Incorporating High-Quality Surfing Breaks into Multi-Purpose Reefs

A thesis submitted in fulfilment of the requirements for the Degree of

Doctor of Philosophy
in Earth Sciences
(Centre of Excellence in Coastal Oceanography and Marine Geology)

by
Shaw Trevor Mead

The University of Waikato
2000

FRONTISPIECE: High-quality surfing waves breaking on the Narrowneck Artificial Reef on the Gold Coast, Queensland, Australia. (13 May 2000. Image from www.Burleighcam.com).

Abstract

The studies presented in this thesis have focussed on surfing. Bathymetries, aerial photographs and wave vortex information at natural surfing breaks were measured and collected. These data were applied to understand the morphology that creates world-class surfing reefs, to predict wave-breaking intensity and to develop a dataset of surfing breaks (seabed bathymetries, peel angles and wave vortex shapes). In addition, the results were applied to the production of a coastal resource consent to construct a multi-purpose reef at Mount Maunganui Beach in north-eastern New Zealand.

Bathymetry surveys were carried out using a custom-built, portable, surveying system that was developed to enable surfing reef surveys at remote sites worldwide. Along with peel angle and wave vortex information, the bathymetric surveys of 28 surfing locations around the Pacific Rim and Indonesia were recorded and constitute the first international dataset of world-class surfing breaks. A full geomorphic range was measured including coral reefs, rocky reefs, headlands, rock ledges, river and estuarine deltas and sand beaches.

Analysis of these bathymetries revealed meso-scale surfing reef geomorphic components that were classified as ramp, platform, wedge, ledge, focus, ridge and pinnacle, which constitute and account for the quality of world-class surfing reefs. The function of these components in relation to wave refraction and wave breaking is considered.

There were repeating combinations of meso-scale surfing reef components and, with numerical modelling, it was found that the combinations of reef components occur in configurations that explain why these breaks are consistently high-quality. Components are sub-categorised by function into two basic groups, components that pre-condition waves and components that break waves. Components are arranged in functional order, with larger offshore components (ramp, focus and platform) aligning and shoaling waves prior to breaking on the smaller inshore components. Small wave breaking components (ridge and pinnacle) rest on the larger wave breaking components (wedge

and ledge) and modify small sections of the wave. The study indicated that relative sizes and placement of the components determines the overall quality and length of the surfing break and that changes to either will reduce surfing wave quality.

A surf break that very effectively combines the components is Bingin Reef in Bali, Indonesia. Refraction modelling of the waves at Bingin was in close agreement with field measurements and highlighted how the reef components behave as a unit to produce consistent, high-quality waves.

One feature of Bingin was that it maintains a fast surfable peel angle (~35°) over a range of wave heights and directions. A defined take-off zone was also persistent, resulting from wave-focusing over a large-scale reef component. Also very obvious in the model simulations, was the fast-breaking, steeper faced, part of the wave at Bingin, that is produced by a smaller scale reef component positioned on top of a larger feature. When the reef components that comprise Bingin were manipulated, and sometimes omitted, in most cases, the consequent changes to wave refraction produced waves that broke with less than world-class characteristics. The most common result was that waves broke too fast for surfing, or 'closed-out. In some cases this could be overcome by re-orientating components at angles greater than those that exist at Bingin. However, this resulted in greater changes to peel angles with changing wave height and directions than normally experienced at Bingin. Re-positioning or omitting smaller reef components had less effect on wave breaking, but these changes still down-graded the quality of the wave for surfing. Because the components combine and interact in a holistic way through wave refraction and pre-conditioning of the wave orientations, designs of artificial surfing reefs must apply these holistic principles in order to produce high-quality surfing facilities that optimise the characteristics of specific sites.

The dataset of world-class surfing break bathymetries and the accompanying wave vortex profiles were used to develop a method for predicting and describing the breaking intensity of plunging surfing waves. This method uses the orthogonal seabed gradient to predict the wave vortex height to width ratio, which was found to be the best indicator of wave breaking intensity. The subtle differences in the vortex shape of plunging waves on different seabed gradients can now be described much better than with simplistic indicators, such as the Irribarren number. Description of the shape of plunging waves, or the tube-shape, is critical for defining quality surfing waves. These quantitative predictions of tube shape will be incorporated into artificial surfing reef design.

A multi-purpose, artificial, offshore reef was designed for construction at Mount Maunganui Beach, New Zealand. The proposed reef will form the basis for research into coastal protection, amenity enhancement (particularly surfing, but also diving, fishing and beach recreation), biological response and social and economic impacts. In order to proceed with reef construction, a 5-year resource permit is being sought from the regulatory authority, and this application required an assessment of the likely environmental impacts of the proposed reef. The studies undertaken for the Assessment of Environmental Assessment for resource consent included physical, biological, reef design and socio-economic impacts. A comprehensive design process was undertaken to incorporate the amenity of surfing into a submerged reef shape. Programs to monitor physical and biological responses, as well as social and economic impacts, were also established. These studies support the use of multi-purpose, artificial, offshore reefs as an environmentally-friendly solution to coastal protection. The reefs also cater to the growing demand for more coastal-amenity development.

Acknowledgements

To my wife Angela, thank you for your support all the way through. From videoing me paddling endlessly back and forth at surfing spots, to keeping me going while I sat in front of the computer for countless hours, you've been with me in this the whole way. All my love to you and our two beautiful children that have come into our lives while this thesis was proceeding – we've done a lot in 5 years!

Thanks also to the rest of my family, especially my folks, Bill and Lilian, but all the rest of the Meads and Roddas – you've all been a tremendous support. To my friends (too many to name), thanks for all your help – from just being friends to providing work to make life easier.

Kerry Black, thank you for your awesome supervision and friendship – you made the ARP possible. Getting rubbed across the reef in Tonga was a small price to pay for what I (and most surfers) consider the best PhD topic in the world! Thank you to my other supervisors, Terry Healy, Terry Hume, and Roger Williams, for also helping through the course of this study – it was great to have such a huge depth of knowledge and support to draw upon.

Thank you to the whole team that put together the Mount Maunganui Reef proposal Hamish, Rob, Dylan, and all the others that played a part – I look forward to surfing it very soon. And, to all the other people who supported me during the course of this thesis or somehow had a positive input - technicians (Dirk and John to name a couple), friends and associates who gave us somewhere to stay overseas (Helmo and family in Rio; R & K in San Francisco; and all the others), and all the rest un-named – thanks heaps.

Angela and Shaw in Rio de Janeiro – June 1996

Surf to Live – Live to Surf!

Contents

ABSTRACT.. I
ACKNOWLEDGEMENTS.. IV
CONTENTS.. V
APPENDICES... VI
LIST OF FIGURES.. VI
LIST OF TABLES... XII
LIST OF PLATES... XIII

CHAPTER 1 INTRODUCTION 1

1.1 BACKGROUND.. 1
1.2 THE ARTIFICIAL REEFS PROGRAM 2
1.3 OBJECTIVES OF THIS RESEARCH 4
1.4 THESIS STRUCTURE 6

CHAPTER 2 SURFING BREAK SURVEYS.. 9

2.1 INTRODUCTION 9
2.2 SYSTEM SPECIFICATIONS 10
2.3 DEVELOPMENT OF THE PORTABLE SURVEYING SYSTEM 12
2.3.1 GPS receivers.. 13
2.3.2 Data Logging 14
2.3.3 Power Supply and Duration.. 14
2.3.4 System Containment.. 16
2.3.5 Operating Horatio.. 16
2.4 SYSTEM TESTS AND DEPTH SOUNDER CALIBRATION 17
2.4.1 GeoExplorer® Error.. 17
2.4.2 Full System Tests.. 21
2.4.3 Depth Sounder Calibration.. 24
2.5 SURVEY SITES.. 25
2.6 SURVEY TECHNIQUE.. 28
2.7 SURVEY DATA CORRECTION.. 29
2.7.1 Positional Corrections 29
2.7.2 Heave Compensation 32
2.7.3 Tidal Correction.. 32
2.8 AERIAL PHOTOGRAPHS AND WAVE VORTEX PROFILES.. 33
2.9 SUMMARY.. 35

