively less towards the inner part of the platform (Fig. 3.15). At the centre-landward sensor site (104 m from the seaward edge), infragravity energy became more dominant, especially at mid tide (Fig. 3.15a, b). At the cliff toe, more than 85% of the total wave energy was contained in the infragravity-wave band at falling and rising tide (Fig. 3.15a, b) compared with 45% to 60% at high tide (Fig. 3.15c). A summary of wave energy and height transmission during the experiment is presented in Table 3.5.
Figure 3.15. Percentage of the composition of different wave types (bar graphs) and percentage of the transmission of gravity and infragravity-wave energy (dashed and solid lines) across the platform at: (a) falling mid tide (MF); (b) rising mid tide (MR); and (c) high tide (HT).
The observed across-shore pattern in wave-energy distribution was closely related to the marked attenuation of gravity-wave energy and the increase in infragravity-wave energy across the platform (Fig. 3.15a, b, c; Table 3.5). The energy contained in the gravity-wave band was strongly attenuated across the platform, with the highest attenuation occurring at the central part of the platform (Fig. 3.15). Only 5% of gravity-wave energy was transmitted (i.e. 95% attenuation) to the cliff toe (Fig. 16a, b). A slightly higher rate of energy transmission (~15%) was observed during high tide (Fig. 3.15c). Infragravity-wave energy, on the other hand, increased towards the cliff toe (Fig. 3.15). The amount of energy amplification in the infragravity band varied during the experiment. At the cliff-toe infragravity-wave energy reached 165% to 280% of the values recorded at the seaward edge (Table 3.6). Although infragravity-waves were highest at the cliff toe during high tide, no clear pattern in energy amplification was observed in relation to tidal stages (Table 3.6). It should be noted that infragravity-wave energy amplification was minimal at the central part of the platform during falling and high-tide stages (Fig. 3.15a, c).

### 3.3.4.3 Directional wave spectra

Directional wave spectra measured at the mid platform (M3) reveal several features of wave processes on the platform surface. An example of a directional wave spectra recorded at high tide is presented in Figure 3.16. The figure shows that incident waves arrived from north-east, nearly perpendicular to the shoreline at the study site. Second, there was a relatively wide directional spread in energy density (Fig. 3.16a), which was likely to be due to the shallow depth on the platform and the complex reflection and refraction processes induced by the irregular platform edge.
Third, there is evidence that waves at infragravity frequencies propagated from the cliff face towards the open sea. As seen in Figure 3.16a, there are small concentrations of infragravity energy on the left hand side (landward), near the centre on the directional plot. As there was no source of wave energy towards the cliff, this wave energy was likely to be infragravity waves that had been reflected from the cliff face. In contrast, energy at gravity-wave frequencies from the landward direction was not evident. Similar patterns were observed at falling and rising tidal stages.

Figure 3.16. Directional spectra recorded at the central part of the platform M3 (50 m from the seaward edge): (a) directional spectra at high tide and (b) location of the directional wave gauge. IGW, infragravity waves.

A summary of directional wave properties including the direction of peak frequency and the proportion of reflected wave energy to the total energy is provided in Table 3.7. Incident and reflected wave energy were calculated for a 90° window measured from the peak direction for the frequency range of <0.05 Hz for infragravity waves and 0.05 to 0.4 Hz for gravity waves from the directional spectral
density. The amount of wave reflection from the cliff ranged from 11% to 31% for the infragravity-wave band and 3% to 8% for the gravity-wave band. On average, reflected waves accounted for 20% and 5.7% of the total infragravity and gravity-wave energy present respectively. The proportion of reflected infragravity-wave energy appeared to increase towards high tide while no particular trend was apparent for gravity waves (Table 3.7).

Table 3.7. Wave energy and the amount of reflection recorded at M3 for IGW and GW.

<table>
<thead>
<tr>
<th>Burst No.</th>
<th>Tidal Stage</th>
<th>Total Energy (m²/Hz)</th>
<th>Peak Direction (°)</th>
<th>Energy Reflection (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>IGW</td>
<td>GW</td>
<td>IGW</td>
</tr>
<tr>
<td>8</td>
<td>H</td>
<td>2.81</td>
<td>13.32</td>
<td>61</td>
</tr>
<tr>
<td>9</td>
<td>MF</td>
<td>1.42</td>
<td>9.54</td>
<td>58</td>
</tr>
<tr>
<td>10</td>
<td>MF</td>
<td>1.69</td>
<td>5.69</td>
<td>28</td>
</tr>
<tr>
<td>18</td>
<td>MR</td>
<td>1.73</td>
<td>7.22</td>
<td>36</td>
</tr>
<tr>
<td>19</td>
<td>MR</td>
<td>2.71</td>
<td>10.16</td>
<td>102</td>
</tr>
<tr>
<td>20</td>
<td>H</td>
<td>2.57</td>
<td>13.37</td>
<td>86</td>
</tr>
<tr>
<td>Ave.</td>
<td></td>
<td>2.71</td>
<td>10.55</td>
<td>62</td>
</tr>
</tbody>
</table>

Incident and reflected wave energy were calculated for a 90° window measured from the peak direction for the frequency range of <0.05 Hz for IGW and 0.05–0.4 Hz for GW. IGW, infragravity waves; GW, gravity waves; H, high tide; MF, mid tide (rising); MR, mid tide (falling).

3.3.5 Discussion

Results of this experiment represent one of the first detailed investigations of wave processes and directional wave properties on a shore platform. Analysis of the field data provides insights into the behaviour of waves and their transformation on rock platforms.
3.3.5.1 **Boundary wave conditions**

Results confirm that wave energy arriving at the seaward edge of the platform is tidally modulated (Fig. 3.13). Previously, Stephenson and Kirk (2000a) reported that offshore wave height was attenuated by 91% to 99% before reaching the platform edge due to topographic effects at their study site on Kaikoura Peninsula, New Zealand. Results are also in accordance with Trenhaile and Kanyaya (2007) and Porter et al. (2010), who reported wave-energy modulation at the seaward edge of shore platforms on the micro-tidal coast of Gaspe, Quebec, Canada.

Water depth directly off the seaward edge of near-horizontal (Type B) platforms has been identified as a control on shore platform elevation (Sunamura, 1992; Dickson, 2006). The front depth, as termed by Sunamura (1991), has been used as a proxy for wave height at the edge of a shore platform because wave height in shallow water environments is a function of water depth. At low tide gravity waves were absent at M5 despite relatively large water depth \((h=1.3 \text{ m})\). Significant reduction in incident wave energy at low tide, as seen in Figure 3.13, is attributed to the nearshore and offshore morphology. The presence of a rock shoal resulted in wave breaking before reaching the platform. Consequently wave characteristics at the platform edge were regulated by the water depth over the nearshore structure (i.e. rock shoal), which acts like a breakwater, rather than the front depth.

3.3.5.2 **Platform wave processes**

Wave-energy density spectra clearly show that the landward and the seaward sections of the platform were dominated by different wave frequencies. Such
differences in dominant wave types were controlled by wave breaking and dissipation processes. The outer platform was dominated by energy at incident gravity-wave frequencies, and waves at these frequencies rapidly dissipated on the outer to central platform surface (Fig. 3.15; Table 3.6). Consequently, the transmission of incident wave energy from the seaward edge to the cliff toe was very limited. Gravity waves are known to be depth limited and the decrease in water depth towards the cliff induces turbulent and frictional dissipation (Komar, 1998). Consequently, the rate of wave-energy attenuation is also modulated by the tide. Higher water depths at high tide allow larger gravity waves to propagate towards the cliff as seen in Figures 3.14 and 3.15. The result is consistent with a study conducted by Ogawa et al. (2011) on a 250 m shore platform at Tatapouri, New Zealand, although they reported a much higher rate of gravity-wave height attenuation on the seaward part of the platform surface, despite the greater platform water depth observed during their experiment. At Tatapouri, wave height was reduced from 0.51 m to 0.30 m (56% height reduction) between the seaward edge and the second sensor located 100 m from the edge at high tide (Ogawa et al., 2011). At Oraka, gravity-wave height ($H_{m0}$) was reduced from 0.54 m at the seaward edge to 0.46 m (15% reduction) at the second sensor location 50 m from the seaward edge. The difference may be due to the greater distance between the sensors deployed on the Tatapouri platform and/or the effect of micro-topography on the Tatapouri platform, as noted by Ogawa et al. (2011). Interestingly, the overall amount of wave-height attenuation at high tide on those two platforms are comparable (40% to 61% at Oraka and 57% at Tatapouri), despite the differences in platform widths and water depths.
While a large amount of gravity-wave energy was attenuated across the width of the platform, energy contained in the infragravity-wave band increased towards the cliff toe (Fig. 3.14 and 3.15; Table 3.6). Consequently, the inner platform surface was dominated by infragravity-wave energy. Infragravity energy present on the platform surface was likely associated with the release of group-bound long waves (Masselink, 1995) during the initial wave breaking over the nearshore rock shoal. Because of the water depth limitation across the platform, infragravity waves shoal and increase in height towards the cliff toe (Fig. 3.15). The observed landward increase in infragravity-wave energy is consistent with previous studies on sandy beaches (Wright et al., 1982; Sénéchal et al., 2001) and shore platforms (Beetham and Kench, 2011; Ogawa et al., 2011). Furthermore, because of the long wave length and the small amplitude of infragravity waves they do not break but are reflected off the cliff face and travel seaward, as shown by the directional wave spectra (Fig. 3.16a, Table 3.7). It is interesting to note that the increase in infragravity energy was most significant towards the cliff toe while it was much smaller or negligible at the centre of the platform. Beetham and Kench (2011) investigated infragravity wave transformations on sub-horizontal shore platforms and reported similar results. They suggested that the greater energy increase seen at the cliff toe was likely due to the presence of a ramp (i.e. increase in slope) at the cliff toe, and the little increase in infragravity-wave energy observed at the central part could be due to the presence of a nodal structure and standing waves.

Infragravity motions, with a mean wave period of 65 s, modulated local water level by up to 0.27 m especially during mid-tide stages at the cliff toe. Importantly, infragravity-wave height at the cliff toe was independent of water depth while
gravity-wave height was linearly dependent on local water depths (Fig. 3.17). The periodic pulsing of water associated with infragravity waves has implications for gravity wave behaviour. For example, Nelson and Gonsalves (1992) observed a significant shoreward reduction in wave height to water depth ratio (H/h) by up to 48% induced by underlying infragravity motions in the surfzone on a mildly sloping beach (≈0.6°). On the other hand, Kamphuis (1996) reported that infragravity waves, along with wave setup, effectively increase water depth at the toe of structures and therefore allow larger gravity waves access the structures. The results reported in this paper indicate that careful analysis of sea-surface time-series is required when considering wave processes on shore platforms especially towards the cliff toe and a simple time-domain analysis of wave height may not be adequate for fully resolving the wave characteristics.

Figure 3.17. Infragravity and gravity-wave height versus water depth at the cliff toe.
3.3.5.3 Geomorphic implications

In a previous study, Stephenson and Kirk (2000a) reported that over 90% of incident wave energy was attenuated on gently sloping (1.5°) shore platforms on Kaikoura Peninsula, New Zealand. In contrast, Stephenson and Thornton (2005) investigated wave height attenuation across a 35 m Type B shore platform at Marengo, Victoria, Australia and reported that wave attenuation was limited to 10% to 40%. Based on these studies, Stephenson and Thornton (2005) suggested that shore platforms may have dissipative and reflective forms much like sandy beaches as proposed by Wright and Short (1984). They suggested that sloping (Type A) and sub-horizontal (Type B) platforms may attenuate wave energy in different ways; Type A platforms being more dissipative and Type B more reflective.

The platform investigated in this study has a slope of 0.4° which is broadly comparable to dissipative and low gradient intermediate type beaches. While the overall amount of wave-height attenuation across the platform appears to be moderate (56% at high tide) compared with the values reported by Stephenson and Kirk (2000a), spectral analysis shows that the platform surface effectively dissipates wave energy at the study site. Reflection of gravity waves was fairly limited during the experiment (Fig. 3.16; Table 3.7), but given sufficient water depth it is apparent that waves would transmit across the platform and the cliff would then act as a reflective wall. Hence, the platform surface at Oraka is dissipative whereas the cliff toe is reflective. The wave spectra from Oraka resemble spectra taken from a dissipative beach, where incident waves dominate the outer beach surf zone and infragravity waves dominate the inner shore (Wright and Short, 1984).
Wave energy arriving at the edge of the platform is attenuated by the offshore topography and then further dissipated on the platform before reaching the cliff toe. Therefore, waves do not appear to be directly responsible for eroding the cliff. However, relatively low rates of wave attenuation observed at the seaward part compared with a previous study by Ogawa et al. (2011) indicate that waves may be capable of performing some geomorphic work (erosion) at the central part of the platform. In fact, a few small blocks (~20 cm) of mudstone clearly dislodged along joints can be found at the central part of the platform. The primary role of waves at Oraka is likely to be transporting debris from the cliff toe. This process is important, as removal of sediments exposes the cliff toe to further wave and weathering processes. Furthermore, removal of the cliff-toe debris reduces the buttressing effect and enhances sub-aerial erosion caused by mass wasting (de Lange and Moon, 2005). Waves are also responsible for attrition and abrasion of sediments, as the weathered mudstone cliff debris at the study site is particularly fragile. The presence of a thick sand layer at the toe of the cliff and the absence of major debris indicate that such processes are active on the study platform. This interpretation is consistent with Stephenson and Kirk (2000a) and Porter et al. (2010) who also considered the contemporary role of waves as a direct agent of erosion to be limited at their micro-tidal study sites. It should be noted that the short duration of the experiment and the lack of high-energy storm conditions mean that the results reported and the interpretation presented here need to be verified with further field studies. Increase in water depth due to wave and wind setup during a storm event and/or king tide would increase the water depth threshold required for larger waves to propagate across the platforms. In addition, the lack of wave energy at the
cliff toe under current conditions does not mean that waves were not an important erosion process in the past (Dickson, 2006; Porter et al., 2010).

The dominance of infragravity waves at the cliff toe implies that those waves may have an important geomorphic role today. In particular, by periodically increasing the water level they facilitate the transmission of gravity waves towards the cliff toe. Furthermore, the height of infragravity waves is known to increase in a linear fashion with increasing incident wave height (Holman, 1981). Therefore, the geomorphic role of infragravity waves must become more pronounced during storm episodes, as an increase in offshore wave height should result in larger excursions of water level against the cliff face. However, transformation and amplification of infragravity waves on shore platforms are yet to be investigated in detail. To date no study has described the behaviour of infragravity waves on shore platforms in relation to varying incident conditions.

3.3.6 Conclusions

Field observations of wave characteristics on the shore platform at Oraka, Mahia Peninsula, New Zealand, provided new insights into the behaviour and transformation of different wave types on platforms. The following conclusions were made:

1. The outer platform surface was dominated by incident gravity-wave energy. Wave-energy spectra from the surface time-series data collected across the platform surface showed across-shore dissipation in gravity-wave energy.
Gravity-wave height attenuation between the seaward edge and the cliff toe averaged between 40% and 81%.

2. The inner platform surface was dominated by energy at infragravity-wave frequencies. Infragravity-wave heights were largest at the cliff face and modulated water level by up to 0.27 m. Infragravity waves are not depth limited and their amplitude is positively correlated to offshore wave energy. Hence, they are likely to be an important agent of geomorphic change.

3. Directional wave data measured at the centre of the platform showed that up to 32% of energy in the infragravity band was reflected while only 3% to 8% of gravity energy was reflected by the cliff.

4. Waves do not appear to be the primary control on platform development at the study site at present. However, waves are responsible for removing weathered cliff debris from the platform–cliff toe junction. Further studies under higher energy conditions (i.e. storms) with varying water depths are required to confirm this interpretation.
CHAPTER 4

Wave Transformations on Type B Shore Platforms under Storm Conditions

*Case Studies from the Northeast Coast of Auckland, New Zealand*

4.1 Introduction

This chapter presents the results of two experiments conducted on the northeast coast of Auckland, New Zealand, under storm conditions. The case studies presented in this chapter focus on the interaction of storm waves with the platform surface and describe how changes in incident wave conditions affect wave processes and characteristics on the inner platform surface. These two case studies build onto the results of the Gisborne experiments presented in the previous chapter which described spatial and temporal characteristics of waves on shore platforms under swell wave conditions. The case studies presented in this chapter focus mainly on the following objectives as stated in chapter 1 section 1.3:

**Objective (a):** To describe and quantify wave-energy transmission and dissipation from the seaward edge to the cliff toe.

**Objective (d):** To investigate and assess tidal controls on wave transformations.
Objective (e): To investigate how platform wave processes are affected by the variations in incident wave conditions and tide conditions.

The experiments were conducted at Rothesay Bay and Red Beach, Auckland. During the passage of the storms, incident wave conditions changed significantly. The changes in incident wave height observed during the two experiments provide excellent opportunities to explore how platform wave characteristics responded to the increase in incident wave height.

The first study (section 4.2), which was conducted on the 150 m platform at Rothesay Bay, describes wave-height transmission across the platform surface under storm conditions and identifies various hydrodynamic thresholds, including the wave breaking criterion. Results are used to extend the observation of the breaking criterion presented in the previous chapter. The applicability of the empirical equation proposed by Nelson (1987) discussed in chapter 2 is also tested. The study also identifies a relative water depth threshold for gravity and infragravity wave propagation across the seaward edge to the cliff toe. Furthermore, the width of the surf zone on the platform surface, identified in the previous chapter as zone 1, is examined. In addition to the first order wave transformation, an attempt is made to describe wave setup across the platform surface. Significantly, this is the first study to describe wave setup on shore platforms.

The second case study (Section 4.3) reports the results of a field experiment conducted on a 90 m shore platform at Red Beach, Auckland. During the experiment, wave conditions changed from high energy storm conditions to moderate energy post-storm swell conditions. The study describes and compares the inner platform
wave characteristics on the wind-wave day and the swell day. It examines whether changes in incident wave conditions affected the inner platform wave characteristics and identifies inconsistencies in cliff-toe wave characteristics reported by previous studies.

The case studies presented in this chapter (Ogawa, submitted; Ogawa et al., submitted) have been submitted for publication and are currently under review.
Chapter 4: Wave Transformations under Storm Conditions

4.2 Case Study 3

Hydrodynamic Constraints and Storm Wave Characteristics on a Sub-Horizontal Shore Platform

4.2.1 Introduction

Wave processes are a critical control on the initiation and subsequent evolution of shore platforms (Trenhaile, 1987; Sunamura, 1992). The relative dominance of wave induced erosion and sub-aerial weathering on shore platform development has been the subject of considerable debate, and varies according to morphological characteristics of platforms, stages of evolution and energy setting (Trenhaile and Porter, 2007; Kennedy et al., 2011). The efficiency of such physical processes also differs temporally and spatially within a shore platform system (Trenhaile, 2002b). Nevertheless, numerical models suggest that shore platforms are unlikely to evolve without wave erosion (Trenhaile and Porter, 2007; Trenhaile, 2008a; Walkden and Dickson, 2008). Of the spectrum of wave conditions that impact rocky coasts, waves generated during high energy storm events are considered to be particularly important in forcing geomorphic change (Edwards, 1941; Trenhaile, 1972; Naylor and Stephenson, 2010; Hall, 2011). Furthermore, in sheltered low energy environments such as estuaries and bays, episodic storm waves are believed to play a key role in eroding rock surface and transporting debris produced by sub-aerial weathering (Kennedy et al., 2011).
Hydrodynamic processes on shore platforms erode the substrate through hydraulic and mechanical action (Trenhaile, 1987; Sunamura, 1992). Waves exert erosive forces through pressure loading by breaking, water hammer effect and trapping and compressing air in joints and cracks (Trenhaile, 2000). Recent studies suggest that wave-generated seismic motions can also fatigue sea cliffs; thereby rendering them susceptible to direct erosion and mass wasting (Adams et al., 2002; 2005).

Mechanical wave action includes abrasion and attrition of rock through sediment entrainment and transport (Robinson, 1977; Trenhaile, 1987; Sunamura, 1992; Woodroffe, 2002). Removal of cliff-toe debris and weathered rock material from the platform surface by wave action is an important process on shore platforms where sub-aerial processes dominate (McLean and Davidson, 1968; Stephenson and Kirk, 2000b; Kennedy and Beban, 2005; Trenhaile, 2008b; Trenhaile, 2008a).