CHAPTER 3 FIELD STUDIES LEADING TO THE BATHYMETRIC CLASSIFICATION OF WORLD-CLASS SURFING BREAKS.. 36

3.1 ABSTRACT 36
3.2 INTRODUCTION 37
3.3 STUDY SITES AND SURVEY TECHNIQUE 38
3.4 DATA PROCESSING.. 45
3.5 IDENTIFICATION OF MESO-SCALE REEF COMPONENTS.. 46
3.5.1 Ramp 53
3.5.2 Platform 53
3.5.3 Focus.. 54
3.5.4 Wedge.. 55

3.5.5 Ledge ... *56*
3.5.6 Ridge ... *56*
3.5.7 Pinnacle ... *57*
3.6 COMPONENT SCALE ... 58
3.7 CONCLUSION ... 61
3.8 ACKNOWLEDGEMENTS ... 62
3.9 REFERENCES ... 62

CHAPTER 4 FUNCTIONAL COMPONENT COMBINATIONS CONTROLLING SURFING WAVE QUALITY AT WORLD-CLASS SURFING BREAKS ... 67

4.1 ABSTRACT ... 67
4.2 INTRODUCTION ... 68
4.3 PEEL ANGLE ... 68
4.4 COMMON REEF COMPONENT CONFIGURATIONS AT WORLD-CLASS SURFING BREAKS ... 71
4.4.1. The Ramp/Wedge Configuration ... *76*
4.4.2 The Ramp/Platform/Wedge Configuration ... *77*
4.4.3 The Ramp/Focus/Wedge Configuration ... *78*
4.4.4 The Ramp/Ledge/Platform Configuration ... *79*
4.4.5 Ridges and Pinnacles ... *80*
4.5 GENERAL DISCUSSION ... 80
4.6 CONCLUSION ... 86
4.7 ACKNOWLEDGEMENTS ... 86
4.8 REFERENCES ... 87

CHAPTER 5 CONFIGURATION OF LARGE-SCALE REEF COMPONENTS AT A WORLD-CLASS SURFING BREAK: BINGIN REEF, BALI, INDONESIA. ... 91

5.1 SUMMARY ... 88
5.2 1. INTRODUCTION ... 89
5.3 2. COMPONENT CONFIGURATION ... 90
5.4 3. METHODS ... 90
5.4.1 3.1 Bingin Reef Survey ... *90*
5.4.2 3.2 Numerical modelling ... *91*
5.5 4. RESULTS ... 91
5.5.1 4.1 The arrangement and function of components at Bingin Reef ... *91*
5.5.2 4.2 Numerical Modelling ... *93*
5.6 5. COMPONENT MANIPULATION ... 93
5.7 6. CONCLUSION ... 97
5.8 7. ACKNOWLEDGEMENTS ... 98
5.9 8. REFERENCES ... 98

CHAPTER 6 PREDICTING THE BREAKING INTENSITY OF SURFING WAVES ... 103

6.1 ABSTRACT ... 103
6.2 INTRODUCTION ... 104
6.3 THE IRRIBARREN NUMBER ... 107
6.4 CUBIC CURVE FITTING ... 108
6.5 IMAGE ANALYSIS ... 110
6.6 ANALYSIS OF SEABED GRADIENTS ... 114
6.7 RESULTS ... 115
6.8 DISCUSSION ... 121
6.9 CONCLUSION ... 127
6.10 ACKNOWLEDGEMENTS ... 127
6.11 REFERENCES ... 128

CHAPTER 7 A MULTI-PURPOSE, ARTIFICIAL REEF AT MOUNT MAUNGANUI BEACH, NEW ZEALAND 132

7.1 ABSTRACT 132
7.2 INTRODUCTION 132
7.3 LOCATION AND DESCRIPTION OF THE PROPOSED REEF 135
7.4 ASSESSMENT OF PHYSICAL PROCESSES AND IMPACTS 138
7.5 ECOLOGICAL IMPACTS 141
7.6 SURFING ASPECTS 142
7.7 MONITORING 145
7.8 CONCLUSION 146
7.9 NOTES 147
7.10 REFERENCES 148

CHAPTER 8 DISCUSSION 152

8.1 INTRODUCTION 152
8.2 HIGH-QUALITY SURFING BREAKS 153
8.3 SURFING BREAK SURVEYS 156
8.4 ANALYSIS OF SURFING BREAK BATHYMETRIES 157
8.5 MESO-SCALE REEF COMPONENTS 158
8.6 REEF COMPONENT FUNCTIONS 162
8.6.1 Pre-conditioning Components 163
8.6.2 Wave Breaking Components 163
8.7 COMPONENT SCALE 163
8.8 COMBINATIONS OF REEF COMPONENTS 166
8.9 THE EFFECT OF SURFING BREAK SCALE ON COMPONENT CONFIGURATIONS 167
8.10 REFRACTION COMPENSATION ON HEADLAND AND ISLAND BREAKS 173
8.11 PREDICTING THE BREAKING INTENSITY OF SURFING WAVES 177
8.12 CREATING A MULTI-PURPOSE OFFSHORE REEF 181
8.12.1 Introduction 181
8.12.2 Mount Maunganui Reef 182
8.12.3 Amenity Enhancement 184
8.12.4 Surfing Reef Design 186
8.12.5 Coastal Processes and Protection 191
8.12.6 Biological Enhancement 195
8.13 SUMMARY 197

CHAPTER 9 CONCLUSIONS 199

9.1 INTRODUCTION 199
9.2 SURFING BREAK SURVEYS 199
9.3 SURFING REEF GEOMORPHIC COMPONENTS 200
9.4 SURFING WAVE BREAKING INTENSITY 201
9.5 MOUNT MAUNGANUI REEF 201

REFERENCES 203

Appendices

Appendix One: List of Publicity associated with the Artificial Reefs Program.

Appendix Two: Examples of the various file formats used during the operation of Horatio and the post-processing of the bathymetric survey data.

Appendix Three: Protocol for Operating Horatio; depth sounder calibration, the base station and the survey.

Appendix Four: Wave Refraction Model WBEND.

List of Figures

Page

Figure 2.1. Adjustable aluminium fitting to connect the sonar to the surveying vessel. 12

Figure 2.2. Results of three different routes (differentially corrected) around a 30 x 30 m grid (single cells 10 x 10 m) marked out on the sand flats at Raglan Harbour entrance. 18

Figure 2.3. GPS Spread of GPS point fixes of shoreline points at Angourie, New South Wales Australia. 20

Figure 2.4. The distance of the recorded positions from 4 known positions. n = 336, mean = 0.38 m (st.dev. = 0.23), mode = 0.35 m, median = 0.33 m. 22

Figure 2.5. The results of a typical depth sounder calibration (multiplier = 6.3532, offset = 0.998). 24

Figure 2.6. Location map of surfing break surveys – indicated by ★. (Pacific Map from www.maps.com) 25

Figure 2.7. Contour map of Bingin Reef, Indonesia, showing the corrected survey run-lines in red. Surveyed 23/9/96 – northings and eastings relative to base station. 28

Figure 2.8. Examples of differentially corrected bathymetric surveys before and after editing using the Matlab® program EDSHAW. 31

Figure 3.1. Sites of surfing break surveys (represented by ★). (Pacific Map from www.maps.com). 39

Figure 3.2. Curve fitting is applied to the forward face of a wave and used to calculate the length to width ratio the vortex (tube) angle (Black *et al.*, 1997). 41

Figure 3.3. The distance of the recorded positions from 4 known positions. n = 336, mean = 0.38 m (st.dev .= 0.23), mode = 0.35 m, median = 0.33 m. 44

Figure 3.4. Bathymetry map of Kirra Point surfing break in Queensland, Australia, with surveyed landmarks overlaid. (Surveyed October, 1997) 49

Figure 3.5. Reef components that comprise the bathymetry at world-class surfing breaks. Isobaths of components become shallower in the direction of wave propagation (up the page). The large arrows represent the 'favoured orthogonal direction' and the small arrows represent transformations to the wave orthogonals. Schematic diagrams are accompanied by an example of a reef component from a measured bathymetry. Note, the platform has not been included here because it is essentially a flat component that does not refract waves that pass over it. 51

Figure 3.6. The functional order of surfing reef building blocks. Refer to Table 2 for reef components in each category. 58

Figure 3.7. The functional scales of surfing reef components. 59

Figure 4.1. Reef components that comprise the bathymetry at world-class surfing breaks. Isobaths of components become shallower in the direction of wave propagation (up the page). The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. Note, the platform has not been included here because it is essentially a horizontal component that does not refract waves that pass over it. 72

Figure 4.2. Common combinations of reef components found at world-class surfing breaks. For each set of three diagrams, from left to right, the first is an example of a measured surfing break bathymetry; the second is a numerical model output of refraction of waves over the particular surfing break bathymetry; and the third is an idealised schematic of the component combination - the multi-faceted bathymetry of natural surfing reefs has been simplified to highlight the dominant components. The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. Isobaths of components become shallower in the direction of wave propagation (up the page), and break point is represented by ☆. Note, the model bathymetry has been rotated so that wave input is from the left-hand side. 74

Figure 4.3. Schematic diagrams of wedge orientation changes required to maintain a surfable peel angle at break point with increasing size/depth of the wedge. The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. The dashed lines represent wave crests. Note the small difference between the favoured orthogonal direction and the direction of the wave orthogonal at break point in 3.a (shallow water wedge), compared to the relatively large difference between these directions in 3.b (large deep water wedge or headland). 77

Figure 4.4. Raglan headland on the west coast of North Island, New Zealand (Nautical chart NZ43, RNZN Hydrographic Office). The dominant swell and wind directions are from the southwest. The main surfing breaks at Raglan are orientated away from the dominant swell direction, towards the north. 81

Figure 5.1. The configuration of large-scale reef components at Bingin Reef, Bali, Indonesia. The large arrow represents the favoured orthogonal direction, the smaller arrows represent the alignment of wave orthogonals as they pass over the various components. Stars indicate breakpoint for a 1 m wave at mid-tide. Depth contours approximate the measured Bingin Reef bathymetry. 95

Figure 5.2 Bingin A - Idealised component bathymetry of Bingin Reef. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m above datum). Wave input was +20° relative to the model grid. 97

Figure 5.3 Bingin B - Idealised component bathymetry of Bingin Reef with the platform omitted. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m above datum). Wave input +20° relative to model grid. 98

Figure 5.4 Bingin C - Idealised component bathymetry of Bingin Reef with the platform and focus omitted and the wedge moved to a greater depth. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m). Wave input +20° relative to model grid. 98

Figure 5.5 Bingin D - Idealised component bathymetry of Bingin Reef with the platform and focus omitted and the wedge in deeper water and rotated. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m). Wave input +20° relative to model grid. 99

Figure 5.6 Changes in wave peel angle with respect to wave height for Bingin A (idealised bathymetry of existing Bingin Reef) and Bingin D (idealised bathymetry of Bingin Reef with no platform component and a rotated wedge at greater depth). Wave input +20° relative to model grid. 99

Figure 5.7 Bingin E - Idealised component bathymetry of Bingin Reef with the focus omitted. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m). Wave input +20° relative to model grid. 100

Figure 6.1. Curve fitting is applied to the forward face of a crest parallel wave image and used to calculate the vortex length (l), width (w) and angle (θ). H is the estimated wave height (after Black *et al.*, 1997). 109

Figure 6.2. The profile of the cubic curve (Longuet-Higgins, 1982). 110

Figure 6.3. The error is derived from the mean-squared distance (eqn. 4) of digitised points from the fitted curve, where D_i is the distance from the mean x and y position and d_i is the distance from the fitted curve (after Sayce 1997). 110

Figure 6.4. Example of seabed gradient profile created by digitising a bathymetry grid and then plotting using GRAPHER software (V. 1.3 1993-1996 Golden Software, Inc.). 114

Figure 6.5. Orthogonal seabed gradient versus the ratio of vortex height to vortex width (R^2 = 0.71). The orthogonal seabed gradient (given as the horizontal distance to one vertical unit) is the gradient along the direction of wave propagation. Additional data points are the Gold Coast artificial reef and the mean of Couriel *et al.*'s (1998) results. 116

Figure 6.6. The relationship between the contour normal seabed gradient and the ratio of vortex height to vortex width (R^2 = 0.57). The contour normal seabed gradient (given as the horizontal distance to one vertical unit) is the steepest possible seabed gradient. 117

Figure 6.7. Wave vortex angle vs the ratio of vortex height to vortex width (R^2 = 0.03). 118

Figure 6.8. Wave vortex angle vs the ratio of vortex width to wave height (R^2 = 0.02). Wave height for the Lyall Bay video image could not be estimated, and so Whangamata is shown as the break with the lowest seabed gradient. 119

Figure 6.9. Wave vortex angle vs the ratio of vortex length to wave height (R^2 = 0.03). Wave height for the Lyall Bay video image could not be estimated, and so Whangamata is shown as the break with the lowest seabed gradient. 119

Figure 6.10. Contour normal seabed gradient (expressed as an angle (deg.)) vs the vortex angle (R^2 = 0.07). 120

Figure 6.11. Orthogonal seabed gradient (expressed as an angle (deg.)) vs the vortex angle (R^2 = 0.07). 121

Figure 7.1. Locality map of proposed artificial, offshore reef at Tay Street, Mount Maunganui, New Zealand. 136

Figure 7.2. Plan view of proposed ARP reef at Tay Street, Mount Maunganui, New Zealand. (Approximate scale 1:500). 137

Figure 7.3. Large-scale modelling grid (100 x 100 m) of Mount Maunganui offshore area (rotated 220°). The dashed lines represent the surfable swell window. 138

Figure 7.4. Predicted salient formation in the lee of the ARP reef. Represented at lowest astronomical tide. 140

Figure 8.1. An example of a depth contour map generated from the bathymetric survey data of Kirra Point in Queensland, Australia, using Surfer© software. Landmark information has been overlaid, and isobath normal seabed profiles and wave orthogonal seabed profiles are indicated by the solid lines through the break. (Surveyed October, 1997) 157

Figure 8.2. Reef components that comprise the bathymetry at world-class surfing breaks. Isobaths of components become shallower in the direction of wave propagation (up the page). The large arrows represent the 'favoured orthogonal direction' and the small arrows represent transformations to the wave orthogonals. Schematic diagrams are accompanied by an example of a reef component from a measured bathymetry. Note, the platform has not been included here because it is essentially a flat component that does not refract waves that pass over it. 160

Figure 8.3. The functional order of surfing reef components. Refer to Table 8.1 for reef components in each category. 162