The role of waves in shaping coastal cliffs and platforms have been investigated in the laboratory (Sanders, 1968b; Sanders, 1968a; Sunamura, 1973; 1976; 1992), simulated numerically (Sunamura, 1978a; 1982; Trenhaile, 2000; 2005; 2008b), discussed using morphological evidence in the field (Tsujimoto, 1987; Sunamura, 1992; Kennedy and Beban, 2005; Dickson, 2006; Hall, 2011) and assessed directly and indirectly in the field (Stephenson and Kirk, 2000a; Adams et al., 2005; Trenhaile and Kanyaya, 2007; Lim et al., 2011). Despite being an important process in shore platform evolution, field studies of wave processes on shore platforms have long been neglected. Recently there has been an increase in observational studies of wave processes on shore platforms which have focussed on three areas: simple wave-height measurements (Stephenson and Thornton, 2005; Farrell et al., 2009); waves and their erosion potential (Stephenson and Kirk, 2000a; Trenhaile and
Kanyaya, 2007); and wave transformation processes (Beetham and Kench, 2011; Marshall and Stephenson, 2011; Ogawa et al., 2011; 2012). Stephenson and Kirk (2000a) were first to measure wave-height attenuation and potential geomorphic action on two shore platforms on Kaikoura Peninsula, New Zealand. They concluded that waves were not important agents of erosion on the contemporary platform due to significant energy attenuation. Similarly, Trenhaile and Kanyaya (2007), using a set of wave poles and a video camera, recorded wave height and period and calculated their erosive capacity at two study sites in Canada: the micro-tidal coast of Gaspe, and; and the micro-tidal coast of Bay of Fundy. Trenhaile and Kanyaya (2007) concluded that waves are important agents of erosion on sloping platforms, but less effective on sub-horizontal platforms due to water depth constraints. Stephenson and Thornton (2005) measured wave height on a sub-horizontal platform on Otway Coast, Victoria, Australia and identified a relatively low rate of attenuation (Stephenson and Thornton, 2005); furthermore, Stephenson and Thornton (2005) suggested that wave-energy dissipation may differ between different platform types. Farrell et al. (2009) investigated the wave breaking criterion on a sub-horizontal platform and reported that root-mean-squared wave height ($H_{rms}$) was limited to 42% of the platform water depths. This number is similar to the value reported by Thornton and Guza (1982) for inner surf zone stable wave height.

Most recently a number of studies have examined wave transformation across platform surfaces, using both time and frequency domain analyses. Ogawa et al. (2011) investigated the importance of different wave frequencies and wave types on a 250m shore platform in Tatapouri, New Zealand. They reported that wave
characteristics on their study platform varied temporally and spatially. At the seaward edge waves in the incident swell frequencies (0.05 – 0.125Hz) dominated the spectra, while at the cliff, infragravity waves became more dominant. Ogawa et al. (2011) also reported that significant wave height ($H_{m0}$) on the platform was limited to 40% of the platform water depth. Beetham and Kench (2011) investigated the presence of shoaling of infragravity waves at Rothesay Bay, Auckland and Oraka, south of Gisborne, North Island, New Zealand, and showed that infragravity waves shoaled and increased in height toward the cliff toe. In another study, Marshall and Stephenson (2011) measured wave height and characteristics on four morphologically different shore platforms in Otaway, Victoria, Australia, and Kaikoura, South Island, New Zealand. They identified platform gradient and water depth as two primary contralss on wave-energy dissipation. Furthermore, Marshall and Stephenson (2011) reported infragravity waves to be the most important wave energy component on three out of four platforms they investigated.

Collectively, recent studies have provided useful insights into the role of wave erosion and the characteristics of waves on shore platforms; however, little is known of the critical hydrodynamic thresholds, such as water depth, on the propagation of gravity-wave energy onto platform surfaces and the wave breaking criterion on shore platforms. Only Farrell et al. (2009) and Ogawa et al. (2011) have discussed the threshold wave breaking criterion on shore platforms but there is a discrepancy between the values reported in these studies (significant wave height to water depth ratio ($H_{m0}/h$) = 0.4 by Ogawa et al. (2011) and 0.6 by Farrell et al.(2009)). Marshall and Stephenson (2011) recognised the presence of water depth and slope thresholds on wave-energy dissipation, but did not quantify actual values.
Furthermore, existing studies of wave transformations on shore platforms have mainly been conducted under fair-weather non-storm conditions with little variation in incident wave energy. Consequently, there is a significant gap in knowledge of hydrodynamic thresholds on shore platforms. In addition knowledge of the interaction of high energy storm waves and the hydrodynamic thresholds that exist during storms is lacking. However, knowledge of storm wave processes on rock coasts is paramount for improving our understanding of the entire spectrum of shore platform wave processes, predicting future change (through numerical models) and for underpinning management of rock coasts.

This study presents detailed observations of storm wave transformations on a sub-horizontal platform on the leeward east coast of Auckland, New Zealand (Fig. 4.1a, b). The study is based on a dataset collected at Rothesay Bay, Auckland, as part of a larger project describing shore platform processes and morphodynamics along the coastline of Auckland. Part of the dataset has previously been described by Beetham and Kench (2011) who characterised shoaling transformation of infragravity waves on two shore platforms, including the Rothesay Bay platform. To compare the results from two study sites, Beetham and Kench (2011) focused on nine representative bursts from each study site. This study presents the entire dataset collected during the Rothesay Bay experiment, including still water levels on the study platform. In contrast to Beetham and Kench (2011), this study focuses on how gravity and infragravity waves and water level on the platform surface respond to variations in incident wave conditions and, in particular, storm waves, observed during the experiment. Specific objectives of the study are: (a) to characterise storm wave processes on the study platform; (b) to characterise mean water-level gradient
across the platform surface; (c) to analyse wave height and energy transmission across the platform; (d) to quantify the amount of gravity-wave height attenuation; (e) to identify gravity-wave height thresholds across the seaward edge and on the platform surface and; (f) to characterise infragravity-wave height transformation in response to changes in incident wave conditions. Geomorphic implications of the results are also discussed.

4.2.2 Study site

Rothesay Bay is located in the inner Hauraki Gulf on the northeast coast of Auckland, New Zealand (36° 43’ 4.59” S, 174° 45’ 8.36” E, Fig. 4.1a, b). The east coast of Auckland experiences semi-diurnal, meso-tidal conditions with a spring tidal range of approximately 3 m. Mean sea level (MSL) for the region is approximately 1.3 m above the local Chart Datum. The 100 year sea-level record measured at Port of Auckland shows sea-level rise of 1.3mm/yr on this coastline (Bell et al., 2000; Hannah, 2004).

The coastline is considered a leeward, low energy environment (Brookes and Green, 2001; de Lange et al., 2003). The fetch limitations of the Hauraki Gulf mean that the Rothesay Bay wave climate is characterised by locally generated short-period waves and low-amplitude swell (Brookes and Green, 2001). Waves generally arrive from the north-northeast sector (Gorman et al., 2003). The low energy wave condition is punctuated by episodic storm events several times per year. Offshore wave buoy data recorded near Mokohinau Islands (100 km north-east of Rothesay Bay) in the
outer Hauraki Gulf show that the mean offshore wave height is 1.2 m with only 3% and 0.35% of waves exceeding 3 m and 7 m respectively (Gorman et al., 2003).

Figure 4.1: Location of the study site and platform profile: a) Location of Auckland, New Zealand; b) Location of Rothesay Bay; c) plan view morphology of the study platform at Rothesay Bay and the transect location, and; d) cross-section of the study platform.
Geology of the study area is dominated by the highly deformed sedimentary rocks of East Coast Bays Formation of the Waitamata Group, which are characterised by alternating graded-sandstone and laminated-mudstone (Edbrooke, 2001). Shore platforms often front the cliffs and beaches along the coast (Healy, 1968a). Erosion rates of coastal cliffs along the east coast of Auckland vary significantly due to local lithology and differences in methods used by different studies, with reported erosion rates ranging from 5 to 180 mm/y (de Lange and Moon, 2005).

Figure 4.2: Photographs of the platform at Rothesay Bay: a) across-shore view of the platform from the cliff toe to the seaward edge; b) seaward edge; c) cliff-toe boulders and; d) erosional notch at the cliff base. The mean and the maximum b-axis measurements of the boulder material present in the cliff-toe debris are 0.15 m and 0.71 m respectively (V. Turner, pers. comm.)

The platform at Rothesay Bay is characterised by a sharp seaward boundary, a smooth surface and a curved (concave) slope at the landward end of the profile (Fig. 4.1d and 4.2). The profile is representative of the most common platform shape on the east coast of Auckland (Healy, 1968a). The study transect is 140-m-wide with a mean gradient and elevation of 0.38° and -1.2 m below MSL respectively. The
The elevation of the platform at the seaward edge is -1.4 m below MSL and drops sharply to -3.1 m below MSL in the sub-tidal nearshore environment. Between 0 and 70 m from the seaward edge, the profile surface is very smooth with a mean elevation of -1.39 m below MSL and a mean gradient of 0.08°. The landward section of the platform (70 – 140 m) has an irregular surface with a mean elevation and the gradient for the landward part of the platform are -0.94 m below MSL and 0.71° respectively. At the cliff toe, boulders are present due to cliff erosion (Fig. 4.2c). The presence of a notch at the base of the cliff and semi-organised and rounded boulders indicate that wave action is active at the cliff-platform interface (Fig. 4.2c, d).

### 4.2.3 Field and analytical methods

The experiment was conducted over a 36 hour period between March 4th and March 6th 2009 during a wind-storm event. Metrological and hydrodynamic conditions during the experiment are described in the following section. Five RBR-2050 TWR tide and wave gauges were deployed along a shore-normal transect (Fig. 4.1c, d). For water depth observations, all sensors were tested in the lab to ensure sensor linearity (Table 4.1). Waves were monitored at three locations on the platform surface with near-equal spacing between the seaward edge and the cliff toe (R3 – R1, Fig. 3). All sensors were bottom mounted (fixed to the platform surface) and programmed to sample at 2Hz for 17.1 minutes (2048 sample points) at 30 minute intervals between bursts.
Table 4.1: Results of the sensor accuracy and precision test (measured vs. actual pressure).

<table>
<thead>
<tr>
<th>Sensor ID</th>
<th>15435</th>
<th>15434</th>
<th>15436</th>
<th>12465</th>
<th>15437</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Precision (R²)</strong></td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
</tr>
<tr>
<td><strong>Accuracy (slope)</strong></td>
<td>0.999</td>
<td>1.003</td>
<td>1.001</td>
<td>1.004</td>
<td>0.998</td>
</tr>
</tbody>
</table>

Pressure time-series were converted to sea-surface elevation using a linear transfer function (Tucker and Pitt, 2001). Following Sallenger and Holman (1985) and Rijn et al. (2000), a fixed high-frequency cut-off of 0.33Hz was adopted with a limiting amplification factor of 5 in order to avoid noise injection.

Spectral analysis was performed using Welch’s averaged modified periodogram of spectral estimation (Welch, 1967). The analysis was performed on a contiguous record of 2048 samples using a 256-point Hanning window with a 50% overlap, providing 16 degrees of freedom (DOF). It should be noted that the analytical procedures used in this study differ from Beetham and Kench (2011), including the selection of low and high frequency cut-offs and the calculation of significant wave height and period. Descriptive values of wave height and period were calculated for the gravity wave band (0.05 – 0.33Hz) and the infragravity wave band (< 0.05Hz) by filtering the time-series data in the frequency domain. Following Hardy and Young (1996) two methods were used to calculate wave statistics. Significant wave height for gravity waves (designated simply as $H_{m0}$) and infragravity waves (designated as $H_{m0L}$) were determined from the zeroth moment of the variance spectrum for the respective frequency ranges. Wave period for gravity waves ($T_1$) and infragravity waves ($T_{1L}$) were estimated from the zeroth and the first-moment of the variance spectrum. Maximum gravity-wave height ($H_{max}$) and infragravity-wave height ($H_{maxL}$)
were determined by performing a zero-down crossing analysis on the time-series data.

Pressure time-series data were also utilised to investigate differences in water-level on the study platform caused by wave setup. All pressure data were post-corrected for barometric pressure and sensor offsets in order to determine mean water depth for each burst. Absolute water level values were then determined by reducing water level data to a common datum (i.e. R1). A total station was used to precisely determine the elevation of each pressure sensor.

4.2.4 Metrological and hydrodynamic conditions

Meteorological records show that the experiment was conducted during a northeasterly storm (Fig. 4.3). Barometric pressure dropped significantly during the experiment as the storm developed (Fig. 4.3a). Onshore winds blew from the northeast and east (60 to 90°) at speeds up to 50 km/h (Fig. 4.3b) and peaked in the afternoon of the 5th March. Incident waves recorded at the nearshore sensor site (R0) increased from $H_{m0} = 0.8$ m at the start of the experiment to a maximum of 1.45 m observed near the second high tide (Fig. 4.3c). Maximum wave height ($H_{max}$) reached 2.30 m during the peak storm period associated with peak wind speed (Fig. 4.3c).
4.2.5 Results

4.2.5.1 Water depth across the platform

Water depth records reflect the differences in surface elevation and tidal stage across the platform (Fig. 4.4). Off the seaward edge of the platform (R1), water depth ranged from 1.4 m to 3.4 m at low and high tide respectively. At the seaward edge and central platform (R2 and R3), water depth ranged 1.9 m at high tide to <0.1 m at low tide. The mean water depth off the edge of the platform was below the level of

Figure 4.3: Meteorological and incident wave conditions: a) barometric pressure; b) wind speed and direction; c) water depth and wave height measured at R0. Meteorological data source: Auckland airport weather station.
the platform surface at low tide; however, wave breaking at the seaward edge, and associated surges constantly forced water onto the platform surface. At the cliff toe (R4), water depth peaked at 1.3 m at high tide and was exposed at low tide. The platform surface at the cliff-toe sensor site was inundated for 71% of the experimental period.

![Graph showing water depths recorded at different locations](image)

**Figure 4.4:** Water depths recorded off the seaward edge (R1), at the edge (R2), centre (R3) and cliff toe (R4).

Figure 4.5 illustrates the still water level differences recorded across the platform surface. Water level records were averaged over three bursts for low, mid and high tide levels from the peak storm period (bursts 37 – 51) and the post storm period (bursts 57 – 75) (Fig. 4.5) for each sensor sites and were reduced to a common point (R1) in order to determine spatial variations in water levels across the platform surface. The differences in still water level across the platform were tidally modulated, with the highest water level recorded at the seaward edge (R2) and the central platform (R3) during low tide (up to 0.2 m greater than at R1). At mid and high tide, the highest values were recorded either at R3 or R4. The observed differences in water level between the two inner platform sensor sites were small during the experiment. The highest still water levels on the platform were recorded
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4.2.5.2 Spatial and temporal variations in wave characteristics

Gravity wave (GW, 0.05 – 0.33Hz) and infragravity wave (IGW, < 0.05Hz) heights and periods measured during the experiment are summarised in Figure 4.6. In general, all gravity wave records show evidence of tidal modulation and a progressive reduction in wave height between the nearshore, platform edge and central platform locations (Fig. 4.6b, c). Significant gravity-wave height ($H_{m0}$) measured at the seaward location (R1) varied from 0.4 m to 1.6 m. $H_{m0}$ at R1 was modulated by the tide during the lower tidal stages, but was controlled by the incident wave condition during mid to high tide stages as evidenced by the variation in $H_{m0}$ values at three tidal cycles (Fig. 4.6a, b). Wave-height characteristics during

during the peak storm period, with maximum mean water level reaching 0.21 m (standard deviation = 0.02).

Figure 4.5: Water level gradient across the platform surface during the peak and post storm periods. Note that data points on the graph are slightly offset from each other in order to avoid overlaps.
the three tidal cycles were different, with the highest $H_{m0}$ values of 1.6 m observed during the second tidal cycles (peak storm period). The maximum wave height ($H_{max}$) measured at R1 reached 2.0 m at the second high tide.

Gravity-wave height recorded at the seaward edge of the platform (R2) followed a similar temporal pattern as R1 (Fig. 4.6b, c). Both $H_{m0}$ and $H_{max}$ were slightly smaller than at R1 and peaked at 1.3 and 1.7 m respectively. It is likely that wave breaking was initiated on the slope leading to the platform edge (hence the smaller wave height at R2). Visual observation during the experiment suggests that waves were breaking at or near the seaward edge. Some larger waves were breaking before

\[ GW = \text{gravity wave}; \quad IGW = \text{Infragravity wave}. \]
reaching the platform edge. The differences in gravity-wave height between R1 and R2 were most significant at low tide and during the peak storm period when incident wave height was highest (Fig. 4.6b, c). $H_{m0}$ was reduced by 60% during low tide and up to 40% at high tide during the peak storm period between R1 and R2. During the first tidal cycle (bursts 8 – 15), and the last part of the experiment (bursts 62 – 73) wave-height reduction between R1 and R2 was very small. Despite the shallow water depths during low tide, gravity-wave height at R2 never reached zero.

Significant gravity-wave heights on the central platform (R3) and cliff toe (R4) were smaller than the platform edge and ranged from 0 m at low tide to 0.8 m at high tide. The maximum wave height recorded on the central platform and at the cliff toe reached approximately 1.0 m at high tide (Fig. 4.6b, c). The largest amount of wave-height attenuation on the platform (50%) was observed between the seaward edge (R2) and the centre of the platform (R3). In contrast, gravity-wave height recorded at the centre (R3) and the cliff toe (R4) sensor sites were very similar R2 and R3 throughout the experiment, despite the differences in surface elevation, water depth and distance from the seaward edge. It is also evident in Figure 4.6b and c that gravity-wave heights recorded at those two sites were strongly modulated by the tide.

The behaviour of infragravity waves ($H_{m0L}$ and $H_{maxL}$) on the platforms differed markedly to gravity waves (Fig. 4.6f, g). The largest infragravity-wave height ($H_{maxL} = 0.4$ to $0.6$ m) was observed off the seaward edge of the platform (R1) during low to mid tidal stages (Fig. 4.6f, g). In contrast, at the platform edge (R2), infragravity waves were larger during mid to high tidal stages and the lowest wave height values were observed during low tide. On the platform, infragravity-wave height generally
reached maximum at the cliff toe (R4) and the highest values were observed during high tide (0.3 m). At high tide, $H_{m0L}$ reached 140 to 200% of the values recorded at the seaward edge. The largest increase in wave height took place between the centre of the platform and the cliff toe.

Gravity-wave period ($T_1$) was generally constant between 5 and 6 s across the platform, but increased slightly at the centre and the cliff toe sites at low tide (Fig. 4.6d). Infragravity-wave period ($T_{1L}$) was generally between 32 and 40 s at R1, R2 and R3 (Fig. 4.6h). Slightly higher wave periods (40 to 45s) were observed at the cliff toe (R4). As with gravity-wave period ($T_1$, Fig. 4.6d), $T_{1L}$ increased towards low tide, albeit a small amount (Fig. 4.6h).

### 4.2.5.3 Wave-energy transformations

Figure 4.7 presents the time-stacked wave-energy power spectral density (PSD, Fig. 4.7a-d) and normalised PSD (Fig. 4.7e-h) measured across the platform and highlight a number of aspects of wave energy and its transformation. First, wave energy off and at the seaward edge (R1 and R2) was predominantly contained in locally generated wind wave frequencies between 0.15 and 0.2Hz. Towards the end of the experiment, residual swell energy at 0.1 – 0.11Hz became more apparent (Fig. 4.7a, e). Second, wave energy on the platform was strongly modulated by tide, and the temporal window in which wave energy could access the platform surface decreased landward. Third, gravity-wave-energy transmission across the platform, from R1 to R4, was lowest during the peak storm period (bursts 30 – 45), which is most apparent in the normalised PDS (Fig. 4.7g, h). During the second tidal cycle,
less than 20% of wave energy (represented by dark blue in Fig. 4.7g and h) was transmitted across the platform. More wave energy was transmitted to the inner platform locations at the first and the third tidal cycles during which incident wave energy was lower. Fourth, there was a contrasting pattern in infragravity-wave energy between the off platform (R1) and central platform locations (R3 and R4). Energy at IGW frequencies was highest during low tide at R1 (Fig. 4.7a, e), whereas IGW energy peaked at high tide at the cliff toe (Fig. 4.7g, h). Of note, the level of IGW energy at the cliff toe (R4) was strongly associated with incident wave energy, and peaked during the second high tide (Fig. 4.7a, d).
Figure 4.7: Time-stacked power spectral density (PSD) (a-d) and normalised PSD (e-f) measured off the seaward edge of the platform (a and e), at the edge (b and f), centre (c and g) and at the cliff toe on the platform. Normalised PDS was calculated by dividing the PDS recorded at each sensor site by the corresponding PSD at the peak frequency recorded off the seaward edge. Normalised PDS show the energy distribution about the peak frequency and relative increase (or decrease) in energy in comparison to incident values off the seaward edge.
4.2.6 Discussion

This study presents the most detailed observations of the interaction of storm-generated waves with a shore platform. Interaction of large waves (~2 m) with the platform showed that the behaviour of gravity waves and infragravity waves was markedly different. While incident wave conditions varied significantly during the experiment, gravity-wave height at the inner platform sites was modulated by the tide. Gravity waves were most strongly attenuated between the seaward edge and the centre of the platform. In contrast, infragravity-wave height on the platform was highest during the peak storm period, suggesting that infragravity-wave height on the platform was associated with the incident wave conditions. Furthermore, infragravity wave characteristics were distinctively different on and off the platform. These general patterns of wave transformations on the study platform have previously been reported by Beetham and Kench (2011), but the limited temporal framework of their observations precluded detailed analysis of results in the context of changes in incident wave conditions. The storm event provides an excellent opportunity to examine critical thresholds of wave-platform interaction that control wave propagation and delivery of wave energy at different frequencies to cliffs.

4.2.6.1 Controls on gravity wave transformations

Relationship between $H_{m0}$ and $H_{max}$

Significant wave height ($H_{m0}$) and maximum wave height ($H_{max}$) exhibit a close and linear relationship ($R^2 = 0.96$, Fig. 4.8). Maximum wave heights are 1.34 times higher than $H_{m0}$. The relationship between maximum wave height and significant wave
height (or other wave-height parameters) values changes according to wave period and the wave-height probability density function. The $H_{m0}$ to $H_{max}$ ratio reported here are lower than theoretical values assuming the Rayleigh distribution but closer to the value of approximately 1.5 calculated from the data presented in Hardy et al. (1990) and Kamphuis (2000). Since a linear relationship between the two parameters is found, only significant wave-height values are considered in the following discussion.

![Graph showing the relationship between significant wave height and maximum wave height.](image)

**Figure 4.8:** Relationship between significant wave height and maximum wave height recorded between R0 and R4 during the experiment.

**Transformation of gravity waves**

For geomorphic and engineering purpose, it is critical to quantify the amount of wave energy delivered to cliffs under specific wave conditions. Previous studies of waves on shore platforms simply identified the amount of wave attenuation across the platform surface (Stephenson and Kirk, 2000a; Stephenson and Thornton, 2005;
Ogawa *et al.*, 2011). However, results of this study show that the amount of wave-height and energy attenuation on shore platforms needs to be considered in terms of incident conditions and tide level, before comparisons are made amongst different platforms.

Figure 4.9 illustrates the transmission of gravity waves as a function of relative platform widths \( \left( \frac{W}{T(gh)^{0.5}} \right) \) using a total of 45 bursts representing the period during which the entire platform surface was submerged. Relative platform width represents the number of wave cycles (wave lengths) between the seaward edge and a given location on the platform surface \( W \). Wave transmission is quantified as transmission coefficient \( (K_t) \), which is calculated as the wave height recorded at a given position on the platform divided by the incident wave height recorded in front of the platform \( (R1) \). The observed values of \( K_t \) are plotted according to the relative
platform edge submergence \((h/H_{m0})\). During the experiment, the values of relative edge submergence varied from 0.13 and 2.2 at high tide and low tide respectively.

Three things are apparent in Figure 4.9. First, the transmission coefficient was found to be controlled by incident wave energy. Higher values of \(K_t\) were associated with higher relative edge submergence values. Second, an increase in relative platform width generally resulted in greater reduction in \(K_t\) at a given location. Third, there is little (or only a small) change in the \(K_t\) values observed between R3 and R4 while there is significant reduction in the \(K_t\) values between R1 and R3.

Previous studies on coral reefs and nearshore breakwaters demonstrated relative submergence as an important control on wave height and energy transmission (Gourlay, 1994; Blenkinsopp and Chaplin, 2008; Cappietti, 2011). The pattern of wave transmission between the seaward edge and the central platform sensor sites are broadly comparable to the results of laboratory experiments on breakwaters (Blenkinsopp and Chaplin, 2008; Cappietti, 2011): the reduction in relative edge submergence results in the reduction in wave transmission. Relatively high values of \(K_t\) observed across the seaward edge (0.9) and to the central platform surface (>0.8) under low breaking conditions (relative edge submergence > 2) suggest that the presence of a relative edge submergence threshold beyond which no wave dissipation occurs. Indeed, the extrapolation of the data presented in Figure 4.9 indicates that a relative edge submergence of approximately 2.5 to 2.7 is required for waves to propagate onto the platform surface without being dissipated. This value is consistent with the values reported for coral reef platforms (Gourlay, 1994).
The observed reduction in $K_t$ values associated with the increase in relative platform width (for $W/T\sqrt{gh} > 6.5$), especially at the cliff toe (R4), suggests that platform width plays an important role in wave-energy dissipation. In contrast, the small difference in $K_t$ values observed between R3 and R4 (for $W/T\sqrt{gh} < 6.5$, $H/h > 1.2$) indicates propagation of reformed waves on the platform surface. As demonstrated in Figure 4.6 and 4.7, wave height and energy at the inner platform locations were similar at mid to high tidal stages. Results demonstrate that there was little wave breaking taking place between the two sensor sites. On coral reef platforms, Gourlay (1994) reported that waves reform and cease to dissipate energy by turbulence after two to three wave lengths away from the reef edge. He suggested that the distance required for wave reformation and therefore the width of the surf zone on reef platforms can be predicted as:

$$\frac{W}{T\sqrt{gh_e}} = (2 + 1.1 \frac{H_i}{h_e}) \quad \text{Eq. 4.1}$$

Unfortunately, a lack of data between $W/T\sqrt{gh} = 1$ and 3 means the applicability of the equation on the Rothesay Bay platform cannot be tested. Nevertheless, the result challenges the commonly accepted assumption used in numerical models that waves continue to dissipate across the entire width of subhorizontal platforms and reaches the cliff toe as bores (Sunamura, 1992; Trenhaile, 2000).

**Water depth thresholds on wave transformation**

Water depth appears to be an important control on wave transformation on the platform surface. The relationship between water depth and significant wave height (Fig. 4.10) indicates that characteristics of the wave field seaward of, and at the edge
of the platform are dissimilar to the wave fields at inner platform locations. Waves recorded off the seaward edge are generally independent of water depth (Fig. 4.10a). At the seaward edge, wave height is more dependent on water depths at low to mid tide (depth < 0.6 m) but becomes less dependent at higher water depths (Fig. 4.10a). In contrast, wave height at the centre of the platform and the cliff toe is a direct function of local water depth (Fig. 4.10b). Such spatial differences demonstrate the presence of hydrodynamic zones that are unique to sub-horizontal shore platforms.

Figure 4.10: Gravity-wave height versus water depth near: a) the seaward edge (R1 and R2), and b) the central platform and the cliff toe sensor sites (R3 and R4).

A strong dependence of wave height on local water depth occurs when waves become energy saturated (Thornton and Guza, 1982). A saturated surf zone, as defined by Thornton and Guza (1982), occurs when all waves are breaking or broken and wave height becomes a direct function of water depth; whereas unsaturated surf contains breaking and unbroken waves and is not represented by a
simple dependence of wave height on water depth. At the platform edge, waves are forced to break due the sudden change in water depth. The transition from unsaturated to saturated conditions takes place as waves traverse the seaward edge. After the initial breaking, waves form periodic bores and eventually reform and propagate as stable oscillatory waves. In shallow water, the height of broken wave and reformed oscillatory waves are also known to be a direct function of water depth (Nelson, 1994). Wave height under depth-limited conditions is expressed as:

\[ H = \gamma h \]  \hspace{1cm} \text{Eq. 4.2}

where \( \gamma \) is the proportionality factor. The most commonly known value of \( \gamma \) is 0.78 which was derived by McCowan (1894) from solitary wave theory. However, \( \gamma \) values are known to vary significantly (Galvin and Eagleson, 1965; Goda, 1970). On shore platforms, Ogawa et al. (2011) reported \( \gamma \) for significant wave height to be 0.4, while Farrel et al. (2009) suggested this value to be around 0.6. Ogawa et al. (2011) argued that the discrepancy between the two studies is likely due to the difference in bottom slope or wave period (and therefore wave length and steepness). At Rothesay Bay, significant wave height recorded on the central platform is constrained by \( \gamma = 0.4 \) while at the cliff toe \( \gamma \) is much closer to 0.6. The observed difference in \( \gamma \) appears to be consistent with the empirical equation of Nelson (1987) who found that \( \gamma \) values were a function of substrate gradient:

\[ \gamma_{\text{max}} = 0.55 + 0.88 \exp(-0.012 \cot \theta) \text{ for } \theta \leq 0.1 \]  \hspace{1cm} \text{Eq. 4.3}

where \( \gamma_{\text{max}} \) is the wave breaking criterion for maximum wave height and \( \theta \) is bed slope.
Using the relationship between $H_{m0}$ and $H_{max}$ (Fig. 4.9) we can determine the envelop values of $0.4h$ and $0.6h$ for $H_{m0}$ to be equivalent of $0.54h$ and $0.80h$ for $H_{max}$. The gradients between R2 and R3 (seaward edge to centre), and R3 and R4 (centre to cliff-toe sensor) are 0.0014 (0.08°) and 0.09 (0.53°) respectively. Nelson's (1987) equation gives $\gamma_{max}$ values of 0.55 and 0.78 for these slopes. The agreement between the field and predicted values suggests that the bottom slope is the primary control on the proportionality factor on the study platform. The value of 0.54 for the central platform is also in accordance with theoretical (Massel, 1996; Massel, 1998) and empirical values of wave-height limit on a flat surface on coral reef platforms (Nelson, 1985; Nelson, 1994; Hardy and Young, 1996; Kench et al., 2009). Consequently, maximum wave height on a horizontal shore platform is unlikely to exceed 55% to 60% of the platform water depth. As the bed slope increases, the proportionality factor takes a higher value (Nelson, 1994). As wave hydrodynamics at the cliff toe may be complicated by wave reflection and refraction, the applicability of Eq. 4.3 needs to be assessed further. Nevertheless, it is clear that a range of $\gamma$ values, rather than a single value, are necessary to more accurately predict wave-height conditions across sub-horizontal platform.

### 4.2.6.2 Infragravity waves

Understanding the transformation of infragravity waves across shore platforms is important for resolving their role in forcing geomorphic change. Previously Beetham and Kench (2011) examined morphological controls on infragravity wave shoaling and suggested that cliff-toe gradient and the reef wave-energy window index (Kench
and Brander, 2006) as key controls on infragravity wave shoaling. Results presented in the present study also suggest that infragravity-wave height at the seaward edge and incident wave conditions play important roles in infragravity wave transformation across the platform surface. As illustrated in Figure 4.11a and b there is a significant difference in infragravity-wave height amplification during the peak storm period and post storm period (with lower $H_{m0}$ and $H_{m0L}$ conditions). Although infragravity height at the cliff toe was greater during the peak storm period at all tidal stages than the storm waning period, the amplification in infragravity-wave height across the cliff toe was much higher (30 to 80%) under lower energy conditions. The magnitude of infragravity-wave height amplification is found to be strongly correlated with the relative edge submergence at the seaward edge (Fig. 4.11c, d). Relative submergence values were calculated for infragravity waves (Fig 4.11c) and gravity waves (Fig. 4.11d) observed at R0. Changes in infragravity-wave height are expressed in terms of wave-height transmission coefficient ($K_{t-L}$). The observed correlation between relative edge submergence and infragravity energy transmission is consistent with previous studies on sandy beaches. Previously Ruessink (1998b) reported that across-shore amplification of infragravity-wave energy was largest during low energy conditions. Ruessink (1998) demonstrated that infragravity wave amplification was correlated to the incident wave height to water depth ratio and that bound waves contributed significantly to the across-shore increase in infragravity-wave energy under low energy conditions ($\gamma < 0.33$). Interestingly, the values of the coefficients of determination ($R^2$) between edge submergence and $K_{t-L}$ are very similar for edge submergence calculated from $H_{m0L}$ and $H_{m0}$. However, this is not surprising as infragravity-wave height is known to be linearly correlated to incident wave height (Huntley, 1976;

Figure 4.11: Infragravity wave attenuation and amplification on the study platform: a) absolute change in wave height; b) percent change in wave height; c) relationship between relative edge submergence calculated using $H_{m0L}$ and infragravity-wave height transmission; d) relationship between relative edge submergence calculated using $H_{m0}$ and infragravity-wave height transmission ($K_{t-L}$). Values of $K_{t-L}$ greater than 1 indicate wave height amplification where as values less than 1 indicate reduction in wave height. Different colours in a and b represent different incident wave conditions (Red = storm; blue = post storm) and bold (high tide), dashed (mid) and thin (low) lines represent different tidal stages. HT= high tide. $MT_H$ = mid-high tide. $MT_L$ = mid-low tide.

A notable difference in infragravity wave behaviour was also observed on and off the platform. Infragravity-wave height peaked off the seaward edge during low tide but at the cliff-toe infragravity-wave height peak high tide (Fig. 4.6f). Previously
Beetham and Kench (2011) suggested that infragravity waves on the Rothesay Bay platform may be reflected at the seaward edge during low tide. Examination of the complete wave record presented in this study confirms their observation, which was based on 9 selected bursts. As illustrated in Figure 4.6 and 4.7, infragravity-wave height and energy at R1 peaked at low tide, while at R4 infragravity waves peaked at high tide. Results suggest that there is a temporal window in which infragravity-wave energy can propagate onto the platform surface. Figure 4.11 (c and d) illustrates a relative water depth threshold above which infragravity waves are able to get onto the platform and shoal towards the cliff toe. For infragravity waves to propagate onto the centre of the platform without dissipation, the relative edge submergence value of 8.8 (0.81 for gravity wave submergence value) is required. At the cliff toe the value is 3.5 (1.15 for gravity wave submergence value). The difference in the critical values between the two sites is attributed to the difference in surface elevation of the platform and the amount of shoaling experienced between the two sensor sites (Beetham and Kench, 2011).

4.2.6.3 Platform water level and wave setup

Field and laboratory observations on beaches and coral reefs have shown that wave breaking produces across shore variations in the mean water level (Bowen et al., 1968; Guza and Thornton, 1981; Holman and Sallenger, 1985) due to pressure gradients balancing the cross-shore component of the momentum flux (radiation stress) of waves (Longuet-Higgins and Stewart, 1962). Results show that there was a water level gradient across the platform surface, particularly during the peak storm
period, indicating that water level on the platform was super-elevated by wave setup. The observed difference in the magnitude of wave setup during the peak storm period and the post storm period is in accordance with the theory proposed by Longuet-Higgins and Stewart (1962), as a greater wave height should result in greater radiation stress. During the mid and high tide stages, there was little difference in the mean water levels recorded at R2 and R3. This pattern is consistent with the wave setup models proposed by Tait (1972) and Gourlay (1996). However, this pattern of wave setup differs significantly from the field observation reported by Jago *et al.* (2007), who identified the presence of a double set up system at the reef edge and the beach toe on a coral reef platform.

The observed increase in mean water level (~0.2 m) on the platform was significantly lower than the field observation on sandy beaches. For example, Guza and Thornton (1981) demonstrated that wave setup on sandy beaches to be approximately 17% of incident wave height. It is possible that the relatively small wave setup (< 10% of $H_{mo}$ at mid and high tide) observed in this study is due to the plan-form morphology of the platform which allowed water to escape laterally. As illustrated in Figure 4.1c, the Rothesay Bay platform is not laterally confined by headlands; consequently, water can flow out laterally thereby reducing the effect of wave setup (Gourlay, 2011).

The water level gradient on the platform was also tidally modulated, with the highest water levels observed at low tide (Figure 4.5). This is likely due to the difference in relative edge submergence at low tide and high tide. Previously Gourlay (1994) showed that wave setup on coral reef platform is larger at low tide
due to small relative edge submergence. It is also possible that the high water level values recorded at low tide are due to waves breaking directly on the seaward edge and dumping ocean water onto the platform surface, as it is unlikely that the mean water level changes 0.2 m over such a short across-shore distance between R1 and R2 (< 5 m) due to wave setup. Such a process can also generate nearshore currents through “wave pumping” effects (Callaghan et al., 2006).

4.2.7 Implications for geomorphic processes

Analysis of the interaction of storm waves (up to 2 m in height) with the Rothesay Bay platform provide key insights into the critical morphological controls on the spatial and temporal transformation of wave energy. First, a large amount of wave energy is dissipated through turbulent interaction across the seaward portion of the platform, highlighting the critical role of the platform edge in filtering gravity-wave energy. Secondly, not all energy is dissipated at the platform edge; residual energy propagates onto the shore platform. Thirdly, attenuation in gravity-wave height across the platform is found to be a function of relative edge submergence and, to a lesser extent, relative platform width. However, waves reform on the platform surface after the initial breaking and propagate towards the cliff without being significantly attenuated at mid to high tide stages. Fourthly, under storm conditions, gravity waves on the platform were energy saturated, and therefore, independent of incident energy conditions. Consequently, there is a limit on gravity-wave energy delivery to the cliff toe and larger incident wave energy does not equate to higher
wave-energy delivery at cliff toe. Fifthly, transformation of infragravity waves across the platform surface is critically dependent on incident wave and tide conditions.

The results of this study challenge the conventional view that wave height on shore platforms can be modelled with a single proportionality factor ($\gamma$). For example, Stephenson and Kirk (2000a) used the $\gamma$ of 0.78 proposed by McCowan (1894) to assess geomorphic impact of wave forces at the cliff toe. Results suggest that the proportionality factor on sub-horizontal shore platforms is a function of slope and does not exceed 0.6 on very flat platform surfaces as suggested by Nelson (1987) and Hardy and Young (1996). On a very flat shore platform, the use of $\gamma = 0.78$ for geomorphic and engineering purposes results in an overestimation of wave energy. Furthermore, the result has an important implication for boulder transport on shore platforms, as hydrodynamic boulder transport equations use platform wave height to determine whether boulders of certain sizes can be transported (Nott, 1997; 2003).

Of critical importance to wave induced geomorphic processes on shore platforms is the duration and the intensity of gravity waves present on the platform surface and at the cliff toe – platform junction. In previous studies on coral reef platforms, Kench and McLean (1996) and Kench (1998) demonstrated the dependence of sediment entrainment on the presence of gravity waves. Kench and Brander (2006) identified water depth on reef flats as a critical control on the presence of gravity-wave energy.

On rock platforms, gravity waves have been considered responsible for direct erosion of the seaward edge, plucking jointed or fracture rock mass from the surface, transporting sediments and eroding the cliff. On the study platform, relative water
depth at the edge of the platform is found to be a critical control on the dominant wave types operating at each location (Fig. 4.12). Importantly, data from Rothesay Bay show that there is a relative submergence threshold at the seaward edge of the platform, above which waves in gravity wave frequencies (0.05 – 0.33Hz) dominate the platform wave spectra. The critical relative edge submergence threshold during the experiment is found to be 1.1, which was exceeded for 53% of the duration of the experiment. Below this relative submergence, threshold infragravity-wave energy dominates the wave spectra (47% of the experiment).

![Figure 4.12: Relative edge submergence at the seaward edge and peak frequency observed at the centre of the platform and cliff toe](image)

It has been widely assumed that increasing platform width will result in further wave attenuation; therefore the role of sub-aerial weathering becomes more important as platforms evolve (Johnson, 1919; Stephenson and Kirk, 2000a, b;
Trenhaile, 2000; Dickson, 2006). Beetham and Kench (2011) argued that the width of the platform at Rothesay Bay played an important role in attenuating gravity-wave energy. However, results show that the amount of wave-height attenuation between the centre of the platform and cliff is negligible at mid to high tide. The results demonstrate that platform width is important in creating different hydrodynamic zones (e.g. surf zone and shoaling zone). Such a finding is consistent with the previous work by Ogawa et al. (2011) and supports the field observation of wave-transported boulder deposits reported by Hall (2011), who calculated the strength of wave currents based on boulder dimensions and suggested that the attenuation of waves in the inner platform surface was limited. Inevitably, wave attenuation on very wide and irregular shore platforms should be more significant due to increased frictional dissipation. This point is partially demonstrated in Figure 4.9. Nonetheless, the results suggest that waves can perform geomorphic work at an inner platform location on sub-horizontal shore platforms. Waves may be more geomorphologically important on sub-horizontal (Type B) shore platforms than previously thought.

This study has also examined the transformation of infragravity-wave energy across the study platform. Although across-shore increase in infragravity-wave height was larger during lower energy conditions, the role of infragravity waves on shore platforms increased substantially during high energy storm conditions. Infragravity waves introduce long-period oscillations in water level across the platform and at the cliff face, which have a number of implications. First, infragravity waves are known to affect gravity wave processes in the surf zone (Nelson and Gonsalves, 1992). Secondly, periodic fluctuations of local water depth may allow larger gravity
waves to propagate across the platform surface. Within the surf zone, bores at gravity wave frequencies can ride on longer period infragravity waves and propagate towards the shore (Hwung et al., 2007). Thirdly, infragravity wave motions force large excursions (± 0.3 m) in water level at the cliff face. While it is unlikely that long-period infragravity waves are a direct agent of erosion on shore platforms, they are likely to be an important process for modulation of platform wave processes and for sediment transport. Consequently, infragravity waves may be a key mechanism driving abrasion processes, which are important at the cliff toe (Robinson, 1977). The presence of infragravity-wave energy at the cliff toe and their characteristics also has important implications for sloping platforms (or Type A; Sunamura, 1992). As gravity waves are depth limited, they will be progressively attenuated on a sloping platform. Previous studies on swash excursions on a gently sloping beach identified that swash run-up in infragravity frequencies is approximately 70% of offshore significant wave height while swash run-up in gravity wave frequencies are independent of offshore significant wave height (Guza and Thornton, 1982). Considering that shore platforms in macro-tidal environments tend to develop cliff-toe platform junction around high-tide mark (Trenhaile, 2000) and a steeper gradient (Trenhaile, 1974; 1978; 1987), swash run-up at infragravity frequencies have potential to conduct geomorphic work on sloping platforms.