Figure 8.4. The functional scales of surfing reef components. 165

Figure 8.5. Common combinations of reef components found at world-class surfing breaks. For each set of three diagrams, from left to right, the first is an example of a measured surfing break bathymetry; the second is a numerical model output of refraction of waves over the particular surfing break bathymetry; and the third is an idealised schematic of the component combination - the multi-faceted bathymetry of natural surfing reefs has been simplified to highlight the dominant components. The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. Isobaths of components become shallower in the direction of wave propagation (up the page), and break point is represented by ☆. Note, the model bathymetry has been rotated so that wave input is from the left-hand side. 167

Figure 8.6. Schematic diagrams of wedge orientation changes required to maintain a surfable peel angle at break point with increasing size/depth of the wedge. The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. The dashed lines represent wave crests. Note the small difference between the favoured orthogonal direction and the direction of the wave orthogonal at break point in 8.6a (shallow water wedge), compared to the relatively large difference between these directions in 8.6b (large deep water wedge or headland). 171

Figure 8.7. Raglan headland on the west coast of North Island, New Zealand (Nautical chart NZ43, RNZN Hydrographic Office). The dominant swell and wind directions are from the southwest. The main surfing breaks at Raglan are orientated away from the dominant swell direction, towards the north. 174

Figure 8.8. Curve fitting is applied to the forward face of a crest parallel wave image and used to calculate the vortex length (l), width (w) and angle (θ). H is the estimated wave height (after Black *et al.*, 1997). 178

Figure 8.9. Locality map of proposed artificial, offshore reef at Tay Street, Mount Maunganui, New Zealand. 183

Figure 8.10. Large-scale modelling grid (100 x 100 m) of Mount Maunganui offshore area (rotated 220°). The dashed lines represent the surfable swell window. 189

Figure 8.11. Schematic diagram of the Tay Street Reef. The Tay Street Reef is orientated with the longest axis running east-west across shore at an angle to the natural sea bed gradient. 190

Figures 8.12. Predicted salient formation in the lee of the ARP reef. Represented at lowest astronomical tide. 195

List of Tables

Page

Table 2.1. Survey locations, base station positions, survey vessel used and break type of surfing reef surveys. 27

Table 3.1. Survey locations and base station positions and descriptions. 41

Table 3.2. Functions of surfing reef components. 58

Table 3.3. Summary table of meso-scale reef components – refer to notes 1-4 above for clarification of the factors included in the table. 60

Table 4.1. List of international surfing breaks surveyed for seabed investigations, the components that each break is comprised of and a description of wave breaking characteristics (wave steepness and peel speed). 70

Table 5.1. Wave inputs for model simulations with measured Bingin Reef bathymetry. 94

Table 6.1. Wave vortex statistics obtained by curve-fitting to crest parallel images of waves breaking at mostly world-class surfing breaks. Wave height estimates could not be made for some images. 113

Table 6.2. Classification schedule of surfing wave breaking intensity. 122

Table 8.1. Functions of surfing reef components. 162

Table 8.2. Classification schedule of surfing wave breaking intensity. 180

List of Plates

page

Plate 1.1. A high-quality surfing wave breaking on the Narrowneck artificial reef on the Gold Coast, Queensland, Australia (May 13, 2000 - http://www.burleighcam.com.au) 3

Plate 1.2. Algal growth (Sargassum sp.) is well established on the surface of the geotextile ReefBags©, used to construct the Narrowneck artificial surfing reef, after just two weeks (photo – A. Jackson). 4

Plate 2.1. Horatio, the portable surveying system, attached to a drogue-like raft during equipment testing in the University of Waikato swimming pool. 23

Plate 2.2. An inflatable kayak was used to survey many surfing breaks, and was especially useful for surveying breaks in isolated areas. Horatio could be either carried within the kayak (with the depth sounder connected to the stern) or towed on a drogue-like raft (Plate 2.1). 26

Plate 2.3. The author about to depart in a chartered Tiger Moth to take aerial photographs and video of Bells Beach and Winkipop in Victoria, Australia. 34

Plate 3.1. The portable surveying system, known as Horatio. The system is either towed on a drogue-like raft (as shown) or fixed to any type of vessel using a custom-built attachment. 40

Plate 3.2. Surfing inside the vortex of a breaking wave, under the plunging lip of a wave, is known as riding in the 'tube' and takes a high level of skill. 57

Plate 4.1. Aerial view of an island surfing break, where the wedge (reef edge) is continually bending away from the approaching waves, which compensates for refraction and produces surfable peel angles over a very long distance. Note the region at the top of the island where wave peel angles are very low and unsurfable where the island faces the swell direction. (Photo Dick Hoole – In: Uluwatu. Tadevan Holdings Pty Ltd. 1998) 82

Plate 4.2. Pipeline on Hawaii's North Shore is a good example of a large focus break. In this picture the height reduction along the wave crest due to energy extraction from the adjacent wave crest is very obvious. (Photo ASL Vol. 73, Oct. 1994). 85

Plate 6.1. A wave collapsing as it breaks above the very steep seabed of Todo Santos reef in Mexico (after Sayce, 1997). 104

Plate 6.2. The steep wave face close to the peeling crest of the wave, known as the pocket, offers the most speed for surfing. 105

Plate 6.3. A surfer riding under the jet of a breaking wave; the tube ride. 105

Plate 6.4. A wave breaking with extreme intensity on the Gold Coast Reef, Queensland, Australia. 127

Plate 8.1. Plunging waves are preferred for high-performance surfing, as this form of wave breaking presents the opportunity for the surfer to ride under the breaking wave crest, or in the tube, as seen here. (Photo Tony King – In: Uluwatu. Tadevan Holdings Pty Ltd. 1998). 154

Plate 8.2. The peel angle, α, is defined as the angle between the trail of the broken white water and the crest of the unbroken part of the wave as it propagates shoreward (Aerial photo of Indicators at Raglan, New Zealand (Hutt, 1997)). 155

Plate 8.3. Pipeline on Hawaii's North Shore is a good example of a large focus break. In this picture the height reduction along the wave crest due to energy extraction from the adjacent wave crest is very obvious. (Photo ASL Vol. 73, Oct. 1994) 173

Plate 8.4. Aerial view of an island surfing break, where the wedge (reef edge) is continually bending away from the approaching waves, which compensates for refraction and produces surfable peel angles over a very long distance. Note the region at the top of the island where wave peel angles are very low and unsurfable where the island faces the swell direction. (Photo Dick Hoole – In: Uluwatu. Tadevan Holdings Pty Ltd. 1998) 175

Chapter 1

INTRODUCTION

1.1 Background

In many parts of the world, coastal protection is almost at an impasse. Negative down-coast impacts (Bush *et al.*, 1996; Bruun, 2000), compromise of aesthetic and amenity values, recent environmental laws (e.g. the Resource Management Act, 1991) and strong negative public reaction to rock emplacement or structures along the coast (Bush *et al.*, 1996) are putting pressure on existing methods of coastal protection. This has led to uncertainty by regulators and local government authorities about how to treat shoreline erosion (Pilkey and Dixon, 1996; Komar, 1997). Many are resorting to "managed retreat" where buildings are simply removed and the coast is left to erode (Bush *et al.*, 1996). However, managed retreat can be expensive, unnecessary and sometimes impossible. While permission to damage or develop the frontal dune should never be given, coastal erosion and threats to property cannot be easily eradicated and so a solution is required.

Offshore, submerged reefs provide a shoreline protection solution with low environmental impact and potentially bridge the gap between environmentalists, regulators, coastal property owners and other coastal users. Visual amenity is not impaired, the reef is constructed offshore with no disturbance to the foreshore habitat and there is no requirement for rock emplacement along the shoreline. Salient growth in the lee of the reef leads to enhanced shoreline stability and protection (e.g. Black and Andrews, 2000) and the natural character of the coastline is retained. An additional benefit is the incorporation of recreational and public amenity (McGrath *et al.*, 1999) through surfing (Black *et al.*, 1998a; Black *et* al., 1999; Jackson *et* al., 1999; Mead and Black, 1999a; Black, 2000), diving/snorkelling, sheltered swimming, fishing and other water activities, as well as the enhancement of marine habitat.