The study also described the water level gradient on the platform surface during the experiment. During the peak storm period, wave setup of up to 0.2 m was observed on the platform. Significantly, this is the first time that wave setup on shore platforms have been described. As wave height on the platform surface is depth-limited, an increase in water depth on the platform caused by wave setup effectively
increases the amount of wave energy that can propagate onto the platform. Furthermore, the presence of wave setup on the platform indicates that there may be setup generated circulation (current) present on the platform. Such processes may be important for sediment transport and debris removal at the cliff toe; however, no study has investigated the generation and the role of setup induced currents on shore platforms to date.

Results have several important implications for shore platform morphodynamics. Recent studies suggested that wave behaviour on shore platforms are controlled by morphological feedback on incident and secondary hydrodynamic processes (Stephenson and Thornton, 2005; Beetham and Kench, 2011; Marshall and Stephenson, 2011). Marshall and Stephenson (2011) suggested that hydrodynamic processes on shore platforms are a function of two hydrodynamic factors (waves and tide) and three morphological factors (presence of seaward edge, elevation of the platform and platform gradient). In this study, we have identified several quantitative relationships amongst those variables including water depth (hence the tide and the platform elevation) at the seaward edge and incident wave conditions. Furthermore, results indicate that platform gradient may be an important control on wave-height limit. As slope changes locally on many shore platforms, morphological feedback on wave processes should change accordingly across a shore platform. If the wave breaking limit on shore platforms is a function of the local slope, steeper platform gradients do not necessarily result in a greater amount of wave-energy dissipation, as suggested by Marshall and Stephenson (2011). Morphological controls on infragravity waves have been discussed by Beetham and Kench (2011). The importance of incident conditions and relative edge submergence on
infragravity wave transformation found in this study suggests that the importance of shoaling distance and the reef wave energy index (cliff-toe depth divided by platform width) proposed by Beetham and Kench (2011) requires further examination. While platform width and gradient are no doubt important in transforming infragravity-wave energy, it is not possible to determine the role of the surface morphology without adequately comparing the wave conditions under which measurements were taken, because the across-shore increase in infragravity-wave height appears to be significantly influenced by incident conditions and relative edge submergence.

Knowledge of the physical processes operating on shore platforms is critical for understanding the evolution of rock coasts, modelling the process-landform interactions and predicting the future change. Hydrodynamic processes in particular play important roles in shore platform morphodynamics. Further studies on platforms with different morphologies and other hydrodynamic studies including the nature of nearshore currents, wave setup and secondary wave motions on shore platforms will improve our understanding of shore platform morphodynamics.
4.3 Case Study 4

Observation of Wave Transformation on a Sloping Type B Shore Platform under Wind-Wave (Storm) and Swell Conditions

4.3.1 Introduction

Intertidal shore platforms represent the interface between incident ocean waves and coastal cliffs and, in some instances, beaches. Shore platforms therefore act as an important buffer protecting associated coastal features from wave-induced erosion. Shore platforms are common in a wide range of coastal settings, from low to high latitudes, on exposed and sheltered shorelines, trailing- and leading-edge coasts, and in micro- to macrotidal environments. Two types are commonly recognised: Type A platforms, which slope into the nearshore without a break in slope, and type B platforms, which have a sharp seaward edge that plunges into the nearshore (Sunamura, 1992). The latter represent a unique hydrodynamic regime due to the near-horizontal surface being truncated by a sharp scarp at the seaward boundary. Although Type B platforms are generally horizontal, sloping varieties also exist.

Waves and related hydrodynamic and hydraulic processes are considered to be an integral part of shore platform morphodynamics and evolution (Carter et al., 1987; Sunamura, 1992). While the importance of other processes such as sub-aerial physicochemical weathering, mass movements and bio-erosion has been widely recognised in the development of shore platforms, it is unlikely that these can evolve without wave-induced erosion (Trenhaile and Porter, 2007; Trenhaile, 2008). Surprisingly, process-orientated studies on rock coasts have long been neglected.
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(Stephenson, 2000) and there are comparatively few field-based studies of wave processes on shore platforms (Stephenson, 2000; Naylor, et al., 2010; Dasgupta, 2011).

Over the past decade, however, such field-based studies have emerged increasingly for several regions worldwide, including Australia, New Zealand and Canada. Collectively, these have examined wave propagation onto and across platforms (Stephenson and Kirk, 2000a; Stephenson and Thornton, 2005; Trenhaile and Kanyaya, 2007; Farrell et al., 2009; Beetham and Kench, 2011; Marshall and Stephenson, 2011; Ogawa et al., 2011, 2012), and the delivery of wave energy to coastal cliffs (Lim et al., 2011; Young et al., 2011; Dickson and Pentney, 2012). Nevertheless, to date only two studies have compared wave characteristics and energy transmission on shore platforms under different incident-wave conditions. Consequently, there is an overall gap in knowledge about how changes in incident-wave characteristics affect wave transformation across the platform surface and, therefore, energy delivery to the cliff toe. Marshall and Stephenson (2011) recognised the importance of long-period waves on shore platforms and the dependence of energy transmission on incident conditions. Beetham and Kench (2011) reported that infragravity-wave height at the cliff toe of shore platforms in Rothesay Bay and Oraka, New Zealand, was linearly correlated to the incident gravity-wave height, this being the only example known to date of an empirical relationship between nearshore wave conditions and platform wave signatures.

The present study focuses on fieldwork conducted on a Type B platform on the northeast coast of the North Island, New Zealand, and compares wave characteristics and transformation across the platform surface under contrasting hydrodynamic energy conditions: high energy wind-wave conditions, characterised
by locally generated, short-period storm waves, and post-storm swell conditions characterised by low-amplitude, long-period waves. There has been comparatively little work on wave processes on Type B platforms with surface gradients exceeding 1°, with an exception of Stephenson and Kirk (2000a), and thus, such data would make a valuable contribution to the global archive on shore platforms wave studies. The present study aims to (1) assess how changes in nearshore wave climate affect the wave characteristics at this shore platform surface, especially at the cliff toe, and (2) evaluate the results in terms of the scant information currently available on this aspect of shore platforms in general, notably from Marshall and Stephenson (2011) and Beetham and Kench (2011).

4.3.2 Physical setting and study area

The fieldwork experiment was conducted at Red Beach on the northeast coast of Whangaparaoa Peninsula, 25 km north of Auckland, North Island, New Zealand (Fig. 4.13). The east coast of Auckland experiences a semidiurnal, meso-tidal regime with a spring tidal range of approximately 3 m. This is a leeward, low-energy environment (de Lange et al., 2003), with the average significant wave height being less than 0.7 m (de Lange and Moon 2005). Based on offshore wave buoy records, the mean offshore wave height for Auckland is 1.2 m with only 3% and 0.35% of waves exceeding 3 m and 7 m respectively (Gorman et al. 2003). The 50-year sea-level record at Port Auckland shows that the coastline is experiencing an average increase of 1.3 mm/year in annual mean sea level (MSL; Hannah, 2004).

The geology of Whangaparaoa Peninsula is dominated by the highly deformed, alternating sandstone and mudstone of the East Coast Bays Formation (Edbrooke
2001), associated with a significant variation in platform morphology. According to Healy (1968), there are six major types of shore platforms along this coastline, ranging from gently sloping Type A, low tide-level Type B to supra-tidal Type B platforms. At the eastern end of Red Beach where the study transect is located, platform morphology varies from Type A to sloping Type B to horizontal Type B within several hundred meters (Fig. 4.14). The experiment was conducted in the steepest section of the Red Beach platform, along an 81-m-wide transect with a mean gradient and elevation of 1.3° and −0.6 m MSL respectively (Fig. 4.14b).

Figure 4.13: Location of study site: a) New Zealand; b) Red Beach and the Auckland Region, and; c) Photo of the study site.
4.3.3 Material and methods

4.3.3.1 Fieldwork

Five RBR-2050 TWR pressure gauges were deployed directly on the platform surface or offshore along a shore-perpendicular transect (Fig. 4.14, Table 4.2). On the platform, three sensors were deployed at quasi-equal intervals referred to as R1, R2 and R3. Sensor R0 was deployed immediately off the seaward edge, and sensor R00 approximately 33 m offshore. All sensors were programmed to log at 2 Hz for 17.07 minutes every 30 minutes, during a 24-hour deployment on 24–25 November 2008.
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Table 4.2 Summary of field sensor deployment

<table>
<thead>
<tr>
<th>Sensor site</th>
<th>Distance* (m)</th>
<th>Elevation (m)</th>
<th>Sensor type</th>
<th>Sampling (Hz)</th>
<th>Cycle (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R00 (Neashore)</td>
<td>-33</td>
<td>-2.9</td>
<td>RBR-2050</td>
<td>2 Hz</td>
<td>17.07 min</td>
</tr>
<tr>
<td>R0 (Off edge)</td>
<td>-2</td>
<td>-2.5</td>
<td>TWR</td>
<td>2 Hz</td>
<td>very 30 min</td>
</tr>
<tr>
<td>R1 (Seaward edge)</td>
<td>2</td>
<td>-1.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R2 (Centre)</td>
<td>39</td>
<td>-0.63</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>R3 (Cliff toe)</td>
<td>79</td>
<td>0.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Barometric</td>
<td>-</td>
<td>5 m</td>
<td>KPSI 556</td>
<td>0.01 Hz</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

*measured from the seaward edge of the platform

4.3.3.2 Data analysis

Raw pressure time-series data were processed in the frequency domain to assess wave characteristics. Pressure signals attenuate with increasing water depth, and high frequency (short-period) waves are more susceptible to this effect. Therefore, the pressure time-series were converted into the surface motions using a linear transfer function (Tucker and Pitt, 2001). Pressure attenuation correction was applied via a fast Fourier transform, which required a high-frequency cut-off to avoid amplifying noise in the high-frequency regions. A fixed cut-off frequency of 0.4 Hz was used in this study, and the processed pressure data were assessed for the “blow up” effect of pressure over-amplification (Fig. 4.15). The data were also low-pass filtered at this frequency for zero downcrossing analyses.
A spectral analysis was performed using Welch’s modified-periodogram method (Welch, 1967) to characterise wave-energy distributions across different frequency bands and to determine peak frequency/period \( (f_p/T_p) \), using a contiguous record of 2,048 points, with a 256-point averaging window with a 50% overlap (16 degrees of freedom). Infragravity waves are known to be very energetic on shore platforms (Marshall and Stephenson, 2011). Therefore, waves at infragravity frequencies (<0.05 Hz; Masselink and Hughes, 2003) were removed by high-pass filtering, to calculate gravity-wave height and period. Descriptive values of significant gravity-wave height \( (H_{m0}) \) were calculated from the spectral moments. Significant gravity-wave periods \( (T_s) \) corresponding to the average period of the highest 33% of the waves in a given record were determined by a zero-down crossing analysis using low-passed. Similarly, significant wave heights \( (H_{mol}) \) and periods \( (T_{sl}) \) were calculated for infragravity waves by low-pass data filtering.
For descriptive purposes, gravity-wave frequencies are subdivided into long-period swell-wave frequencies (0.05 to 0.125 Hz, 8 to 20 s) and locally generated, short-period wind-wave frequencies (>0.125 Hz, <8 s), following Brander et al., (2004).

4.3.4 Results

4.3.4.1 Incident condition

During the first tidal cycle on the so-called wind-wave day, the nearshore peak wave period ($T_p$) was about 4–5 s (Fig. 4.16a). The nearshore significant wave height ($H_{m0}$) ranged from 0.7 to 1.2 m, and peaked 1 h before high tide on the wind-wave day. During the second tidal cycle on the so-called swell day, there was a dominance of long-period swell waves ($T_p=8–10$ s). As the storm waned, $H_{m0}$ gradually decreased to 0.45 m towards the end of the field study.

Nearshore wave spectra show the dominance of broadband, high-frequency waves on the wind-wave day (predominantly at 0.19–0.23 Hz; Fig. 4.16b). By contrast, peak frequency was consistently lower at 0.1–0.11 Hz on the swell day. The power spectral density at peak frequency ($PSD_{h,peak}$) was 0.6 – 1.1 m$^2$/Hz on the wind-wave day and approximately 0.4 m$^2$/Hz on the swell day (Fig.4.16b).
Figure 4.16: Incident conditions at Red Beach (Instrument R00): a) nearshore water depth, significant wave height and peak period, and; b) time-stacked plot of spectral energy density. HT = high tide; LT = low tide; h = water depth.

4.3.4.2 Across-shore wave characteristics

The Red Beach time-series data show that, on the wind-wave day, short-period waves dominated at the seaward edge of the platform (R1), with a peak period ($T_p$) and significant gravity-wave period ($T_s$) of 4.8 s, and wave height ($H_{m0}$) of 0.86 m (Fig. 4.17a). Both $T_p$ and $T_s$ increased landwards, whereas $H_{m0}$ decreased. At the cliff toe (R3), the wave field was dominated by low-frequency motions, with a $T_p$ of 32.0 s (Fig. 4.17e). $T_s$ increased to 10.5 s and $H_{m0}$ was 0.24 m. On average, $H_{m0}$ was attenuated by 75% between the seaward edge (R1) and the cliff toe (R3) on the wind-wave day.
On the swell day, the wave field at R1 was characterised by long-period, low-amplitude swell waves, with a $T_p$ of 9.9 s, $T_s$ of 7.1 s and $H_{m0}$ of 0.53 m. The presence of wave groups was also evident at R1 (Fig. 4.17b). Similarly low $T_p$ and $T_s$ values were observed at the centre of the platform (R2; Fig. 4.17d), but both $T_p$ and $T_s$ increased strongly at the cliff toe (Fig. 4.17f). The values of $H_{m0}$ were similar at R1 and R2 (0.53 and 0.50 m respectively), but considerably lower at R3 (0.21 m). On average, $H_{m0}$ was attenuated by 66% between the seaward edge (R1) and the cliff toe (R3) on the wind-wave day (approximately 11% reduction between R1 and R2). Of note, wave periods at the cliff toe were similar on the wind-wave day and swell day, despite the variations in wave conditions in the nearshore and at the seaward edge of the platform.

![Figure 4.17](image.png)  
**Figure 4.17** High tide water level records across the platform from the seaward edge (a,b), the centre (c,d) and the cliff toe (e,f) sensor sites.
4.3.4.3 **Gravity wave significant wave height and period**

Despite the differences in nearshore wave conditions between the wind-wave and the swell days, wave-height characteristics at R2 and R3 were markedly similar. The significant wave heights \((H_{m0})\) were locally depth-dependant at the R2 and R3 sensor sites on the platform surface (cf. strong linear relationships between wave height and water depth with \(R^2>0.9\) in Fig. 4.18e, g). At R0, however, \(H_{m0}\) was depth-limited up to water depths of 2.5 m and 1.6 m on the wind-wave day and swell day respectively (Fig. 4.18a, c). The wave height limit at R0 was approximately 40% of the local water depth. A similar pattern was observed at R1 (Fig. 4.18c); however, the slope of the limiting wave-height to water-depth ratio was offset by 0.3 m due to the difference in platform elevation across the seaward edge (between R0 and R1).

Strikingly similar values of significant gravity-wave period (\(T_s\)) were observed at the cliff toe (R3) on the wind-wave day and the swell day, despite the differences in \(T_s\) recorded at the seaward edge (R0; Fig. 4.18b, h). Generally, longer wave periods were observed on the swell day (about 8–9 s) near the seaward edge (R1; Fig. 4.18d). On the wind-wave day, \(T_s\) was tidally modulated, albeit weakly, at R0 and R1. At the central platform site (R2; Fig. 4.18f), \(T_s\) was strongly controlled by the tide on the wind-wave day, ranging from >10 s at low tide to 5 s at high tide. On the swell day, slightly higher \(T_s\) values (~9 s) were observed at low tide at this site. At high tide, \(T_s\) varied between 7 and 8 s. At the cliff toe (R3), \(T_s\) values remained stable between 11 and 13 s (Fig. 4.18h) throughout the deployment.
Figure 4.18: Summary plots of significant wave height (a, c, e and g) and wave period (b, d, f and h) versus water depths from the off-edge (R0) sensor site to the cliff toe (R3) collected during the study.
4.3.4.4 Infragravity wave significant wave height and period

Infragravity-wave heights ($H_{m0L}$) were generally between 0.10 and 0.15 m at the R1 and R2 sites on the platform (Fig. 4.19a). Slightly higher $H_{m0L}$ values were observed towards low tide at R0 and R1. In general, $H_{m0L}$ was highest at the cliff toe (R3), reaching 0.27 and 0.28 m at high tide on the wind-wave day and swell day respectively. Of note, cliff-toe $H_{m0L}$ values did not differ markedly between the wind-wave day and the swell day. Across-shore increase in infragravity-wave height was tidally modulated and the largest increases in $H_{m0L}$ having been recorded during high tide on both the wind-wave day (114±11% standard error) and the swell day (134±17%).

Infragravity-wave periods ($T_{sl}$) were longer on the swell day than the wind-wave day (Fig. 4.19b). In general, $T_{sl}$ remained relatively stable between 30 and 40 s at R0 and R1 on the wind-wave day. A markedly stronger variation was observed on the swell day, the values ranging from 30 to 65 s. At R2, $T_{sl}$ increased substantially towards low tide, reaching 65 s.

Figure 4.19: Summary plots of significant infragravity wave height (a) and period (b) versus water depths from the off-edge sensor site to the cliff toe collected over the entire experiment
4.3.4.5 Wave-energy transmission and cliff-toe wave-energy characteristics

To assess the transmission and the relative magnitude of wave energy at a given wave frequency, the power spectral density (PSD) recorded at each sensor site on the platform (R1–R3) was normalised by the PSD at the corresponding peak frequency (PSD\textsubscript{i-peak}) recorded at R0 (Fig. 4.20). Four things are apparent in Figure 4.20. First, a substantial amount of wave energy at the peak frequency was attenuated between R1 and R2 (Fig 4.20a, b). Of note, a markedly larger amount of wave energy was attenuated on the wind-wave day. Second, there is a clear shift in wave-energy distribution across the platform. At R0 (Fig. 4.20a) incident wave energy dominated the wave spectra but at the cliff toe (Fig. 4.20d) a large amount of wave energy was transferred to the infragravity band (<0.05 Hz). Third, short-period wind waves were more severely attenuated on the platform. On both days, little energy at wind-wave frequencies was transmitted to the cliff toe (Fig. 4.20d). Fourth, the transmission of wave energy was tidally modulated, with a greater amount of energy transmission at high tide.

Cliff-toe wave-energy spectra were characterised by energy at infragravity frequencies (Fig. 4.21). In general, the PSD at the peak infragravity frequency was similar on the wind-wave day and the swell day, albeit with slightly lower peak frequencies for the latter. Smaller secondary “sub-harmonic” peaks were observed between 0.04 and 0.06 Hz on the wind-wave day, making cliff-toe wave spectra more broadband. Only a small amount of wave energy was present in the swell frequency band, with little energy at frequencies exceeding 0.12 Hz (Fig. 4.21).
Nevertheless, wave-energy characteristics at the cliff toe were very similar on the wind-wave day and swell day.

Figure 4.20: Normalised power spectral density (PSD) at: a) directly off the seaward edge (R0); b) seaward edge (R1); c) central platform (R2), and; d) cliff toe (R3). Wave spectra at all locations were normalised by the peak spectral density (PSD\textsubscript{peak}) recorded off the seaward edge (R0) in order to illustrate the transmission of wave energy across the platform surface. The blue line in the top panel (a) shows the peak frequency recorded at R0.

Figure 4.21: Cliff-toe wave spectra on the wind-wave day and the swell day. Dashed lines indicate wave type boundaries according to Brander \textit{et al.} (2004). IGW = infragravity waves, SW = swell waves, Wind = wind waves
4.3.5 Discussion

Results show several important characteristics of wave transformation across the shore platform surface and demonstrate that there was a significant modification of wave-energy characteristics from the nearshore to the cliff toe. Nearshore wave conditions differed significantly on the wind-wave day and the swell day. On the wind-wave day, incident waves were characterised by large, short-period waves with wave energy broadly distributed across the incident wind-wave band (0.125-0.33 Hz), while on the swell day, waves were characterised by long-period and small-amplitude swell waves (Fig. 4.17a, b). Incident wave energy was significantly attenuated across the seaward edge of the platform on the wind-wave day. The strong dependence of gravity-wave height on local water depth directly off and at the seaward edge (Fig. 4.18a, c) observed on the wind-wave day indicates that waves were energy saturated (Masselink 1993; Thornton and Guza 1982) before reaching the seaward edge of the platform. A further attenuation of wave energy at the incident wind-wave frequencies occurred between the seaward edge (R1) and the central platform surface (R2), as waves were dissipated due to the sudden change in water depth at the seaward edge (Fig. 4.20). In contrast, wave-energy attenuation at the peak incident frequency on the swell day was relatively small across the seaward edge at mid to high tide, as waves were not energy saturated. As illustrated in Fig. 4.18 (a, c), wave height was not linearly dependent on local water depths on the swell day, indicating a lack of wave breaking at the seaward edge. The observed difference in wave energy and height transmission at the seaward edge on the wind-wave day and the swell day suggests the presence of a water depth threshold at the seaward edge that controls wave-energy propagation onto the
platform surface. Importantly results verify Marshall and Stephenson (2011)’s observation and confirm that water depth at the seaward edge as an important control on wave-energy transmission onto the platform. In fact, on coral reef platforms, which are morphologically analogous to Type B shore platforms, reef edge water depth has been recognised as a critical control on the wave climate on reef flats (Brander et al. 2004; Kench 1998). The wave-height record at R0 and R1 indicates that the threshold wave-height to water depth-ratio is $\gamma = 0.4$ (Fig. 4.18a, c). The value is consistent with the wave breaking criterion on barred and dissipative beaches (Certain et al. 2005; Wright et al. 1982) and on coral reef platforms (Hardy and Young 1996; Hardy et al. 1990). The value is also in accordance with the threshold value reported for wave transmission across the seaward edge of coral reef platforms (Gourlay 1994) but is lower than the value reported for inner shore platform surfaces by Farrell et al. (2009).

Although nearshore peak frequency on the wind-wave day was around 0.2 Hz, this energy was removed on the outer platform surface (Fig. 4.20). Consequently wave-energy characteristics at the cliff toe on both days were represented by long-period infragravity waves ($<0.05$ Hz, $>20$ s) and swell waves ($0.05 - 0.125$ Hz). High frequency waves are known to be more susceptible to energy attenuation. Previously, Marshall and Stephenson (2011) identified swell waves and infragravity waves to be more persistent on platforms at Kaikoura, New Zealand and Otway Coasts, Victoria, Australia. Ogawa et al. (2012) reported a progressive attenuation of wind-wave energy on a shore platform at Oraka, New Zealand. Results presented in this study confirm that short-period (high frequency) waves were preferentially attenuated across the platform surface (Fig. 4.20).
Given the dominance of long-period swell waves and infragravity waves on shore platforms, Marshall and Stephenson (2011) concluded that swell waves are more important than short-period wind waves on the inner platform surfaces. Indeed, long-period swell waves are known to generate greater dynamic pressure than short-period swell waves upon breaking (Noormets et al. 2004). While the results confirm that short-period wind waves were more susceptible to attenuation, the differences in nearshore wave conditions were not reflected in the wave characteristics observed on the shore platform surface. It is likely that preferential attenuation of short-period waves resulted in the similarity in wave characteristics at the inner platform locations.

Wave-energy saturation and the dependence of wave height on the platform surface observed in this study have important implications for wave-energy gradients on shore platforms. Previously, Marshall and Stephenson (2011) reported platform gradient as the most important control on wave-energy dissipation and that wave attenuation was more severe on sloping platforms. In contrast, Trenhaile and Kanyaya (2007) suggested, based on field measurements, that wave attenuation was more severe on a sub-horizontal shore platform in a mesotidal environment than on a sloping platform in a macrotidal environment. In another study, Stephenson and Thornton (2005) argued that platform types (i.e. Type A or B) determined the magnitude of wave-energy attenuation. The water depth on the Red Beach platform decreases progressively towards the cliff toe due to the relatively steep platform gradient (1.3°). As wave height on the platform surface is depth-limited (Fig. 4.18), the water depth gradient on the platform directly controls the amount of gravity-wave attenuation. Indeed, the effect of bottom slope on incident and local energy
fluxes is well explained in a model proposed by Dally et al. (1985). Wave breaking criterion in depth-limited conditions is known to be significantly affected by bottom slope (Sallenger and Holman 1985; Masselink 1993; Nelson 1987; Raubenheimer et al. 1996; Sénéchal et al. 2001). Furthermore, the wave breaking criterion in the surf zone is known to decrease due to bottom friction, turbulence and the temporal fluctuation in water depths associated with the presence of infragravity wave (Nelson and Gonsalves 1992; Dally 1990; Dally et al. 1985; Brander et al. 2004). As such, a systemic study on breaking criterion on shore platforms with different surface gradients and wave conditions is required to precisely estimate gravity-wave-energy gradients on sloping shore platforms.

Infragravity-wave energy increased substantially towards the cliff toe on both wind-wave and swell days. As gravity waves were progressively attenuated on the platform surface, the ratio of infragravity to gravity-wave energy density increased towards the cliff toe. The shoreward increase of infragravity-wave energy and the relative dominance of infragravity waves at the cliff toe have been reported by Ogawa et al (2011), Beetham and Kench (2011) and Marshall and Stephenson (2011) on shore platforms. The observed cliff-toe infragravity-wave height (~ 0.28 m) and the across-shore increase in infragravity-wave height at Red Beach (> 110%) is significantly greater than the values reported by Beetham and Kench (2011). Beetham and Kench (2011) reported that platform gradient, width and water depth are important controls on infragravity wave shoaling on shore platforms. It is possible that the steeper platform gradient at Red Beach in comparison to the platforms at Oraka and Rothesay Bay (both 0.3°), where Beetham and Kench (2011) conducted their experiments, is responsible for the greater increase in infragravity-
wave height. It should be noted, however, that the platform width at Red Beach is significantly narrower than the platforms studied by Beetham and Kench (2011). While it is not possible to isolate the importance of platform width on infragravity wave characteristics without controlling for other morphological factors, the results indicate that the importance of “shoaling distance” reported by Beetham and Kench (2011) needs be further investigated.

In contrast to Beetham and Kench (2011) who reported a positive linear correlation between incident wave height and cliff-toe infragravity-wave height, there was little difference in the significant infragravity-wave height and peak infragravity-energy density on the wind-wave day and the swell day at Red Beach (Fig. 4.19; 4.21). A number of studies have suggested that infragravity-wave energy increases with increasing offshore wave height (e.g. Guza and Thornton 1982; Holman 1981). However, it has also been reported that the dependence of infragravity-wave energy is greater on long-period swell energy than short-period wind-wave energy (Ruessink 1998). Furthermore, Ruessink (1998) reported that the across-shore amplification in infragravity-wave energy was dramatically reduced under high energy breaking conditions. In fact, the percentage increase in infragravity-wave height was greater on the swell day at Red Beach, albeit only slightly. In another study Certain et al. (2005) reported a delay in changes of infragravity-wave energy level in response to the changes in offshore incident wave-energy conditions on a barred beach. It is possible that one (or more) of those mechanisms is responsible for the discrepancy between the results reported in the present study and those reported by Beetham and Kench (2011).
4.3.6 Conclusion

This study reported the first direct comparison of wave transformation on a Type B shore platform under two contrasting wave conditions. Results confirmed the pattern of gravity-wave-energy dissipation and infragravity-wave amplification on shore platforms previously reported by other researchers including Farrell et al. (2009), Ogawa et al (2011, 2012), Beetham and Kench (2011) and Marshall and Stephenson (2011). However, there are discrepancies between this study and results reported by other studies, including the dependence of infragravity-wave energy on incident conditions. A recent study on microseisms on coastal cliffs by Young et al. (2011) suggests that infragravity waves are a major source of energy for wave induced cliff motions, indicating that waves at infragravity frequencies may be causing a large amount of strain within the cliff material. The potential hydrodynamic and geomorphic importance of infragravity waves on shore platforms has been suggested recently (Beetham and Kench 2011; Ogawa et al. 2011), but the roles of infragravity waves and their relative importance in shore platform morphodynamics and evolution are yet to be investigated.

Wave characteristics at the central platform surface and the cliff toe were found to be similar regardless of incident wave conditions. Given the short duration of the experiment, it is not possible to determine the universality of this result. However, if found to be correct, such results are likely to have important morphodynamic implications on shore platforms located in swell dominated and storm-wave dominated environments. Furthermore, if the cliff-toe wave conditions are controlled by the platform morphology, rather than incident wave conditions, there must be a significant variability in wave-energy delivery to the cliff toe locally within
a platform-cliff system, as surface morphology varies significantly on many shore platforms (as seen at Red Beach). Therefore, it is recommended that future studies on shore platform hydrodynamics consider a longer experiment duration and a research design that allow researchers to investigate along shore variability in wave characteristics on shore platforms.

As field studies on wave hydrodynamics on shore platforms remain limited in number, there is a strong merit in conducting both new and confirmatory studies on shore platforms in various coastal settings and wave conditions. Investigating and understanding hydrodynamic processes is an important step towards the development of a robust shore platform – cliff morphodynamic framework, underpinning numerical models and evaluating the pattern and the rate of coastal cliff erosion, especially in the face of rising sea-levels, global climate change and increasing anthropogenic pressure on rock coasts.
CHAPTER 5
Generalised Observations of Wave Processes on Type B Shore Platforms

5.1 Introduction
Detailed analyses of wave characteristics and transformations on four individual shore platforms were presented in Chapters 3 and 4. These chapters focused on describing temporal and spatial characteristics of waves on Type B shore platforms of different widths and wave exposure. This chapter presents a meta-analysis of the case studies presented in the previous chapters. Wave processes observed on each of the study platforms are compared and generalised observations of wave characteristics are presented. In addition to the four datasets described in the previous chapters, two extra datasets are included so that additional comparisons can be made and the generality of the results verified. Results are used to address the following objectives proposed in Chapter 1:

**Objective (f):** To identify morphological controls on wave transformations by comparing the results obtained from each of the six platforms.

**Objective (g):** To discuss the significance of wave processes in the context of shore platform morphodynamics.

The chapter (Ogawa, in prep) serves as a discussion and synthesis of the project.
5.2 **Generalised Observations of Wave Processes on Sub-Horizontal (Type B) Shore Platforms: A Meta-Analysis of Case Studies from the North Island, New Zealand**

5.2.1 **Introduction**

Shore platforms are erosional features found on rocky coasts around the world and are thought to be an important control on wave-energy transformation and delivery to coastal cliffs (Carter *et al.*, 1987; Stephenson and Thornton, 2005; Trenhaile and Kanyaya, 2007; Marshall and Stephenson, 2011). However, there is a paucity of literature regarding morphological feedbacks on wave processes on shore platforms. A few detailed descriptions of wave characteristics on shore platforms have become available recently (Beetham and Kench, 2011; Marshall and Stephenson, 2011; Ogawa *et al.*, 2011; Ogawa *et al.*, 2012); however, generalised characteristics of wave process signatures on shore platforms are yet to be established.

Recent studies on micro-seismic motions on coastal cliffs demonstrate that platform morphology is indeed a very important control on wave-energy delivery to coastal cliffs (Adams *et al.*, 2005; Lim *et al.*, 2011; Dickson and Pentney, 2012). For example, Young *et al.* (2011) and Adams *et al.* (2005) found wave-induced cliff shaking to be greater at high tide on the cliffs fronted by sloping shore platforms, while Dickson and Pentney (2012) reported significantly stronger seismic signals at low tide on a cliff fronted by a sub-horizontal shore platform with a sharp seaward edge. It is likely that the difference in platform types is responsible for the different patterns observed (Young *et al.*, 2011). In another study, Lim *et al.* (2011) found two topographical focuses of wave-induced micro-seismic activities that were likely to
be associated with platform and cliff morphology. These studies further attest that shore platforms are an important control on how wave energy is delivered to coastal cliffs.

Morphology of shore platforms can be classified according to the relationship between surface gradient and tidal range (Trenhaile, 1974; 1999), and in micro-tidal environments, a presence/absence of the steep seaward edge (Tsujimoto, 1987; Sunamura, 1992). Trenhaile’s model broadly classifies shore platforms into sloping (> 1°, macro – mega tidal environments) and sub-horizontal (<1°, micro – lower meso tidal environments) regardless of the presence/absence of a sharp seaward edge (Fig. 5.1a). Tide and platform elevation combine to control the inundation period of a platform and the temporal and spatial distribution of wave energy across the platform surface. On the other hand, Sunamura (1992) categorised shore platforms into Type A platforms, which slope into the nearshore without a break in slope, and Type B platforms that have a sharp seaward scarp (Fig. 5.1b). According to Sunamura (1992), Type A and Type B morphologies result from the balance between wave force and rock substrate resistance (Fig. 5.1c). In Sunamura’s model destruction of the seaward edge of Type B platforms due to wave erosion results in the sloping morphology that is characteristic of Type A platforms (Sunamura, 1992). Importantly, both models imply that there is a morphodynamic feedback relationship (Wright and Thom, 1977; Short, 2006) among the hydrodynamic forcing (tide and waves), material response (erosion of substrate) and resulting morphology (platform types) that emerges at longer time scales.
Coastal morphodynamics describes an intricate relationship between hydrodynamic forcing and resulting morphology (Wright and Thom, 1977) and provides a conceptual framework within which short-term process studies can be linked to the long term evolution of a coastal system (Cowell and Thom, 1994; Kench and Brander, 2006). It has been widely demonstrated that morphological feedback on hydrodynamic processes is crucial in understanding how coastal systems change in response to changes in external forcing (Wright and Short, 1984; Kench and Brander, 2006; Masselink et al., 2006). However, a comparative lack of field data exists regarding wave processes on shore platforms (Stephenson, 2000; Trenhaile, 2002b; Dasgupta, 2011). Consequently conceptual and numerical models of shore platform morphodynamics have been developed without taking into account the
morphological feedback on wave processes (e.g. Sunamura, 1992; Trenhaile, 2000; Naylor et al., 2012).

It has been assumed that wave energy available to drive cliff retreat diminishes over time as platforms widen (Johnson, 1919; Trenhaile, 1983; Sunamura, 1992; Trenhaile, 2000; Trenhaile, 2003). Based on this assumption, Trenhaile (2000) developed the following expressions to model wave transformation on the platform surface.

\[ S_f = 0.5p_w(H_b/0.78)e^{kW_s} \quad \text{Eq. 5.1} \]

where \( S_f \) is surface force, \( p_w \) is water density, \( H_b \) is breaker height, \( k \) is wave decay constant and \( W_s \) is surf width, which is calculated as:

\[ W_s = \frac{h}{\beta} \quad \text{Eq. 5.2} \]

where \( h \) is water depth and \( \beta \) is slope.

These expressions imply that waves decay exponentially across the length of the surf zone and that the surf zone extends from the breaker zone over the entire length of the platform surface. Furthermore, Eq. 5.1 implies that the dissipation rate is a direct function of the initial wave height and hence independent of platform water depth and morphology. Crucially, the morphological effects on wave processes appear to be reduced to a simple function of platform width in these expressions. Similar expressions were also proposed by Sunamura (1992). While these expressions have been used in a number of numerical models developed by Trenhaile (e.g. 2000; 2001; 2003; 2004; 2008a; 2010a; 2011), they are yet to be underpinned by field measurements.
Several field studies of wave characteristics on shore platforms have become available in the past decade. In particular, Trenhaile and Kanyaya (2007), Marshall and Stephenson (2011) and Beetham and Kench (2011) compared wave transformation on shore platforms with different morphological characteristics. Trenhaile and Kanyaya (2007) compared wave characteristics on a sloping platform on the macro-tidal coast of Bay of Fundy and a sub-horizontal shore platform on the micro-tidal coast of Gaspe, Canada. They reported that more wave energy reached the inner platform surface on the sloping platform, as greater platform gradient (hence deeper water) allowed waves to propagate without dissipating, while on the sub-horizontal platform waves were forced to break at the seaward edge and dissipate their energy shoreward. Marshall and Stephenson (2011) compared wave processes on two Type A platforms and two Type B platforms on the micro-tidal coasts of New Zealand and Australia. They identified platform water depth and gradient as two important controls on wave-energy dissipation. Marshall and Stephenson (2011) suggested that platform width is the least important control on wave-energy dissipation (Marshall and Stephenson, 2011: 30) indicating a possibility that the generally accepted theoretical assumption that wave-energy delivery to the cliff toe is negatively correlated with platform width may be inaccurate. Beetham and Kench (2011) described the shoaling characteristics of infragravity waves on two Type B shore platforms on the east coast of the North Island, New Zealand, and reported that shore platform width, cliff-toe water depth and cliff-toe slope are key controls on infragravity-wave shoaling on shore platforms. Collectively those studies provided several examples of morphological controls on wave processes on shore platforms. Furthermore, detailed descriptions of wave processes on individual Type B shore platforms have become available (Ogawa et al.,
However, the differences in research focus and methodology used in those studies, and the relatively small number of shore platforms investigated mean that the roles of platform gradient, elevation and width in transforming wave energy have yet to become established. A systematic analysis of wave data on shore platforms with varying morphology under different incident conditions is required to clearly identify the role of platform morphology on wave-energy transformation and verify the results reported by a limited number of studies published previously.

This paper presents a meta-analysis of wave data collected on six Type B shore platforms on the east coast of the North Island, New Zealand. Six platforms presenting narrow (~90 m), intermediate (~150 m) and wide (~270 m) platforms with different gradients and wave exposure were selected for this study. The aims of the present study are to: 1) compare and contrast gravity and infragravity-wave characteristics and wave-energy transmission on the study platforms; 2) to present generalised observations of wave data and identify wave signatures that are characteristic of sub-horizontal ‘Type B’ shore platforms; 3) investigate the roles of shore platform morphology (elevation, width and slope) in transforming wave energy, and; 4) discuss morphodynamic implications of wave processes on shore platforms.

### 5.2.2 Material and methods

This study is based on six hydrodynamic experiments conducted on shore platforms at Red Beach (site 1) and Rothesay Bay (site 2) on the northeast coast of Auckland, and Tatapouri (site 3), Oraka (two profiles – sites 4 and 5), and Pouawa Beach (site 6) on the coastline of Gisborne region, the North Island, New Zealand (Fig. 5.2 and 5.3).
Individual case studies presented in this study have previously been reported, except for Pouawa Beach. Raw data for the Rothesay Bay and the Oraka platforms are described by Beetham and Kench (2011) and Ogawa et al. (2012) and for Tatapouri by Ogawa et al. (2011). Raw data for Red Beach will be described elsewhere (article submitted for publication). An additional dataset from Pouawa Beach is included in order to complement the datasets. For the purpose of description, the study sites are described using site numbers rather than geographical names in this article (e.g. Site 1 = Red Beach).

Cross-sectional survey profiles of the study transects are presented in Figure 5.3. Morphologically the platforms span a range of gradients (0.2 – 1.3°) and widths (80 – 270 m). In order to sample different boundary wave conditions, the Auckland experiments (site 1 and 2) were conducted under storm conditions, while the Gisborne experiments were conducted under fair-weather swell conditions. Collectively the study sites provide a suite of morphological characteristics and hydrodynamic conditions for a multi-site comparison.

In general, three to five wave gauges were deployed on each platform with quasi-equal intervals. Detailed descriptions of the field methods including deployment and sampling strategies are described in each of the studies and are not repeated here (see Chapter 1).
Figure 5.2: Location of the study platforms. a) New Zealand; b) the Auckland region, and; c) the Gisborne region. Numbers in brackets are site numbers assigned to each of the study sites.
Synchronised high-frequency measurements of sea-surface elevations were recorded using various types of wave gauges including RBR-2050 Tide and Wave Recorders, KPSI Series 550 and 551 Water Monitor gauges and the InterOcean S4 bidirectional electromagnetic current meters. All experiments used the same sampling frequency of 2 Hz with a burst length of 17.1 minutes; however, the experiment duration and the sampling interval varied from 24 hours to 36 hours, and 30 minutes to 60 minutes respectively.

Analytical methods used varied slightly from the original case studies to ensure consistency. Recorded pressure time-series data were corrected for pressure attenuation effects (Tucker and Pitt, 2001). Tidal trend was removed using a linear
detrending method. Spectral analysis (Welch, 1967) was used to determine peak frequency \( f_p \) and variance associated with energy in the infragravity-wave (IGW) frequency \( 0 - 0.05 \) Hz (\( >20 \) s) and the gravity-wave (GW) frequency \( >0.05 \) Hz (\( <20 \) s). For descriptive purposes, gravity waves were further subdivided into swell \( (0.05 - 0.125 \) Hz, \( 8 - 20 \) s), locally generated wind-wave \( (0.125 - 0.33 \) Hz, \( 3 - 8 \) s) and short-period capillary wave \( (>0.33 \) Hz, \( <3 \) s) bands. The proportion (%) of energy within each frequency band in a given time-series was determined by dividing the variance in that band by the total variance in the time series. All spectra were estimated with 16 degrees of freedom (DOF). Estimates of significant wave height \( (H_{m0}) \) were calculated from the zeroth moment of the variance density spectra (Tucker and Pitt, 2001). Significant infragravity-wave height \( (H_{m0L}) \) and gravity-wave height (simply donated as \( H_{m0} \)) were determined separately for the respective frequency bands. Zero downcrossing was also used to determine the maximum gravity-wave height \( (H_{max}) \). In addition, the spectral bandwidth parameter \( (v) \) and the spectral peakedness parameter \( (Q_p) \) (Prasada Rao, 1988; Tucker and Pitt, 2001) were used to characterise wave-energy transformation across the study platforms. A spectrum with a single and narrow peak takes a smaller value of \( v \), while a broadband spectrum with multiple peaks takes a greater value. The peakedness \( (Q_p) \) parameter quantifies the concentration of energy within the peak frequency band. A larger \( Q_p \) value indicates a high concentration of wave energy at \( f_p \), while a smaller value indicates even distribution of wave energy across different frequency bands (i.e. less distinct peaks).