1.2 The Artificial Reefs Program

This research was undertaken within the Artificial Reefs Program. In 1995, the Artificial Reefs Program (ARP) was established by Professor Kerry Black to investigate alternative solutions to coastal protection that would mitigate environmental impacts as well as increase amenity values (Black *et al.*, 1997). The ARP is a response to the need for positive development and environmentally-sensitive solutions to coastal protection (prompted by the Resource Management Act (1991)), and to the continued growth in recreational usage of our beaches. The Program operates within the Coastal Marine Group in the Department of Earth Sciences at the University of Waikato. By unifying scientists, environmental managers and experienced industrial partners, the ARP aims to,

- enhance the coastal amenity value of the New Zealand shoreline by evaluating multiple use options (surfing, diving, recreational and commercial fishing, navigation and swimming safety) for incorporation into coastal constructions; and

- focus and further develop expertise within the research community, and within industry, while providing a sound basis for senior student education.

A series of related studies provide the input into the broader programme so that offshore reefs can be designed to incorporate the proposed concepts that will fulfil the demands and requirements of the appropriate government authorities, the marine environment, the public and developers. Many ARP studies have been completed to date, of which three are very relevant to this thesis. The topics of these studies include:

- An investigation to quantify sandy shoreline response to submerged and emerged breakwater, reefs and islands (Andrews, 1997). This study identified a new mechanism for the formation of salients and tombolos (based on the wave protection, rather than patterns of refraction and diffraction as previously believed (Gourlay, 1981; Hsu and Silvester, 1990; Pilarczyk & Zeidler, 1996)) in the lee of offshore obstacles and methods to predict the extents of these coastal features using specific parameters of offshore reefs.

- An examination of the bathymetry and wave parameters defining surfing quality with respect to wave peel rates at five adjacent surfing reefs (Hutt, 1997). This study was used to develop a new classification scheme relating wave height and peel angle to surfer's skill level, specifically designed for the development of offshore surfing reefs (Hutt, 1997; Hutt *et al.*, 2000).

- Quantification of breaking wave characteristics, such as breaking intensity and wave 'hollowness', and how these relate to the underlying bathymetry (Sayce, 1997; Sayce *et al.*, 1999). This study particularly focussed on wave transformation over an area of complex bathymetry at a high-quality surfing site.

Plate 1.1. A high-quality surfing wave breaking on the Narrowneck artificial reef on the Gold Coast, Queensland, Australia (May 13, 2000 - http://www.burleighcam.com.au)

Results from the previous studies and the study presented here, have been brought together and, in conjunction with numerical modelling, used to design an offshore submerged reef at Narrowneck on the Gold Coast in Queensland, Australia (Black *et al.*, 1998; Hutt *et al.*, 1998), and a research reef at Mount Maunganui (described in Chapter 7). The Narrowneck reef was designed to protect the coast from erosion, whilst widening the beach and dunes and improving the surfing conditions on this part of the coast. At present construction of the reef is approximately two thirds complete, however, the beach in the lee of the reef has visibly widened and the surfing climate has been significantly enhanced (Plate 1.1). In addition, the biological response has been very fast and positive (Plate 1.2), and is a part of the ongoing environmental monitoring (Walsh *et al.*, 1999).

Plate 1.2. Algal growth (Sargassum sp.) is well established on the surface of the geotextile ReefBags©, used to construct the Narrowneck artificial surfing reef after just two weeks (photo – A. Jackson).

The ARP and its associated projects have generated a huge amount of public interest, which is supported by the large amount of media coverage over the past 5 years (Appendix 1).

1.3 Objectives of this research

This thesis documents the full process of developing an artificial surfing reef, from identifying the actual bathymetric shape of world-class surfing breaks and investigating their function, to designing a full-scale artificial surfing break. This is the first time that the bathymetries of high-quality surfing reefs have been measured for the purpose of artificial surfing reef design, except for some basic work in the early 1970's in Hawaii (Walker, 1971, 1974a, b; Walker *et al.*, 1972). However, the work here goes far beyond the coral reefs of Hawaii, utilises equipment and analytical techniques that were not available three decades earlier and draws upon the combined research of the ARP.

While the aim of this thesis is bold, it is achievable with the complementary studies of the ARP, especially those directed towards surfing (e.g. Hutt, 1997; Sayce, 1997; Sayce *et al*., 1999; Hutt *et al*., 2000). Here, I am reporting on my component of the ARP, specifically focussing on how the bathymetry at world-class surfing breaks affects the quality of surfing waves. Once the structure and function of surfing reef bathymetries is determined, these findings will be applied to the development of an artificial surfing reef at Mount Maunganui in north eastern New Zealand. Coastal processes such as sediment transport are not considered in detail in this research, high-quality surfing breaks and how to reproduce them is the prerogative.

Specifically, the objectives of this thesis are to:

- Measure the seabed of world-class surfing breaks;
- Provide general design concepts for incorporation high-quality surfing breaks into multi-purpose, offshore reefs.
- Identify bathymetric features common at world-class surfing breaks;
- Use numerical modelling to develop hypotheses about the purpose and function of bathymetric features in relation to the production of high-quality surfing breaks;
- Develop methods to predict the breaking intensity of surfing waves;
- Produce an artificial surfing reef.

The objectives are achieved by:

- Measuring the bathymetries at 28 mainly world-class surfing breaks around the Pacific Rim and Indonesia;
- Numerical modelling of 34 surfing reefs to identify the shape, function and common combinations of the meso-scale bathymetric components that constitute world-class surfing breaks;
- Re-organizing a common reef component combination to assess the impacts on wave quality using numerical modelling;
- Collecting images of wave vortex shape of waves breaking at the measured surfing breaks;

- Utilising aerial photography/photographs to find the location of wave breaking and the wave peel angles on measured reefs;
- Designing and developing a coastal resource consent application for a full-scale artificial reef to be constructed at a New Zealand beach.

1.4 Thesis Structure

The chapters of this thesis are mainly comprised of peer-reviewed papers that have been published in, or accepted by, scientific journals and/or conference proceedings. In addition, there are some chapters that have been written specifically for this thesis to report on topics not fully covered by the peer-reviewed papers and to consolidate this work.

The thesis is structured as follows:

Chapter 2 is a detailed description of the field studies undertaken to compile the surveys of world-class surfing breaks. This chapter includes techniques that were used to analyse data and test field equipment.

Chapter 3 is the first of two companion papers that have been accepted by a special issue of the Journal of Coastal Research (surfing issue). This paper briefly describes some of the field studies and tests detailed in chapter 2 and then proceeds into an analysis of the surfing reef bathymetries measured at world-class surfing breaks. Individual meso-scale reef components are classified in terms of their shape and function. However, before this new information on surfing reef morphology could be applied to reef design, an understanding of how reef components are combined to produce world-class surfing breaks was required.

Chapter 4 is the second of the companion papers accepted by the special surfing issue of the Journal of Coastal Research. This paper takes the individual reef components identified in chapter 3 and develops the links between components. Common combinations of meso-scale reef components are identified, and numerical modelling is used to determine how these combinations function to consistently produce high-quality surfing waves.

Chapter 5 is a peer-reviewed paper published in the proceedings of the Coasts and Ports '99 conference (Vol. 2:438-443). In this paper the common combination of reef components at Bingin reef in Bali, Indonesia, are re-positioned or omitted to assess the impacts on wave quality. This case study demonstrates the holistic nature of configurations of surfing reef components and the detrimental effects (in terms of surfing wave quality) of re-positioning or omitting reef components.

Chapter 6 is a peer-reviewed paper presented at the International Coastal Symposium 2000 and accepted for a special issue of Journal of Coastal Research (ICS 2000). Existing descriptions of breaking wave characteristics are far too simplistic to predict the likely shape of the breaking wave for surfing reef design, which is imperative for describing surf quality. A definitive description of wave breaking intensity was required to relate the subtleties of surfing waves in a way that could be universally understood. This paper presents a method of predicting the wave breaking intensity of surfing waves based on the seabed gradient. The breaking intensity is defined using wave vortex shape parameters, and so better defines the actual shape of the plunging/surfing wave profiles. Thus, the shape of the breaking wave can be determined during surfing reef design.

Chapter 7 is a peer-reviewed paper published in the Coastal Management Journal (Vol. 27(4): 355-365). The final objective of this thesis is to produce an artificial surfing reef, drawing on the knowledge gained from the earlier research here and by others in the ARP. This paper outlines the Assessment of Environmental Effects (AEE) undertaken for the consent application of the multi-purpose offshore reef that is proposed at Mount Maunganui. The paper summarizes studies that were undertaken to specify the physical and biological processes at a proposed reef site, briefly considers reef design and discusses the predicted impacts and monitoring programs planned for the reef. The proposed reef will enable the field-testing and evaluation of previous findings, as well as several other areas of research including coastal protection, amenity enhancement (specifically surfing but also diving, fishing and beach recreation), biological response and social and economic impacts of a multi-purpose reef.

Chapter 8 is a general discussion linking the studies that have been undertaken to advance the incorporation of surfing into multi-purpose artificial reefs. The full process of developing a surfing reef is described, from identifying the shape and function of bathymetric components, through to the production of a resource consent to construct an artificial reef.

Chapter 9 presents the conclusions that were drawn from the related studies in this thesis.

Chapters 3 to 7 of this thesis are co-authored with my supervisor, Professor Kerry Black. While it is a stipulation that all papers written while under supervision must also be contributed to the supervisor (i.e. co-authored with Black), I worked in close association with Prof. Black on all of the co-authored papers in this thesis, with the exception of Chapter 7 which was developed from the Assessment of Environmental Effect reports for Mount Maunganui Reef (Mead *et al.*, 1998) that Prof. Black also co-authored and had input in many different areas. All of the data collection, data analysis and numerical modelling was carried out by Mr. Mead, with Prof. Black providing the numerical models. Simple Fortran programmes used for data correction and wave transformation were written by Mr. Mead, while more complex programmes were written by Prof. Black. The original text was written by Mr. Mead for each paper and in some cases restructured by Prof. Black as a co-author with my direct participation.

Chapter 2

SURFING BREAK SURVEYS

2.1 Introduction

"The main influence on the shape and peel angle of a breaking wave is the underlying bathymetry (Peregrine, 1983; Battjes, 1988). Since the wave shape (Button, 1991; Sayce, 1997; Couriel *et al.*, 1998; Sayce *et al.*, 1999; Mead and Black, 2000c) and peel angle (Walker, 1974a, b; Dally, 1990; Black *et* al., 1997; Hutt, 1997; Hutt *et al.*, 1998; Mead and Black, 1999b) are very important parameters of surfing waves, it is essential to ascertain what it is about the seabed shape of the world's best surfing breaks that consistently produces high-quality surfing waves in order to be able to incorporate such features into multi-purpose offshore reefs.

Even though previous studies of surfing reefs have addressed wave breaking characteristics (Sayce, 1997; Sayce *et al.*, 1999) and wave peel angles (Walker, 1974a, b; Dally, 1989; Hutt, 1997; Hutt *et al.*, 2000), none of these studies were able to consider how these relate to bathymetry in any detail. These two parameters are critical for defining the quality of surfing waves because they define the speed that a surfer must attain to successfully negotiate the wave face (peel angle) and the steepness and 'hollowness' of the breaking wave (breaking intensity). Refraction changes the direction of wave propagation because celerity is dependent on water depth, as is wave breaking. Therefore the bathymetry prior to and during wave breaking will have a major influence on the wave peel angle. Similarly, the gradient of the seabed has the greatest effect on the shape and steepness of the face of a breaking wave (wave height and period to a lesser degree). Consequently, understanding how peel angle and breaking intensity of surfing waves relates to bathymetry is vital to the design of high-quality surfing breaks. In order to investigate the relationships between these parameters, the relevant information first needed to be collected at existing surfing breaks.

Bathymetric surveys, aerial photographs and wave vortex profiles were measured and collected for 28 mostly world-class surfing reefs in New Zealand, Australia, Indonesia, Hawaii, California and Brazil. In order to survey these surfing breaks (sometimes in remote locations), it was necessary to develop a portable surveying system that could easily be taken on international flights. The custom-built system incorporates a Global Positioning System (GPS) and a 30 m depth-range echo sounder. This chapter describes the development of the portable surveying system (nick-named Horatio, after the explorer), the field studies undertaken to compile a database of world-class surfing breaks, and includes a description of the techniques that were used to process the bathymetric data. These data are the basis of the following 4 chapters.

2.2 System Specifications

Specifications of Horatio, the compact, portable, bathymetric surveying system;

- two GeoExplorer® GPS receivers,
    - Horizontal error < 3 m (determined from system tests)
- Simrad Mesotech 807 depth sounder,
    - 200 kHz
    - 10° cone
    - 0.61-30.5 m range
    - Error ± 0.1 m
- data logger/control unit, incorporating a model 5 Tattletale programmable logic chip, and signal processing circuitry,
- four rechargeable 12 V batteries,
- Kinetics™ waterproof case (531 x 328 x 213 mm),
- laptop PC, and,
- communication cable.

In addition, a range of software was used for communicating with Horatio, logging data, and correcting and editing surveys, including,

- software for communicating with GeoExplorer® GPS receivers and Horatio,
  - TxTools© for MS-DOS V. 4.02
  - Pathfinder© V3.00-11
  - Procomm Plus® V. 2.01
- Matlab® m-files for differentially correcting and editing the survey data (Gorman, 1996),
  - Mainshaw.m
  - Inshaw.m
  - Inshawb.m
  - Edshaw.m

An aluminium fitting for fixing the portable surveying system to a variety of boats, was also constructed. The sonar bolts onto the end of a 1m long vertical arm that is connected to a semi-circular support casting with a groove cut through it to allow for the angle of the sonar to be adjusted (Fig. 2.1). By adjusting the angle of the sonar arm (depending on how the survey vessel sits in the water), the angle of the sonar can be kept vertical so that depth soundings are correct.