In the following sections wave-height transformation is represented as percentage reduction or increase in \( H_{m0} \) and \( H_{m0L} \) relative to the values recorded at the most seaward sensor on each experiment transect (most seaward = 100%). Particular
attention is given to high tide (HT) and the initial stage of tidal inundation of the entire platform surface (referred simply as low tide or LT), encompassing a range of hydrodynamic conditions experienced at each platform location. Unless otherwise stated, all wave-height data were averaged for high and low tidal stages using three to four bursts from each tidal stage for the purpose of inter-site comparisons. However, raw data from the representative bursts are presented in Table 5.1 as the information is used to portray wave conditions at each site.

5.2.3 Results
This section focuses on the following aspects of the results: wave-energy transformation, and; gravity and infragravity-wave transformation across the platform surface. Note that an emphasis is given to an inter-site comparison rather than a detailed description of the results from individual case studies. Data from each of the experiments is documented in Tables 5.1 and 5.2. Wave-energy characteristics at high and low tide and across-shore transformation of gravity and infragravity waves at each site are presented in Figures 5.4 and 5.5.
Table 5.1: Wave-energy characteristics across the platform surface on the study platforms.

<table>
<thead>
<tr>
<th>Study Sites (Site No.)</th>
<th>Distance from Seaward Edge (m)</th>
<th>High Tide</th>
<th>Low Tide*</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>( h ) (m)</td>
<td>( f_p ) (Hz)</td>
</tr>
<tr>
<td><strong>Site 1: Red Beach</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off Edge</td>
<td>-2</td>
<td>2.89</td>
<td>0.22</td>
</tr>
<tr>
<td>Edge</td>
<td>2</td>
<td>1.86</td>
<td>0.22</td>
</tr>
<tr>
<td>Centre</td>
<td>39</td>
<td>1.14</td>
<td>0.12</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>79</td>
<td>0.40</td>
<td>0.03</td>
</tr>
<tr>
<td><strong>Site 2: Rothesay Bay</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off Edge</td>
<td>-5</td>
<td>3.41</td>
<td>0.15</td>
</tr>
<tr>
<td>Edge</td>
<td>0</td>
<td>1.96</td>
<td>0.15</td>
</tr>
<tr>
<td>Centre</td>
<td>69</td>
<td>1.92</td>
<td>0.14</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>128</td>
<td>1.35</td>
<td>0.14</td>
</tr>
<tr>
<td><strong>Site 3: Tatapouri</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge</td>
<td>2</td>
<td>1.71</td>
<td>0.09</td>
</tr>
<tr>
<td>Centre 1</td>
<td>103</td>
<td>1.51</td>
<td>0.09</td>
</tr>
<tr>
<td>Centre 2</td>
<td>174</td>
<td>0.85</td>
<td>0.15</td>
</tr>
<tr>
<td>Cliff toe</td>
<td>245</td>
<td>0.81</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Site 4: Oraka 1</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off Edge</td>
<td>-4</td>
<td>2.73</td>
<td>0.11</td>
</tr>
<tr>
<td>Edge</td>
<td>2</td>
<td>1.53</td>
<td>0.11</td>
</tr>
<tr>
<td>Centre 1</td>
<td>50</td>
<td>1.19</td>
<td>0.02</td>
</tr>
<tr>
<td>Centre 2</td>
<td>104</td>
<td>0.77</td>
<td>0.07</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>141</td>
<td>0.57</td>
<td>0.01</td>
</tr>
<tr>
<td><strong>Site 5: Oraka 2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off Edge</td>
<td>-1</td>
<td>4.16</td>
<td>0.07</td>
</tr>
<tr>
<td>Edge</td>
<td>0</td>
<td>1.79</td>
<td>0.11</td>
</tr>
<tr>
<td>Centre 1</td>
<td>121</td>
<td>1.38</td>
<td>0.08</td>
</tr>
<tr>
<td>Centre 2</td>
<td>203</td>
<td>0.90</td>
<td>0.07</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>253</td>
<td>0.50</td>
<td>0.02</td>
</tr>
<tr>
<td><strong>Site 6: Pouawa</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge</td>
<td>0</td>
<td>1.58</td>
<td>0.09</td>
</tr>
<tr>
<td>Centre 1</td>
<td>35</td>
<td>1.02</td>
<td>0.09</td>
</tr>
<tr>
<td>Centre 2</td>
<td>61</td>
<td>1.05</td>
<td>0.07</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>87</td>
<td>0.53</td>
<td>0.09</td>
</tr>
</tbody>
</table>

* Low tide = the lowest tidal level at which the entire platform surface was covered with at least 0.1 m of water. \( h \) = water depth; \( f_p \) = peak frequency; \( Q_p \) = spectral peakedness; \( v \) = spectral width.
Chapter 5: Generalised Observations

Table 5.2: Gravity and infragravity-wave transformation on the study platforms.

<table>
<thead>
<tr>
<th>Study Sites (Site No.)</th>
<th>Distance from Seaward Edge (m)</th>
<th>High Tide</th>
<th>Low Tide</th>
<th>Low Tide</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>h</td>
<td>$H_{sew}$ (SE)</td>
<td>$H_{h}$</td>
<td>$H_{ratio}$</td>
</tr>
<tr>
<td><strong>Site 1: Red Beach</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off Edge</td>
<td>-2</td>
<td>2.84</td>
<td>0.90 (±0.01)</td>
<td>0.10 (±0.00)</td>
</tr>
<tr>
<td>Edge</td>
<td>2</td>
<td>1.80</td>
<td>0.84 (±0.01)</td>
<td>0.11 (±0.00)</td>
</tr>
<tr>
<td>Centre</td>
<td>39</td>
<td>1.08</td>
<td>0.59 (±0.00)</td>
<td>0.12 (±0.00)</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>79</td>
<td>0.34</td>
<td>0.25 (±0.01)</td>
<td>0.25 (±0.01)</td>
</tr>
<tr>
<td><strong>Site 2: Rothesay Bay</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off Edge</td>
<td>-5</td>
<td>3.39</td>
<td>1.39 (±0.16)</td>
<td>0.19 (±0.03)</td>
</tr>
<tr>
<td>Edge</td>
<td>0</td>
<td>1.93</td>
<td>1.16 (±0.12)</td>
<td>0.22 (±0.04)</td>
</tr>
<tr>
<td>Centre</td>
<td>69</td>
<td>1.87</td>
<td>0.81 (±0.02)</td>
<td>0.21 (±0.03)</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>128</td>
<td>1.30</td>
<td>0.73 (±0.03)</td>
<td>0.29 (±0.04)</td>
</tr>
<tr>
<td><strong>Site 3: Tatapouri</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge</td>
<td>2</td>
<td>1.68</td>
<td>0.51 (±0.01)</td>
<td>0.09 (±0.00)</td>
</tr>
<tr>
<td>Centre 1</td>
<td>103</td>
<td>1.48</td>
<td>0.34 (±0.01)</td>
<td>0.10 (±0.00)</td>
</tr>
<tr>
<td>Centre 2</td>
<td>174</td>
<td>0.82</td>
<td>0.31 (±0.01)</td>
<td>0.12 (±0.01)</td>
</tr>
<tr>
<td>Cliff toe</td>
<td>245</td>
<td>0.78</td>
<td>0.27 (±0.01)</td>
<td>0.15 (±0.00)</td>
</tr>
<tr>
<td><strong>Site 4: Oraka 1</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off Edge</td>
<td>-4</td>
<td>2.61</td>
<td>0.52 (±0.03)</td>
<td>0.18 (±0.01)</td>
</tr>
<tr>
<td>Edge</td>
<td>2</td>
<td>1.43</td>
<td>0.53 (±0.03)</td>
<td>0.18 (±0.01)</td>
</tr>
<tr>
<td>Centre 1</td>
<td>50</td>
<td>1.09</td>
<td>0.46 (±0.02)</td>
<td>0.22 (±0.01)</td>
</tr>
<tr>
<td>Centre 2</td>
<td>104</td>
<td>0.67</td>
<td>0.28 (±0.03)</td>
<td>0.23 (±0.00)</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>141</td>
<td>0.47</td>
<td>0.21 (±0.03)</td>
<td>0.26 (±0.01)</td>
</tr>
<tr>
<td><strong>Site 5: Oraka 2</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Off Edge</td>
<td>-1</td>
<td>4.07</td>
<td>0.43 (±0.01)</td>
<td>0.14 (±0.01)</td>
</tr>
<tr>
<td>Edge</td>
<td>0</td>
<td>1.70</td>
<td>0.44 (±0.01)</td>
<td>0.15 (±0.01)</td>
</tr>
<tr>
<td>Centre 1</td>
<td>121</td>
<td>1.29</td>
<td>0.53 (±0.01)</td>
<td>0.18 (±0.01)</td>
</tr>
<tr>
<td>Centre 2</td>
<td>203</td>
<td>0.82</td>
<td>0.37 (±0.01)</td>
<td>0.18 (±0.01)</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>253</td>
<td>0.42</td>
<td>0.25 (±0.01)</td>
<td>0.27 (±0.01)</td>
</tr>
<tr>
<td><strong>Site 6: Pouawa</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Edge</td>
<td>0</td>
<td>1.53</td>
<td>0.56 (±0.01)</td>
<td>0.12 (±0.00)</td>
</tr>
<tr>
<td>Centre 1</td>
<td>35</td>
<td>0.97</td>
<td>0.48 (±0.00)</td>
<td>0.12 (±0.00)</td>
</tr>
<tr>
<td>Centre 2</td>
<td>61</td>
<td>1.00</td>
<td>0.37 (±0.00)</td>
<td>0.13 (±0.00)</td>
</tr>
<tr>
<td>Cliff Toe</td>
<td>87</td>
<td>0.47</td>
<td>0.28 (±0.00)</td>
<td>0.14 (±0.00)</td>
</tr>
</tbody>
</table>

* Low tide = the lowest tidal level at which the entire platform surface was covered with at least 0.1 m of water.
### 5.2.3.1 Incident Wave Conditions

Incident wave-energy conditions observed during each of the experiments differed between the Auckland sites (sites 1 and 2) and the Gisborne sites (sites 3–6). High tide wave characteristics recorded off the seaward edge of platforms at sites 1 and 2 show high energy storm conditions with peak frequency \( f_p \) in the wind-wave band at 0.22 and 0.15 Hz (4.6 and 6.7 s) respectively. High tide incident wave-energy density measured off the seaward edge was 55 and 164 m²/Hz at sites 1 and 2 respectively. During the experiments, significant wave height \( (H_{m0}) \) reached 0.90 m (HT=high tide) and 0.71 m (LT=low tide) at site 1 and 1.39 m (HT) and 0.99 m (LT) at site 2 (Table 5.2).

Fair-weather swell conditions were experienced during the Gisborne experiments. Incident \( f_p \) values observed were in the swell band at 0.09 Hz (11 s) at sites 3 and 6, 0.1 to 0.11 Hz (10 to 9.1 s) at sites 4 and 5, although a lower high tide value of 0.07 Hz (14 s) was observed at site 5. Incident wave energy was significantly lower at the Gisborne sites (Table 5.1), with measured high tide incident wave-energy density consistently below 20 m²/Hz, except for site 4 where a higher value of 36.6 m²/Hz was observed. The values of \( H_{m0} \) recorded at the seaward edge of the platforms were generally comparable, with high tide \( H_{m0} \) values ranging between 0.43 m (site 5) and 0.56 m (site 6).
5.2.3.2 Wave-energy transformation

Comparison of the results presented in Tables 5.1 and 5.2 and Figures 5.4 and 5.5 reveal that there are several distinctive patterns in wave-energy transformation across the platform surface. First, wave energy at the seaward edge is dominated by incident swell waves or wind waves. For example, at site 2, 64% (LT) and 78% (HT) of wave energy was contained in the wind-wave band (Fig. 5.4d, e) reflecting storm conditions. In contrast, approximately 60% of wave energy at the seaward edge of the platform at site 4 was in the swell band, reflecting fair-weather swell conditions. Second, infragravity-wave energy was more evident at the cliff toe at most sites, with the exception of sites 2 and 6 at high tide, where energy in the incident gravity-wave band remained dominant at the cliff toe (Fig. 5.4d, 5.5j). Infragravity-wave energy was significantly more dominant at the cliff toe on all platforms at low tide (Fig. 5.4 and 5.5). In general, 60 to 90 % of wave energy at the cliff toe was contained in the infragravity band at low tide. At site 3, infragravity waves dominated 97 % of the total wave energy present at the cliff toe at low tide.

The observed across-shore changes in dominant wave types are reflected by the changes in $f_p$ (Table 5.1). Furthermore, an assessment of two spectral shape parameters ($Q_p$ and $\nu$) show that there was a consistent pattern on all platforms – the value of $Q_p$ decreased and $\nu$ increased towards the cliff toe (Table 5.1). At the cliff toe, $f_p$ was generally in the infragravity-wave band (<0.05Hz). The observed across-shore changes in $Q_p$ and $\nu$ were associated with the decrease in incident-wave energy and increase in infragravity-wave energy across the platform surface, resulting in broad-band and potentially multi-peaked (high $\nu$ values) and less concentrated (low $Q_p$ values) spectra at the cliff toe (Table 5.1).
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Figure 5.4: Wave characteristics and transformation of gravity and infragravity waves at Site 1 (a–c) and Site 2 (d–f). Wave-energy characteristics at the seaward edge and cliff toe at high tide (a,d) and low tide (b,c) at the respective study site, and transformation of significant wave height off the seaward edge to the cliff toe (c, and f). HT = high tide; LT = low tide. IGW = infragravity waves; Swell = swell waves; Wind = locally generated wind waves and; Cap = short-period capillary waves. Error bars indicate standard error of the average values calculated from the wave height and energy values recorded at the respective tidal stages. On (c) and (f) zero on x-axis marks the seaward edge of the platform. In (c) and (f), wave height transformation is described as percentage change in $H_{m0(L)}$ in comparison to the wave height values recorded at the seaward edge (i.e. most seaward = 100%).
Figure 5.5: Wave characteristics and transformation of gravity and infragravity waves at Site 3 (a-c), Site 4 (d-f), Site 5 (h-i) and Site 6 (j-l). Note that no sensor was deployed off the seaward edge of the platforms at Site 2 and Site 6.
5.2.3.3 Gravity-wave height transformation

In general gravity-waves \((H_{m0})\) were significantly attenuated on all platforms before reaching the cliff toe regardless of tidal stage (Table 5.2; Fig. 5.4c, f and 5.5c, f, i, l). Gravity-wave attenuation was more severe at low tide than high tide at all locations (Fig. 5.4c, f and 5.5c, f, i, l). Attenuation of \(H_{m0}\) between the seaward edge and cliff toe at high tide ranged from 73\% (site 1) and 42\% (site 5). At low tide, across-shore attenuation of \(H_{m0}\) ranged from 97\% (site 3) to 76\% (sites 1, 4 and 6). Of note, despite being the widest platform studied, site 5 (270 m) experienced the smallest amount of wave attenuation at high tide. Across-shore attenuation of \(H_{m0}\) at site 5 was comparable (79\%) to sites 1, 4 and 6 at low tide (Fig. 5.4c and 5.5f, l).

Attenuation of gravity waves across the seaward to the central platform surface varied significantly among the study sites. The largest amount of attenuation occurred across the seaward edge or on the seaward part of the platform surface at sites 1, 2, 3 and 6. On average, 34 to 40\% of incident \(H_{m0}\) was attenuated across the seaward edge and/or between the seaward edge and the central platform surface at sites 1, 2 and 3 at high tide (Fig. 5.4c, f and 5.5c). Less attenuation was observed at site 6 (15\%). In contrast, gravity-wave height increased by 1\% (HT) to 2\% (LT) and 2\% (HT) to 7\% (LT) across the seaward edge of the platforms at sites 4 and 5 respectively. At site 5, the value of \(H_{m0}\) further increased towards the central platform and reached 124\% of the value recorded off the seaward edge. No attenuation of \(H_{m0}\) was observed on the seaward platform surface at low tide at site 5, with 100\% of incident \(H_{m0}\) transmitted to the central platform surface before being attenuated towards the cliff toe (Fig. 5.5i).
5.2.3.4 Infragravity wave transformation

In general, infragravity-wave height \((H_{m0L})\) increased towards the cliff toe and the highest \(H_{m0L}\) values were observed at the cliff toe (Table 5.2; Fig. 5.4, 5.5). Of note, differences in \(H_{m0L}\) recorded at low tide and high tide were relatively small in comparison to the differences observed in \(H_{m0}\) values (Table 5.2). Cliff toe \(H_{m0L}\) values ranged from 0.15 m (site 3) and 0.25 m (site 2) at high tide, and 0.06 (site 3) and 0.23 m (site 4) at low tide.

Although there was a general landward increase in \(H_{m0L}\), the amount of increase in \(H_{m0L}\) differed between the platforms (Fig. 5.4c, f; Fig. 5.5c, f, 1, l). The largest across-shore increase in \(H_{m0L}\) was observed at site 1 at low and high tide (205% and 243% respectively, Fig. 5.4c). At sites 1, 2 3 and 5, a greater amount of increase in \(H_{m0L}\) was observed at high tide, while at sites 4 and 6 a greater increase in \(H_{m0L}\) was observed at low tide. At site 4 the pattern of infragravity-wave transformation was more complex. While \(H_{m0L}\) increased from the seaward edge to the cliff toe by 171% at high tide at site 4, at low tide transformation of \(H_{m0L}\) was complex, with a slight decrease (17%) in \(H_{m0L}\) towards the central platform, followed by a 39% increase and a 47% decrease towards the cliff toe (Fig. 5.5c).

5.2.4 Discussion

Results show there is significant transformation in wave characteristics on all platforms. Several patterns are evident: (1) Wave processes were sensitive to the tidally modulated water-depth change. Although the pattern of wave transformation differed on each platform, gravity waves were attenuated towards the cliff toe on all
platforms and the dissipation rate increased toward low tide. (2) The platform edge is an important control on wave propagation onto the platform surface. Under high energy conditions or towards low tide waves were significantly attenuated as they propagated onto the platform surface (e.g. sites 1 and 2; Fig. 5.4 and 5.5). However, under low energy conditions with relatively deep water depth at the edge, gravity-wave height increased by 1 to 2% as waves propagated onto the platform (sites 4 and 5; Fig. 5.5). (3) Infragravity-wave height increased towards the cliff toe. At site 1 the height of infragravity waves at the cliff toe reached 243% of the height observed off the seaward edge. (4) There was a significant shift in dominant wave types across the platform surface. In general, energy at the incident gravity wave frequencies was the most strongly attenuated. Results also indicate that waves at wind-wave frequencies are more susceptible to attenuation than swell waves. Consequently, wave spectra at the cliff toe were characteristically broadband with peak frequency typically in the infragravity-wave band and residual gravity-wave energy distributed across the swell and wind-wave bands.

While there are broad similarities in wave transformation on the platform surface among the study sites, it is evident that the types and the behaviour of waves vary on shore platforms with differing surface morphologies (i.e. width, depth and gradient). In the following section the role of platform geometry in transforming wave energy is discussed, with particular emphasis given to the transformation of gravity waves.

5.2.4.1 Wave-height transformations and energy attenuation

It has been widely assumed that wave-energy dissipation across a platform is a direct function of platform width (Johnson, 1919; Stephenson and Thornton, 2005)
and that a significant increase in platform width results in a process regime shift at the cliff toe from wave dominated conditions to sub-aerial weathering dominated conditions (Stephenson and Kirk, 2000b; Stephenson and Kirk, 2000a; Trenhaile, 2000; Dickson, 2006). Results show that the magnitude of wave attenuation differs significantly on the study platforms and the width of the platforms does not appear to be an important control on wave attenuation when dissipation rates are directly compared (Fig. 5.6). Total wave-height attenuation between the seaward edge and cliff toe at high tide ranged from 48% (site 5) and 71% (site 1). Despite being the widest platform studied, the profile on site 5 experienced the smallest amount of wave attenuation (48%, Fig. 5.6). This is due to the lack of wave breaking at the seaward edge and shoaling of gravity waves across the seaward part of the platform, caused by low wave height (0.44 m) and comparatively high water depth (1.7 m) at the seaward edge \((H_m/h = 0.26)\). In contrast, the two platforms on which the greatest wave attenuation occurred (i.e. sites 1 and 2 – 61%) experienced storm wave conditions with significantly larger waves recorded off the seaward edge (> 1 m). Total gravity-wave attenuation was generally greater at low tide and ranged from 80% (site 5) and 97% (site 3) (Fig. 5.6). The observed increase in total gravity-wave height attenuation was due to the smaller relative water depth \((h/H_m)\) at low tide at the seaward edge, which resulted in greater breaking intensity (Ogawa et al. submitted). Furthermore, tidal modulation on wave height and energy attenuation across the platform surface has previously been reported (Marshall and Stephenson, 2011; Ogawa et al., 2011). Results confirm that water depths on shore platforms play an important role in wave-energy attenuation across the platform surface and that shore platforms effectively attenuate gravity waves at low tide.
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Figure 5.6: Gravity-wave height dissipation across the study platforms, from the seaward edge to the cliff toe. Note: the values are calculated from wave height recorded at the seaward edge (i.e. seaward edge = 0% reduction).