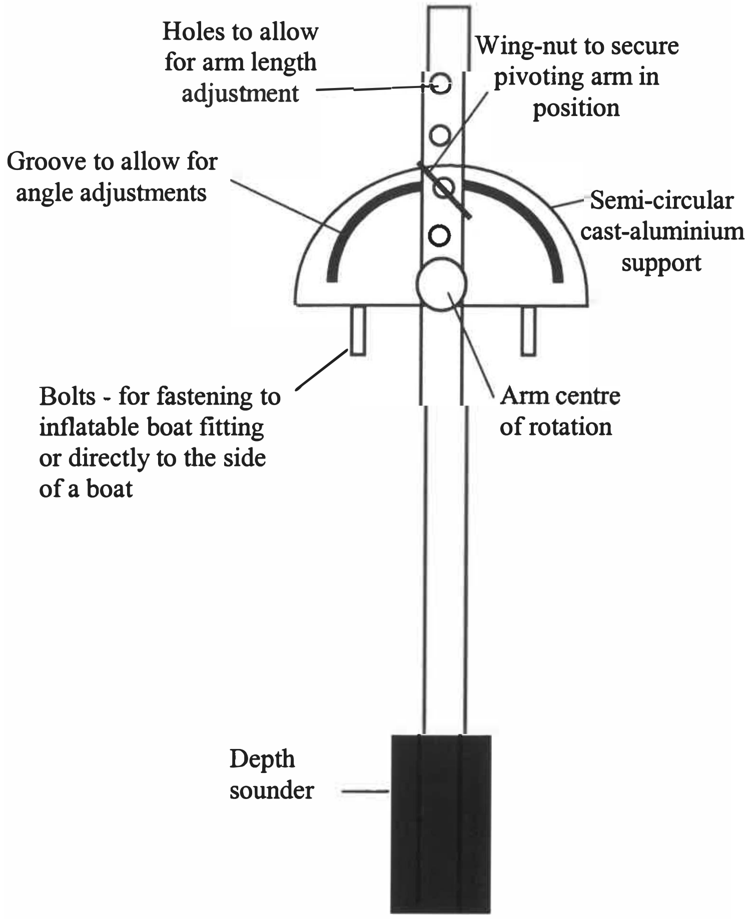


Figure 2.1. Adjustable aluminium fitting to connect the sonar to the surveying vessel.

This fitting can be bolted directly to the side of a boat or to a large curved aluminium plate that is designed to fit over the pontoon of an inflatable boat (such as a zodiac).

2.3 Development of the Portable Surveying System

Although the University of Waikato had equipment that could carry bathymetric surveys, due to the logistics of transporting this equipment and conflicting demands of other users (the system was needed overseas for extended periods), it was necessary to develop a low cost, portable, marine survey equipment. In addition the equipment still needed to provide a high enough degree of accuracy to allow for a good description of reef bathymetry. The concept of a self-contained marine survey system required a compact design that could be transported and operated by a single person without being too large or incurring exorbitant excess baggage charges on international flights.

2.3.1 GPS receivers

In order to independently carry out bathymetric surveys, two GPS receivers were required, one to record the positions of the depth soundings (the Rover), and one to define a static point for differential correction (the Base-station). Differential correction is required to remove the positional errors due to the intentional degradation of the GPS signals available to the public by the US Department of Defence[1]. The degradation feature of the GPS signal, known as Selective Availability (SA), results in a constant shifting of position calculations by a GPS receiver (up to 10's of meters). The base station removes the SA errors by calculating its position from the satellite signals, which is then compared to its known position to calculate the difference. This difference, or correction, is then applied to the rover GPS file to give the corrected survey positions. Differential correction can be applied as a survey is being conducted (real-time) or at a later date (post-processed).

Two hand-held Trimble GeoExplorer® GPS receivers were used to allow for differentially corrected positioning with the portable system. It was decided that survey transects across reefs should be optimally spaced at 10 m intervals to get the appropriate degree of resolution, therefore an error of < 5 m was required. The GeoExplorer® GPS receivers are specified to have an error of 3-5 m, after differential correction, which is within the < 5 m requirement for 10 m spaced survey transects. The tests undertaken to evaluate the error of positioning fixing using the GeoExplorer® GPS receivers during the development of Horatio are described in section 2.4.

[1] Intentional degradation of GPS signals (Selective Availability (SA)), was stopped at midnight 1 May 2000 (US Eastern time). As a result users of GPS are now able to fix positions, without differential correction, up to ten times more accurately than previously.

2.3.2 *Data Logging*

When a GeoExplorer® GPS receiver is used to record base station information, it can internally store data for approximately $1^1/_4$hr when data is collected at the minimum rate required for high accuracy (positions and raw measurements every 5 s). This is too short a time period to carry out a full bathymetry survey, which may take several hours. The actual time available to survey is further reduced because the base station data must extend both before and after the rover file for differential correction, as well as the additional preparation time needed when a survey is conducted by a single person. This limitation was overcome by recording base station data to an external devise, a laptop PC, which greatly increased the data storage capacity (e.g. a 3 hr base station file logged directly to a PC requires ~700Kb of storage space). Procomm Plus® software was used to log the base station data from the GeoExplorer® to a laptop PC.

An external device was also required for the portable surveying system to log data from the roving GeoExplorer® GPS receiver during surveys. The positions from the roving receiver had to be coupled with the readings from the depth sounder (a Simrad Mesotech 807 depth sounder) to produce the undifferentiated XYZ bathymetry file (easting, northing, depth). To achieve simultaneous data recording of these two instruments, a rugged data logger/control unit was designed (J. Radford and K. Black), incorporating a model 5 Tattletale programmable logic chip and signal processing circuitry. The model 5 Tattletale logger has the storage capacity to record bathymetric survey information (time stamp, latitude, longitude, depth) at 1 second intervals for up to 4.5 hours.

Examples of the base station and rover file formats, recorded by the laptop PC and Tattletale logger respectively, are included in Appendix 2.

2.3.3 *Power Supply and Duration*

Various power sources, at various voltages, were required to operate Horatio. These included,

- GeoExplorer® GPS receivers - 12V,
- Simrad Mesotech 807 depth sounder - 24V,
- Model 5 Tattletale programmable logic chip - 12V,
- laptop PC – 110-240V or internal 18V battery.

Four rechargeable 12V batteries were used to power the components of the roving part of the system (GeoExplorer® GPS receiver, depth sounder and data logger/control unit). Two of the batteries were connected in parallel to power the GeoExplorer® GPS receiver and the data logger/control unit. The remaining two batteries were connected in series (equating to 24V) to power the depth sounder.

A GeoExplorer® GPS receiver can run continuously for 15 hrs on two 12V batteries and the data logger/control unit requires only a small amount of power. The two batteries in series could power the depth sounder for at least 12 hrs (J. Radford, pers. comm.). Therefore, with fully charged batteries, the roving part of the system can operate for up to 12 hrs continuously, although surveys of greater than 4.5 hrs cannot be stored on the Tattletale logger and so data must be downloaded during a survey if a longer duration is required.

The laptop PC and GeoExplorer® GPS receiver that collect the base station file can be run by either battery power or off a mains power supply. Depending on the model of the laptop PC, 1.5 to 6 hrs internal battery life is available. The GeoExplorer® GPS receiver connected to a rechargeable 12 V battery can run continuously for 7.5 hrs. If an inverter is connected to a car battery (e.g. using a plug-in adapter in the cigarette lighter socket), both laptop PC and GeoExplorer® GPS receiver (connected via a battery charger) can run for over 24 hrs continuously (J. Radford, pers. comm.). If mains power supply is used to power both laptop PC and GeoExplorer® GPS receiver (connected via a battery charger), the only limitation on running time is storage space on the laptop PC (~233Kb/hr). Thus, the base station set-up can operate for from 1.5 hrs to several days, depending on the power source.

2.3.4 *System Containment*

A Kinetic™ waterproof case was used to protect, contain and waterproof the roving GeoExplorer® GPS receiver, the data logger/control unit and the power supply (4 x 12V rechargeable batteries) of the portable surveying system. The GeoExplorer® GPS receiver is able to receive satellite signals through the high-density plastic of the waterproof case, and so could be contained within the case for protection. Some modifications to the waterproof case were needed to allow for operation and connection of the depth sounder.

A waterproof plug was inserted into the back of the waterproof case to connect the depth sounder. The depth sounder connection included 7 m of cable between the case and transducer to allow for attachment to a variety of survey vessels during surveying and calibration. Two switches and a yellow light emitting diode (LED) were inserted into the front of the waterproof case. One switch was for the power supply (on/off), the other to start/stop data logging. The LED was included as an indicator of logging/not logging of data, with respect to satellite availability. Even if the logging switch is turned to the start position, if there are not enough satellites overhead to get an accurate position fix, positional data is not logged to the Tattletale logger chip. A flashing light indicates not logging and a steady light indicates logging.