Results also demonstrate that the total amount of gravity-wave attenuation across the entire width of a platform is not a useful indicator of wave-energy delivery to the cliff toe and potential for geomorphic work as previously asserted (Stephenson and Kirk, 2000a; Marshall and Stephenson, 2011; Ogawa et al., 2012). Total gravity-wave-energy attenuation has also been considered an important geomorphic indicator on coral reef platforms and submerged breakwaters (e.g. Kench and
Brander, 2006; Cappietti, 2011). However, the patterns of wave-energy attenuation differ considerably depending on hydrodynamic conditions (i.e. incident wave conditions and tide) and morphological configurations. For example, high tide wave attenuation rates at site 2 and 5 were 54% and 58% respectively. However, cliff-toe wave height recorded at site 2 was considerably greater (0.73 m) than the cliff-toe wave height at site 5 (0.25 m), indicating that a much greater amount of wave energy was available for geomorphic work at the cliff of the platform at site 2, despite the similar attenuation rate observed at these two sites. A smaller percentage wave-height attenuation across shore platforms does not necessarily mean that more wave energy is available at the cliff toe for geomorphic work.

The importance of platform morphology in attenuating wave energy is best demonstrated by comparing the dissipation rates across the inner platform surface rather than using the total amount of wave attenuation across the entire width of the platforms. This is because the attenuation rate on the seaward section of a shore platform is largely controlled by incident wave conditions and the presence/absence of wave breaking at the edge. In contrast, inner platform wave conditions inside the surf zone are more likely to be independent of incident wave conditions (Thornton and Guza, 1982; Marshall and Stephenson, 2011; Ogawa et al., 2011). As demonstrated in Figure 5.6 gravity waves were attenuated on the inner platform surface on all study platforms regardless of tidal stage and incident conditions. However, the pattern of wave attenuation on the inner platform surface appears to be site specific (Fig. 5.6). It is likely that the pattern of wave attenuation on the inner platform surface is controlled by the surface morphology of the platforms.
5.2.4.2 **Morphological controls on wave height attenuation**

Two factors control wave-height attenuation on the inner platform surface: water depth (hence elevation) and platform gradient. Figure 5.7 illustrates the importance of water depth on gravity-wave-energy attenuation across the inner platform surfaces. The rate of gravity-wave height attenuation (percent per meter) was consistently higher at low tide at all study sites (Fig. 5.7). On average, the attenuation rate was 1.5 times greater at low tide than high tide, with a standard error of 0.21. The observed increase in attenuation rate at low tide is likely due to the increased frictional energy loss at low tide. Previously Jago (2005) demonstrated that the frictional dissipation coefficient on coral reef platforms was tidally modulated and increased at low tide. The same is likely to be true on shore platforms, implying that shore platforms with higher mean elevation for a given tidal range attenuate gravity-wave energy more effectively. It should be noted that the effect of surface friction is strongly dependent on bottom roughness (Nelson, 1996; Lugo-Fernández *et al.*, 1998) as well as the presence/absence of intertidal vegetation (Möller *et al.*, 1999; Möller, 2006), and that further studies are required to accurately quantify the amount of frictional energy loss on shore platforms due to these factors.
Platform gradient also plays an important role in wave-energy attenuation. Previously Gill (1972) suggested that steeper platforms are more effective in dissipating wave energy and Marshall and Stephenson (2011) also identified platform gradient as a first order control on wave attenuation on shore platforms. Figure 5.8 provides further detail on the relationship between gravity-wave attenuation and platform gradient. First, there is a statistically significant relationship ($R^2>0.8$) between inner platform gradients and dissipation rates both at high and low tidal stages. Greater attenuation rates associated with steeper gradients are directly due to more rapid reduction in water depth on steeper platforms. Second, the differences in dissipation rate at high and low tide become greater as platform gradient increases, suggesting that tidal effects become more important as platform gradient increases. Of note, a large standard error value
associated with the low tide data at Red Beach indicates the greater sensitivity of dissipation rates on water depths on the sloping platform. The only exception to the trend is Rothesay Bay, where dissipation rates at both tidal stages are significantly lower compared to the other study sites (Fig. 5.7).

\[ y = 40.669x + 0.0185 \quad R^2 = 0.8183, \ p<0.05 \]

\[ y = 48.511x + 0.0843 \quad R^2 = 0.904, \ p<0.05 \]

**Figure 5.8:** Dependence of gravity-wave attenuation rates on local slope.

This is likely due to the propagation of reformed waves with a limited amount of energy dissipation, partially due to a change in breaking criterion associated with the change in bed gradient towards the cliff toe (Ogawa *et al.*, submitted, see chapter 4 article 1). Nevertheless, these results empirically support Gill’s (1972) suggestion, confirm the results reported by Marshall and Stephenson (2011) and demonstrate that a greater amount of wave energy is expended on the surface of sloping platforms.
The relationships presented in Figures 5.7 and 5.8 also have important implications on the role of platform widths in filtering gravity-wave energy. Increased dissipation rates observed on the study platforms at low tide show that shallower and wider platforms are more effective in dissipating wave energy. An important difference between the results presented in this study and other studies that reported platform width to be relatively unimportant (Marshall and Stephenson, 2011; Ogawa et al., 2011) is how platform widths and dissipation rates are compared. It is the width of the platform surface landwards of the initial breaker zone where gravity wave processes become independent of incident wave conditions that is important for friction induced energy attenuation. Platform width is an important morphological control on gravity-wave dissipation at low tide and on platforms with high elevation relative to the tidal range (hence, less water depth).

5.2.4.3 Importance of platform gradient and water depth on wave-height limits

For modelling and engineering purposes it is important to be able to estimate the maximum wave height attainable on shore platforms. The propagation of highest waves across the platform surface towards the cliff is ultimately limited by the water depth on the platform surface. Previous studies on shore platforms demonstrated that gravity-wave height on shore platforms is depth-limited and wave height is a direct function of local water depths (Farrell et al., 2009; Ogawa et al., 2011). As demonstrated earlier, gravity-wave height attenuation is lower at high tide (Fig. 5.6). The maximum gravity-wave energy delivery to the cliff toe on a shore platform must therefore be achieved at high tide under depth-limited conditions.
Two morphological factors are very important in determining gravity-wave height limit on sub-horizontal platforms: 1) platform surface elevation relative to the tidal range, and; 2) surface gradient, as these two factors directly control water depth and depth gradients on the platform surface.

Wave-height limit in shallow water coastal environments is generally determined by wave-height to water-depth ratio, or the wave breaking criterion \( \gamma = H/h \). Studies on coral reefs and offshore sand banks, which are also characterised by near-horizontal surfaces, show that the maximum wave height to water depth ratio \( \gamma_{\text{max}} \) on a natural horizontal surface is 0.55 to 0.6 (Tucker et al., 1983; Hardy et al., 1990; Hardy and Young, 1996; Kench et al., 2009). Nelson (1985) compared a series of physical experiments and suggested \( \gamma_{\text{max}} \) on a horizontal surface to be 0.55 or lower depending on the incident wave conditions and wave characteristics. He suggested an empirical equation for determining \( \gamma_{\text{max}} \) on a horizontal surface using the non-linearity parameter \( F_c \) of Swart and Loubser (1979), which is a parameter used to determine wave form and characteristics. Nelson proposed the following expression:

\[
\gamma_{\text{max}} = \frac{H_{\text{max}}}{h} = \left[ \frac{F_c}{(22 + 1.82F_c)} \right]
\]

\textbf{Eq. 5.3}

where \( F_c \) is the non-linearity parameter expressed as:

\[
F_c = g^{1.25} H^{0.5} T^{2.5} / h^{2.5}
\]

\textbf{Eq. 5.4}

Equation 5.3 is confirmed to be applicable under regular and irregular wave conditions (Massel, 1996; Massel, 1998). It has been empirically demonstrated that the breaking criterion is affected by the bottom gradient (Nelson, 1987; Kamphuis, 1991a; Goda, 2010). The dependence of the breaking criterion on bottom gradient has been widely reported in sandy beach environments (Sallenger and Holman,
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1985; Masselink, 1993; Raubenheimer et al., 1996; Sénéchal et al., 2001). The slope
dependant breaking criteria reported in the literature generally do not take into
account horizontal surfaces. In order to predict maximum wave-height limit on
horizontal and near-horizontal surfaces, Nelson (1987) proposed an empirical
expression:

\[ \gamma_{\text{max}} = 0.55 + 0.88 \exp(-0.012 \cot \theta) \quad \text{Eq. 5.5} \]

where \( \theta \) is bed slope.

Gourlay (1994) extended this expression by incorporating Nelson’s (1985)
expression for horizontal surfaces (Eq. 5.3) and proposed the following:

\[ \gamma_{\text{max}} = [0.55 + 0.88 \exp(-0.012 \cot \theta)]\left[ F_c / (12 + F_c) \right] \quad \text{Eq. 5.6} \]

As pointed out by Massel (1996), Eq. 5.3 is transcendental for \( H/h \) (i.e. \( H/h \) is
required to determine \( H/h \)) and therefore \( F_c \) should be replaced by an independent
variable \( h/gT^2 \) for practical applications (Massel, 1996: 557). Hence, Eq. 5.6 can be
rewritten as:

\[ \gamma_{\text{max}} = 1.818 [0.55 + 0.88 \exp(-0.012 \cot \theta)]\left[ \frac{1+0.001054h_{\ast}^{-2.5}-1}{0.1654h_{\ast}^{-1.25}} \right]^2 \quad \text{Eq. 5.7} \]

where \( h_{\ast} = h/gT^2 \), \( g \) is gravitational constant (9.81 m/s²) and \( T \) is wave period (s).

Upper and lower limiting values of \( \gamma_{\text{max}} \) calculated for the wave conditions observed
during the experiments using Eq. 5.7 are plotted in Fig. 5.8. Mean high tide
maximum \( \gamma_{\text{max}} \) data collected on the inner platform surface (central platform and
cliff toe) of each platform are also plotted in Figure 5.8. Only high tide data are used
to avoid complications associated with swash, infragravity waves, increased frictional energy loss and very shallow water depth at low tide which are known to affect breaking criterion (Kamphuis, 1991a; Nelson and Gonsalves, 1992; Brander et al., 2004; Sénéchal et al., 2004). A comparison with the observed $\gamma_{\text{max}}$ values demonstrates that, under the given conditions, high tide $\gamma_{\text{max}}$ values on the six platforms are well constrained by the upper boundary values given by Eq. 5.7. The absence of $\gamma_{\text{max}}$ values greater than 0.55 on gradients below 0.004 m/m confirms Nelson's (1987) results, which showed that the hydrodynamic boundary between horizontal and sloping surfaces lies at slope of 0.004 m/m and that $\gamma_{\text{max}}$ starts to increase dramatically beyond this threshold. Results confirm the validity of Equations 5.5 to 5.7 on shore platforms. Therefore, wave height on Type B platforms with surface gradient below 0.004 m/m is unlikely to exceed 55% of platform water depth, as suggested by empirical data collected in a laboratory setting and on coral reefs (Nelson, 1985; Gourlay, 1994), and that this wave-height limit is likely to increase with increasing bottom gradient.
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Figure 5.9: Relationship between local bottom gradient and maximum wave-height to water-depth ratio ($\gamma_{\text{max}}$) on the inner surfaces of the study platforms and a comparison of results with the modified Nelson-Gourlay equation (Eq. 5.7). The upper and the lower limits of $\gamma_{\text{max}}$ were calculated from the wave period and water depth values observed during the experiments using Eq. 5.7. Note that the upper boundary predicted by Eq. 5.7 is not dissimilar to the limit predicted by Eq. 5.5. Raw values are presented in Table 5.3.

Table 5.3: Inner platform local slope and maximum wave-height to water depth-ratio ($\gamma_{\text{max}}$) recorded on the study platforms. NB: the values were averaged over 3 to 4 bursts representing high tide gravity-wave height data at each site.

<table>
<thead>
<tr>
<th>Local slope (m/m)</th>
<th>$\gamma_{\text{max}}$</th>
<th>Sites</th>
<th>Sensor location</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001</td>
<td>0.48</td>
<td>Site 3</td>
<td>Cliff toe</td>
</tr>
<tr>
<td>0.00147</td>
<td>0.53</td>
<td>Site 2</td>
<td>Centre</td>
</tr>
<tr>
<td>0.00264</td>
<td>0.49</td>
<td>Site 6</td>
<td>Centre</td>
</tr>
<tr>
<td>0.00551</td>
<td>0.59</td>
<td>Site 4</td>
<td>Centre</td>
</tr>
<tr>
<td>0.0061</td>
<td>0.62</td>
<td>Site 4</td>
<td>Cliff toe</td>
</tr>
<tr>
<td>0.00783</td>
<td>0.58</td>
<td>Site 4</td>
<td>Centre</td>
</tr>
<tr>
<td>0.00839</td>
<td>0.58</td>
<td>Site 5</td>
<td>Centre</td>
</tr>
<tr>
<td>0.00925</td>
<td>0.68</td>
<td>Site 2</td>
<td>Cliff toe</td>
</tr>
<tr>
<td>0.00986</td>
<td>0.57</td>
<td>Site 3</td>
<td>Centre</td>
</tr>
<tr>
<td>0.01206</td>
<td>0.80</td>
<td>Site 5</td>
<td>Cliff toe</td>
</tr>
<tr>
<td>0.0155</td>
<td>0.72</td>
<td>Site 6</td>
<td>Cliff toe</td>
</tr>
<tr>
<td>0.021414</td>
<td>0.70</td>
<td>Site 1</td>
<td>Centre</td>
</tr>
<tr>
<td>0.022849</td>
<td>1.05</td>
<td>Site 1</td>
<td>Cliff toe</td>
</tr>
<tr>
<td>0.0237</td>
<td>0.66</td>
<td>Site 6</td>
<td>Centre</td>
</tr>
</tbody>
</table>
5.2.4.4 Wave frequency transformation and the importance of platform geometry

Wave energy on the study platforms was contained in different frequency bands across the platform surface. In general, wave energy shifted from incident swell (0.05 – 0.125 Hz) and/or wind-wave (0.125 – 0.33 Hz) frequencies at the seaward edge to infragravity frequencies (< 0.05 Hz) at the cliff toe. However, the detailed nature of this shift differed between platforms.

The differences in the wave energy and frequency characteristics at the cliff toe on the study platforms are controlled by morphological feedbacks: narrower and lower platforms allow greater amount of gravity waves to propagate across the platform surface than higher and wider platforms. As illustrated in Figure 5.10, at high tide the cliff-toe peak frequency at site 2 and site 6 were similar to the incident wind-wave peak frequency. However at sites 1 and 4 peak frequency at the cliff toe was constantly at infragravity frequencies regardless of tidal stage. Of note, those two sets of platforms have comparable platform widths (~90 m and ~140 m) but different cliff-toe water depths. At site 3 and 5, where platform width was greater than 250 m, peak frequency at the cliff toe was constantly in the infragravity frequency range, despite the relatively deep water depths observed at the cliff toe at site 3 (Fig. 5.10). The observed morphological feedbacks on wave-energy characteristics at the cliff toe are similar to the results reported on coral reef platforms by Kench and Brander (2006) and suggest that: a) there is a water depth threshold below which energy at infragravity-wave frequencies becomes dominant and above which energy at gravity-wave frequencies becomes more important, and; b) the threshold values decrease with increasing platform widths.
Figure 5.10: Contrast between peak frequency \( (f_p) \) measured between the seaward edge and cliff toe on the study platforms, showing the importance of cliff-toe water depth and platform width in transforming wave energy. Positions of the sub-plots indicate relative water depth and width of the study platforms. The colour bars indicate water depths at the cliff toe. \( W = \) platform width; \( h_{clt} = \) mean cliff-toe water depth at high tide.

5.2.4.5 Wave-energy window and morphological controls on cliff-toe wave signature

The progressive attenuation of gravity waves across platforms at low tide in comparison to a greater amount of wave-energy transmission at high tide suggests that there is a temporal wave-energy window within which gravity waves can perform geomorphic work at the cliff toe. In contrast, infragravity waves generally increased in height across platforms regardless of tidal stage at most of the study sites. The onshore increase in infragravity-wave height observed on the study platforms are in accordance with previous studies on dissipative sandy beaches (Holman, 1981; Wright et al., 1982; Certain et al., 2005) and indicates that
infragravity waves are less sensitive to the tide induced water-depth change. As a result, infragravity to gravity-wave height ratio increases toward the cliff toe (Table 5.2). Such a trend is further pronounced on wide and high shore platforms due to limited platform water depths and increased frictional dissipation of gravity waves (e.g. site 5 and 6, Table 5.2; Fig. 5.4, 5.5).

The dominance of different wave types observed at different tidal stages on the study platforms has also been described on coral reef platforms (Kench and Brander, 2006). Given the importance of platform width and water depth on coral reef platforms in determining reef flat wave characteristics, Kench and Brander (2006) proposed the reef energy window index ($\psi = \text{reef water depth} / \text{reef width}$). They found that the dominance of different wave types (i.e. infragravity and gravity waves) was a function of $\psi$: wide and shallow reefs represented by a low $\psi$ value are dominated by infragravity waves, while narrow and deep reefs with a high $\psi$ value are dominated by gravity waves (Brander and Kench, 2006). Beetham and Kench (2011) showed that the concept can be applied to shore platforms. They used the width of shore platforms and cliff-toe water depth to calculate the platform wave energy window and found a statistically significant relationship between the shoaling of infragravity waves and the platform wave-energy window (Beetham and Kench 2011: 1885).

The result suggests that the reef (platform) energy window index ($\psi$) can be a useful indicator of cliff-toe wave characteristics. Figure 5.10 illustrates the relationship between $\psi$ and the relative importance of (intra-) gravity waves at the cliff. A power relationship was found between $\psi$ and infragravity-wave height to gravity-wave height ratio with a coefficient of determination ($R^2$) value of 0.76. The highest values
of $\psi (>0.01)$ are observed at site 2 where the cliff-toe water depth at high tide reached 1.3 m and dominated by gravity waves, while the lowest values were observed at site 3 which had a very wide platform (250 m). There is an increased amount of scatter in data between $\psi = 0.005$ and 0.002, which may be due to the difference in platform gradient and incident wave conditions, as bottom gradient is reported to influence infragravity wave shoaling (van Dongeren et al., 2007; Dong et al., 2009) while incident wave height is known to be an important control on inshore infragravity-wave height (Holman, 1981; Guza and Thornton, 1982; Guza and Thornton, 1985; Beetham and Kench, 2011).

Figure 5.11: The relationship between wave-energy window ($\psi = h_{clt}/W$) and infragravity wave (IGW)/gravity wave (IGW) ratio at the cliff toe ($N=131$). Triangles and squares are mean height tide and low tide values for each of the study sites (indicated by numbers).
5.2.4.6 Morphodynamic implications

The importance of platform geometry on wave transformations across the platform surface and cliff-toe wave characteristics demonstrated in this study suggests that existing conceptual and numerical models of shore platform morphodynamics and evolution can be improved by taking into account morphological effects on wave processes and utilising empirical data collected in the field. Current morphodynamic models for shore platform-cliff systems do not incorporate morphological feedbacks on wave processes (e.g. Sunamura, 1992; Naylor et al., 2012). The latest conceptual model proposed by Naylor et al. (2012: Fig. 11), for example, considers incident wave energy as an indicator of wave exposure and there is no feedback loop among wave processes, their morphological effects and resulting morphology. Similarly, numerical models on shore platform evolution, most notably on hard rock coast, use relatively simple wave transformation models (Eq. 5.1 and 5.2) assuming that incident wave conditions and widths of the surf zone on the platform surface control cliff-toe wave-energy delivery regardless of platform elevation and slope (e.g. Trenhaile, 2000; Trenhaile and Lakhan, 2003; Trenhaile, 2008a; Trenhaile, 2008b). In those models, wave-energy delivery to the cliff toe is determined from the boundary wave conditions and dissipation rate is reduced to a simple function of platform width. However, it is demonstrated in this study that platform width alone is not an adequate indicator of wave-energy dissipation (Fig. 5.6). Furthermore, results show that attenuation rate calculated from incident wave height is not an accurate estimate of wave energy available for geomorphic work at the cliff toe, as inner platform wave processes are generally independent of incident wave conditions. Most importantly gravity-wave height on platforms is limited by local water depths and bottom slope (Fig. 5.9).
The dominance of (infra) gravity-wave energy at the cliff toe was found to be a function of the platform-wave energy window ($\psi$) which raises a possibility that Type B platforms may be classified according to the dominant wave types. Results indicate that cliff-toe wave regimes can switch from a gravity-wave dominated condition to an infragravity-wave dominated condition (Fig. 5.10). Infragravity waves become proportionally more important than gravity waves when $\psi$ becomes smaller than 0.0024. This shift in cliff-toe wave regime can occur over a tidal cycle, as $\psi$ depends on water depth. The majority of platforms investigated in this study shifted from the “infragravity” wave regime to the “gravity” wave regime between low and high tide (Fig. 5.10). When time-averaged, $\psi$ can be used to determine the cliff-toe process regime of a platform system over the course of its evolution. For example, site 4 in this study may be classified as an infragravity-wave dominated platform as the platform was constantly in the infragravity-wave domain during the experiment (Fig. 5.10). The merit of a classification method based on cliff-toe wave regime needs to be tested, as morphological importance of infragravity waves in shore platform evolution is yet to be established (Beetham and Kench, 2011; Ogawa et al., 2011). However, once the importance of the role of infragravity waves is established, an ability to differentiate cliff-toe wave regime based on platform morphology may become important for exploring the way shore platforms evolve.

Morphological controls on wave behaviour on sub-horizontal shore platforms reported in this study also have important geomorphic implications under the current and projected rise in sea-level (Hannah, 2004; Meehl, 2007; Vermeer and Rahmstorf, 2009). Numerical models suggest that rocky coasts, including shore platforms, will significantly be affected by sea-level rise (Dickson et al., 2007;
Trenhaile, 2010b; Ashton et al., 2011; Trenhaile, 2011). The results presented in this study confirm the dependence of gravity-wave height on the inner platform water depth. Furthermore, the relative dominance of gravity-wave energy at the cliff toe was found to be a function of wave-energy window ($\psi$). Rising sea-level will increase the water depth on a shore platform, and consequently the $\psi$ values. An increase in $\psi$ will increase the temporal window within which gravity waves can reach the cliff toe. Consequently, a rise in sea-level has potential to compromise the efficiency of shore platforms in attenuating wave energy spatially and temporally. Such an effect will be most significant on wide and high shore platforms where frictional attenuation currently plays an important role in mitigating gravity-wave energy. It is likely that wide and high shore platforms that are currently dominated by infragravity waves will ‘flip’ to a gravity-wave dominated regime and experience an increased level of gravity-wave activity at the cliff toe with a rise in sea-level. As a result, hydraulic and mechanical wave erosion caused by gravity waves at the cliff toe will be enhanced on wide and high shore platforms where wave-induced geomorphic processes have previously been limited to sediment transport and static loading by infragravity waves.

5.2.5 Conclusions

Despite the common consensus that waves are an important geomorphic agent on shore platforms, field studies of wave processes on shore platforms have long been neglected. This paper has compared and contrasted wave characteristics and energy transformation on six sub-horizontal (Type B) shore platforms to explore the generality of the results presented by recent research and to identify (and clarify)
morphological controls on wave processes on the platform surface and energy
delivery to the cliff toe.

Several important morphological controls have been identified in this study. First,
the importance of platform water depth on gravity-wave transformation was
confirmed. Gravity-wave height on the inner platform surface was depth-limited on
all platforms. Results also showed that gravity-wave attenuation was significantly
greater at low tide, likely due to increased frictional dissipation. On average,
attenuation rate was 1.5 times greater at low tide than at high tide. Consequently,
platform elevation relative to the tidal range is identified as an important
morphological control on gravity-wave-energy delivery to the inner platform
surface. Second, platform width was found to be an important geomorphic control
on gravity wave-energy delivery. Platform width is particularly important for
gravity-wave energy transmission at low tide, due to the increased attenuation rate.
Third, platform gradient was found to affect several aspects of wave transformations
including the wave breaking criterion and dissipation rates. It was found that the
breaking criterion on the inner platform surface and gravity-wave dissipation rate
are positively correlated to the increase in platform surface gradient. Finally the
wave energy widow index ($\psi$), which was originally proposed by Kench and Brander
(2006) for coral reef platforms, was found to be an important indicator of cliff-toe
wave regime. The dominance of (infra) gravity-wave energy at the cliff toe was
found to be a function of $\psi$. It was suggested that Type B platforms may be classified
according to the dominant wave types: infragravity-wave dominated ($\psi<0.0024$),
and; gravity-wave dominated ($\psi>0.0024$) platforms.
Current conceptual and numerical models on shore platforms generally assume that incident wave conditions are the most important control on wave-energy delivery to the cliff toe. Results clearly demonstrate that platform morphology is an important control on wave characteristics on shore platforms. Therefore, it is recommended that morphodynamic and numerical models of shore platform evolution are carefully revised in light of quantitative field wave data. Such a revision is essential, as the ability of shore platforms to attenuate wave energy is expected to decrease with rising sea-level.
CHAPTER 6
Concluding Remarks

6.1 Introduction

This thesis presented some of the first detailed and systematic field measurements of wave characteristics and transformation on a range of shore platforms. The experiments were conducted on six sub-horizontal 'Type B' shore platforms on the northeast coast of Auckland and the coastline of the Gisborne region, North Island, New Zealand. Hydrodynamic data were collected using an across-shore array of pressure type wave gauges deployed on each of the six platforms. High frequency sea-surface time-series data were analysed using time and frequency-domain techniques to characterise platform wave signatures, temporal and spatial variations in wave characteristics and transformation.

In order to sample different boundary wave conditions, the experiments in the Gisborne region were conducted under fair-weather swell wave conditions (ch. 3) with little variation in incident wave height, while the Auckland experiments were conducted under storm conditions (ch. 4). The study also sampled shore platforms with a range of platform widths (80 to 270 m) in order to explore the role of platform widths in transforming wave energy. Variations in platform morphology among the study sites, most notably platform width, allowed morphological controls on wave-energy transformation and energy attenuation to be investigated. All results were combined in chapter 5 with two extra datasets collected on the
Gisborne coast under fair-weather conditions to provide additional detail on morphological controls on wave transformations. Results were used to identify morphological controls of wave characteristics on shore platforms.

The section that follows synthesises the major findings, outlines the most pertinent geomorphic and morphodynamic implications, and concludes with recommendations for future research.

6.2 Major Findings

6.2.1 Wave characteristics and transformation

- Wave characteristics on Type B platforms vary spatially with different parts of the platform surface characterised by different hydrodynamic zones. Three distinctive hydrodynamic zones were apparent across a 250-m wide platform at Tatapouri under swell wave conditions (ch 3), including: a) an outer platform breaker zone (zone 1); b) a central platform propagation zone (zone 2), and; c) an inner platform dissipation zone (zone 3). Each of the three zones was characterised by different wave processes and wave types. Zone 1 was dominated by incident swell waves and characterised by rapid energy attenuation due to wave breaking across the seaward edge. Zone 2 was dominated by shorter period wind waves and characterised by little dissipation as reformed wave propagated towards the inner platforms. Zone 3 was dominated by infragravity waves, with further attenuation of gravity waves. The spatial extent of zone 1 is further investigated at Rothesay Bay under storm conditions. Results of the Rothesay Bay experiment (ch. 4)
showed that the extent of zone 1 was likely to be spatially limited to two to three wave lengths from the edge of the platform. Results indicated that waves were reformed after the initial breaking well within this limit. It was suggested that the width of the surf zone extending from the seaward edge was likely to be similar to that on coral reef platforms and an empirical expression developed by Gourlay (1994) may be useful in estimating surf zone width on Type B shore platforms. However, this pattern was not observed at Red Beach where waves continued dissipate across the entire platform surface on the Red Beach platform (ch. 4) due to the platform water depth gradient caused by the relatively steep platform slope (1.3°).

- **Seaward edge of platforms attenuate gravity-wave energy due to forced breaking.** Results from Tatapouri (ch. 3), Rothesay Bay and Red Beach (ch. 4) showed that wave energy at peak frequency was most severely attenuated across the seaward edge due to forced breaking. In chapter 4 it was shown that water depth at the seaward edge needs to be at least 2.5 times greater than significant wave height \( h/H_{m0} = 2.5 \) or \( H_{m0}/h = 0.4 \) in order for waves to propagate onto the platform surface without dissipating. This relative water depth threshold is similar to values obtained from coral reef platforms (Gourlay, 1994) and dissipative sandy beaches (Wright *et al.*, 1982). In contrast, waves shoal and increase in height as they propagate onto the platform surface when relative water depths were high as observed on the long profile at Oraka (site 5 described in ch. 5).
• **Wave transformation across the platform surface is modulated by the tide and there is a temporal window in which different parts of the platform surface are subject to different wave processes.** Across-shore wave spectra presented in chapter 3 showed that gravity-wave energy propagation was largely controlled by the tide. The spatial extent and the location of the three hydrodynamic zones were also found to be tidally modulated. At high tide, the platform surface was dominated by zone 2 (propagation zone) and attenuation of gravity-wave energy was comparably low; however, zone 3 (inner platform dissipation zone) became much wider towards low tide as water level on the platform dropped, and infragravity waves dominated the platform wave spectra. This temporal migration of wave zones has geomorphic significance. For example results from Tatapouri (ch. 3) identified the presence of temporal wave-energy window in which wave can perform geomorphic work on the inner platform surface.

• **Gravity-wave height on the platform surface is depth-limited and therefore modulated by the tide.** Results from Tatapouri (ch. 3) showed that gravity-wave height on the platform surface was linearly correlated to local water depth, with significant ($H_{\text{med}}$) and maximum wave height ($H_{\text{max}}$) limited to 40% and 70% of local water depth respectively. Results are in accordance with Farrel *et al.* (2009) which is the only other study to date that has described wave-height limit on shore platforms; however, there was a discrepancy between the value reported in chapter 3 ($H_{\text{med}}/h = 0.4$) and the value reported by Farrel *et al.* (2009, $H_{\text{med}}/h = 0.6$). It was suggested that the
differences in wave conditions and bottom gradient between the study sites might be responsible for the discrepancy.

- **Short-period wind waves are preferentially attenuated across the platform surface.** Results from Oraka (ch. 3) and Red Beach (ch. 4) suggest that waves at wind-wave frequencies (0.125 – 0.33 Hz) are more markedly attenuated across the platform surface, confirming the results reported by Marshall and Stephenson (2011). Previously Marshall and Stephenson (2011) reported that longer-period swell waves were significantly more important on the inner platform surface than short-period wind waves at their study sites.

- **Gravity wave characteristics on the inner platform surface are generally independent of incident wave conditions.** Results presented in chapter 4 demonstrated that incident conditions were not a useful indicator of gravity wave characteristics at the cliff toe on the study platforms. Cliff-toe gravity-wave heights measured on the platforms at Rothesay Bay and Red Beach were not affected by variations in incident wave height or incident wave frequencies recorded off the seaward edge. Instead, gravity-wave height at the cliff toe was locally depth limited.

- **Attenuation of gravity waves on the platform surface is tidally modulated and attenuation rate increased towards low tide.** A comparison of wave data on six platforms presented in chapter 5 showed that gravity waves were
more significantly attenuated at low tide, likely due to increased frictional energy loss associated with shallow water depths. Across-shore gravity-wave-height attenuation rate was 24 to 34% greater at low tide. Attenuation rate on the inner platform surfaces was 1.5 times greater at low tide than high tide.

- **Infragravity waves are present on shore platforms and their relative importance increases spatially towards the cliff toe and temporally towards low tide.** Significant infragravity-wave height of up to 0.3 m was observed on the study platforms. Infragravity-wave height increased towards the cliff toe. As demonstrated at Oraka (ch. 3), cliff-toe infragravity-wave height was less dependent on platform water depth. Results of the Rothesay Bay experiment (ch. 4) suggest that relative water depth \( h/H_m0 \) at the seaward edge is an important control on infragravity-wave shoaling. It was found that the amount of increase in infragravity-wave height across the platform surface was positively correlated to the relative water depth at the seaward edge.

### 6.2.2 Morphological controls on wave processes

- **Platform elevation relative to tidal range is an important factor that determines the duration of the temporal window in which gravity waves can access the inner platform surface and the cliff toe.** As gravity-wave height on shore platforms is limited by platform water depths, platform
elevation relative to tidal range determines the amount and the duration of gravity wave activity on shore platforms.

- **Platform width is an important control on wave-energy attenuation at low tide and/or on elevated platforms with very shallow platform water depths.** Increased gravity wave attenuation rate at low tide reported in chapter 5 suggests that platform width becomes increasingly more important towards low tide in filtering wave energy. Results also show that attenuation rates calculated from the incident wave height is not a useful indicator of the effectiveness of shore platforms in filtering wave energy, as inner platform gravity-wave processes are independent of incident wave conditions.

- **The maximum wave height to water depth ratio \( (H_{\text{max}}/h) \) on shore platforms is controlled by bottom gradient.** Results presented in chapter 4 (Rothesay Bay) and chapter 5 (mata-analysis) demonstrated that the breaking criterion on the shore platform surface was a function of local platform slope and that the breaking criterion increased with increasing platform gradient. However, the maximum wave height to water depth ratio \( (H_{\text{max}}/h) \) would not exceed 0.55 to 0.6 on very flat platform surfaces as suggested by Nelson (1987). This is in accordance with theoretical studies, laboratory experiments and field studies on coral reefs and offshore sand banks. Results suggest that the solitary wave theory criterion of 0.78 commonly used on shore platforms may overestimate that the maximum wave-height limit on very flat shore platforms.
• **Cliff-toe wave regime can be characterised by the platform energy window index \( \psi = h/W \).** Gravity waves were significantly attenuated across the platform surface while infragravity-wave height tended to increase towards the cliff toe. As a result infragravity waves became progressively more dominant towards the cliff toe. A comparison of cliff-toe wave characteristics on six platforms presented in chapter 5 showed that there was a correlation between the \( H_{m0L}/H_{m0} \) ratio at the cliff toe and the platform-energy window \( \psi \). The threshold value of \( \psi \) at which infragravity waves become proportionally more dominant was found to be 0.0024.

### 6.2.3 Secondary hydrodynamic processes

- **Wave reflection on the platform surface is mainly limited to infragravity waves.** An analysis of directional wave (p-u-v) data on the Oraka platform (ch. 3) showed that wave reflection was generally limited to infragravity waves. In contrast, up to 32% of infragravity-wave energy was reflected by the cliff. Only a small amount (3 to 8%) of reflected wave energy at gravity wave frequencies (> 0.05 Hz) was observed at the central platform location. This was due to the progressive attenuation of gravity wave across the platform surface as only a small amount of energy at those frequencies were able to reach the cliff toe.

- **Wave breaking off and at the seaward edge of the platform can cause wave setup on the platform surface.** Pressure sensor data recorded in
front of and on the platform at Rothesay Bay (ch. 4) showed that there was a water depth gradient on and off the platform edge. The differences in still water level across the platform surface were tidally modulated, with the highest water level recorded at the seaward edge and the central platform during low tide. The largest difference (~ 0.2 m) in water depth was observed during the peak storm period. The observed value of wave setup (< 10% of incident $H_{m0}$) was much smaller than the values reported on sandy beaches. It was suggested that the effect of wave setup was reduced by the elevated water escaping laterally from the unconfined platform boundaries in the form of setup induced currents.

6.3 Geomorphic implications

- **Morphological controls on platform wave processes must be re-considered in conceptual and numerical models of shore platform evolution.** Historically, it has been assumed that wave-energy attenuates as waves traverse the platform surface (e.g. Johnson, 1919); therefore it has been assumed that platform width was the key control on wave-energy dissipation. Furthermore, numerical models generally calculate wave delivery to the cliff toe from the incident wave height, using an exponential decay function and the initial breaker height determined by a single breaking criterion regardless of the morphological configuration of a shore platform (e.g. Sunamura, 1992; Trenhaile, 2000; Davies et al., 2006). Results suggest platform morphology (geometry) as a key control of wave transformation across platforms and that the theoretical assumptions regarding wave-
energy dissipation and cliff-toe energy delivery traditionally used in shore platform research may not be accurate. Therefore, conceptual and numerical models of shore platform morphodynamics and evolution should be revised in light of quantitative field wave data.

- **Infragravity waves may be an important geomorphic agent at the cliff toe.**

  The presence of infragravity waves identified at the cliff toe raises the prospect that these waves may represent a geomorphic agent on shore platforms. Although infragravity waves are unlikely to be a direct agent of erosion, they may contribute to sediment transport. Furthermore, *vertical excursions of infragravity waves may increase the zone that is subject to physicochemical weathering processes (e.g. salt action, freeze thaw effects, etc) by wetting the cliff face that cannot be reached by gravity waves or tides alone.*

- **Type B shore platforms may be differentiated as infragravity-wave dominated and gravity wave-dominated platforms using \( \psi \).** The dominance of (infra) gravity-wave energy at the cliff toe was found to be a function of the platform wave energy window (\( \psi \)) and infragravity waves become proportionally more important than gravity waves when \( \psi \) becomes smaller than 0.0024 (ch. 5). This raises a possibility that Type B platforms may be classified according to the dominant wave types. The parameter can be applied at two different temporal scales: at process time-scale (hours to days) over which shore platforms may shift to/from a gravity-wave regime to
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an infragravity-wave regime as the tide modulates platform water depths; and at engineering to (1x10\(^1\)~10\(^2\) yrs) to geological (>1x10\(^3\) yrs) time scales over which shore platforms may become gravity-wave dominated to/from infragravity-wave dominated platforms, forced by horizontal extension of the platform surface and/or sea-level change.

- **The efficiency of shore platforms as protective buffer against ocean waves will diminish with rising sea-level.** The correlation between the \(H_{m0L}\) to \(H_{m0}\) ratio at the cliff toe and the platform-energy wave-widow index (\(\psi\)) indicates that the efficiency of shore platforms as protective buffer against ocean waves will diminish with rising sea-level. As sea-level rises, the temporal window in which gravity waves can access the inner platform surface and the cliff toe will increase. An increase in platform water depth will allow larger gravity waves to propagate across the platform surface as gravity-wave height is established to be depth-limited on shore platforms. Increased water depth will also reduce the effect of frictional attenuation. Therefore, the effectiveness of platform width in attenuating wave energy will be compromised (ch. 5). Sea-level rise will therefore result in increased cliff-toe gravity-wave energy delivery.

6.4 Recommendations for future hydrodynamic studies on shore platforms
This thesis has presented a number of detailed studies of shore platform hydrodynamic that have provided several important new insights into shore
platform wave processes and morphological controls on wave characteristics. Future work could usefully extend the understanding developed in this thesis by focussing on the following:

- **Along-shore variability in wave-energy delivery.** The case studies presented in this thesis characterised across-shore wave transformation. If platform morphology is a key control on cliff-toe wave climate, as demonstrated in chapter 5, there should be a significant variability in cliff-toe wave-energy delivery long a coastline, as platform morphology often varies significantly locally and regionally.

- **Infragravity-wave transformation.** The results presented in thesis and those of others (Beetham and Kench, 2011; Marshall and Stephenson, 2011) established general characteristics of infragravity waves on shore platforms. However, as pointed out in Chapter 4, there is a discrepancy regarding the transformation of infragravity waves in response to high energy storm events. As infragravity waves can be an important agent of sediment transport under high energy conditions, the relationship between incident wave height and cliff-toe infragravity-wave height needs to be further investigated.

- **Infragravity waves as a geomorphic agent on shore platforms.** The potential importance of infragravity waves as an agent of geomorphic change has been suggested in this study. However, to date, no study has investigated the geomorphic role of infragravity waves on shore platforms. Studies focusing on infragravity-wave induced sediment suspension and transport,
and their potential roles in surface abrasion and the effect of vertical excursions of infragravity waves against the cliff face may provide further insights into the role of infragravity waves on shore platform evolution.

- **Frictional wave attenuation and roughness co-efficient.** The importance of frictional attenuation at low tide was discussed in chapter 5. However, a roughness coefficient was not determined in this study. Furthermore, platforms with a very rough surface were not sampled in this study. Frictional energy loss is expected to increase with increasing surface roughness. Surface morphology of shore platforms vary significantly depending on geological and lithological controls. Platforms cut into tilted sedimentary rocks (variable dip and strike angles) tend to developed very irregular platform surface (Trenhaile, 1987). Studies should be conducted on shore platforms with varying degrees of surface roughness in order to quantify the relationship between surface roughness and frictional energy loss.

- **Wave setup on shore platforms.** While an attempt was made in this study to describe wave setup at Rothesay Bay, more comprehensive, multi-site studies are required to quantify wave setup on shore platforms. It is likely that the setup patterns on shore platforms are different to the pattern reported on sandy beaches. Previously Jago *et al.* (2007) reported a double setup system on coral reef platforms caused by wave swell waves breaking at the seaward edge (setup zone 1) and wind wave on the beach (setup zone 2). Given the
similarity in morphology between Type B platforms and coral reef platforms, it is like that such a setup pattern is also present on Type B platforms. A greater number of sensors, ideally stilling wells as used by Jago et al. (2007), and co-located wave gauges are required in order to accurately quantify wave setup on shore platform.

- **Along-shore and across-shore currents on shore platforms and their morphological roles.** Currents are an important agent of sediment transport. However no study has measured and/or quantified wave induced and setup induced currents on shore platforms. The presence of wave setup reported in chapter 4 indicates that there was a wave induced pressure gradient on the Rothesay Bay platform during the experiment. It is therefore likely that wave induced and setup induced currents, both of which are generated as a result of pressure gradients generated by across-shore and/or along shore variations in radiation stress, are present on shore platforms.
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