Foam blocks inside the waterproof case were fashioned to allow all the components of the roving part of the system to be constrained to prevent damage. During transport the depth sounder and cable could also be fitted into the case.

Once the self-contained marine survey system was completed further field-testing was undertaken to confirm its accuracy and versatility.

2.3.5 *Operating Horatio*

There are three main components of a bathymetric survey using Horatio,

- depth sounder calibration,

- the base station, and,
- the survey.

The precise steps that describe the order of events for each of the three survey components are detailed in Appendix 3. A brief description of depth sounder calibration is given below.

2.4 System Tests and Depth Sounder Calibration

To ensure that the system could achieve at least the desired degree of horizontal position fixing accuracy (< 5 m error), a series of tests were undertaken. The GeoExplorer® GPS receivers were initially tested by themselves (i.e. not incorporated into the system), and then later, tests of the horizontal accuracy of the complete system were carried out.

2.4.1 GeoExplorer® Error

For the first series of tests, a 30 x 30 m grid (10 m unit squares) was marked out on the low tide sand flats at Raglan Harbour entrance (Fig. 2.2). One GeoExplorer® was walked around the grid (the rover) to record the dimensions of the grid, while the other was left stationary nearby to record a base station file. The survey system was to be used to measure the seabed shape at surfing sites, therefore, the most important type of error was the relative error. The relative error is defined as the difference between the recorded rover position and its position relative to the base station; the absolute position of reefs with reference to an appropriate survey datum was not required. For these preliminary tests, the base station position was estimated by averaging the positions in the base station file.

Three to five different routes were walked along the edges of the 9 cells of the 30 x 30 m grid. Once the rover files had been differentially corrected with the associated PathFinder© software, the various routes (files) were overlaid (Fig. 2.2). This allowed visual comparison of routes taken as well as accurate measurement of grid cells using the 'measure' function of the PathFinder© software. This test was repeated three times.

Visual comparison and measurements of the cell dimensions of the 30 x 30 m grid found that the errors were less than 3 m (better than the manufacturers specifications). When a 30 x 30 m grid was overlaid on the test survey results (as in Fig. 2.2), it was found that in the majority of cases errors were sub-meter. However, there was no way of knowing the exact position of the grid in comparison to the positions recorded (the grid was fitted by eye), and so another type of test was also undertaken.

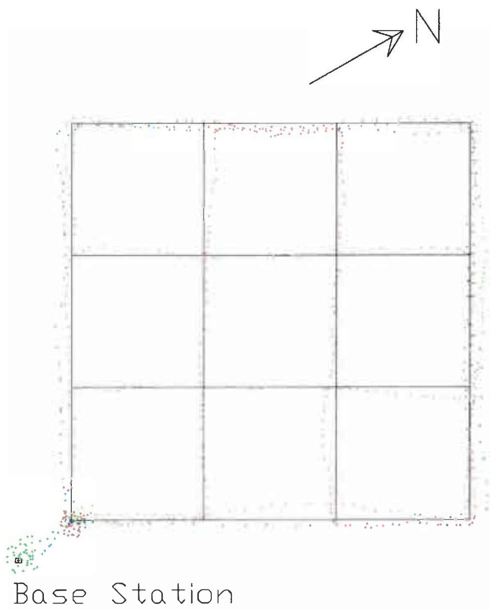


Figure 2.2. Results of three different routes (differentially corrected) around a 30 x 30 m grid (single cells 10 x 10 m) marked out on the sand flats at Raglan Harbour entrance.

The second test involved keeping the rover GeoExplorer® GPS receiver stationary for 10 mins (recording positions every 1 s) and then differentially correcting the data files and measuring the scatter. This test was performed 5 times in 3 different locations.

In every case, the corrected data points were found to be tightly clumped. Measurement of the longest axes of the data scatter for each point found that, in all cases, the greatest separation between recorded positions was less than 3 m. Therefore, if the worst-case scenario is taken as the actual position of the stationary point being located at the end of the major axis of a scatter, the errors are < 3 m. Point measures in the field that were recorded using the two GeoExplorer® receivers alone (i.e. not incorporated into the surveying system), as in the tests described above, confirmed that the relative error was always less than 3 m (Fig. 2.3). It should again be noted that these are a measure of the relative position and not the absolute position in relation to a specified datum.

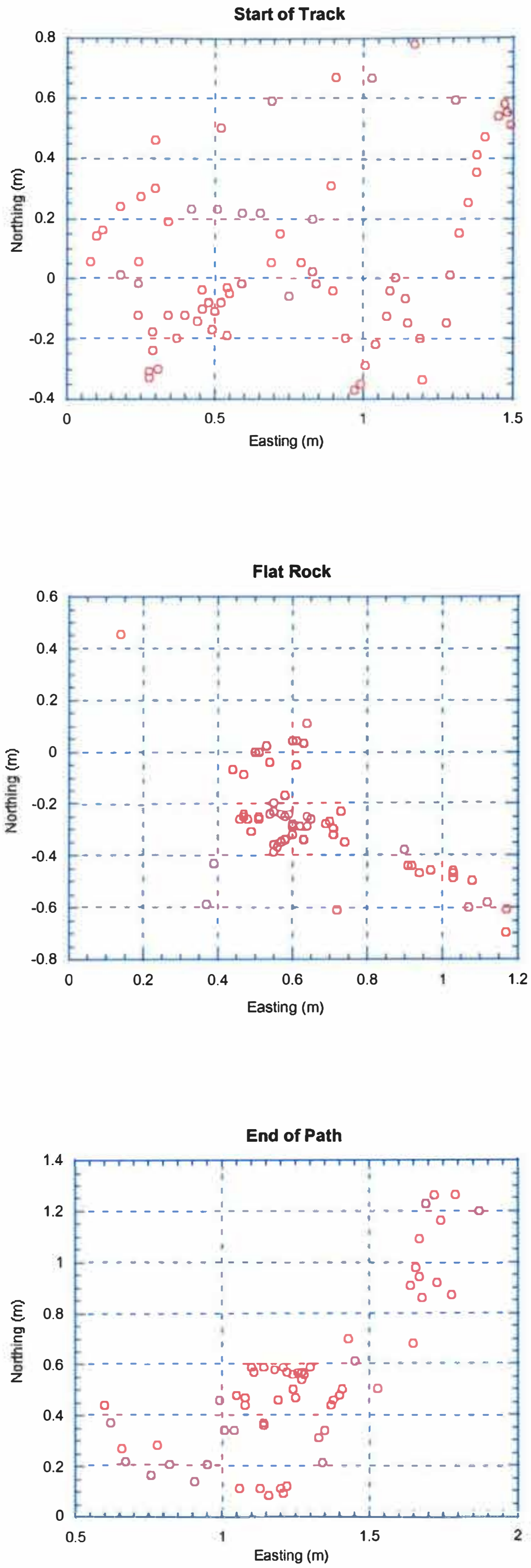


Figure 2.3. Spread of GPS point fixes of shoreline points at Angourie, New South Wales Australia.

The results from these preliminary tests indicated that the relative error when two GeoExplorer® GPS receivers were used together was low enough to be able to incorporate them into a portable surveying system. Similar tests to those described above were repeated using markings on the playing fields at the University of Waikato during the development of the system as different components were added. In all cases, the results found errors of at least similar and often better than those of the preliminary tests with the GeoExplorer® GPS receivers alone.

2.4.2 *Full System Tests*

Once the system was constructed, two types of error were considered: (1) the relative error between the base station and the rover, and (2) the absolute error of the base station position. As described above, for the purpose of the surfing break bathymetry surveys the most important type of error is the relative error, that is, the difference between the recorded rover position and its true position relative to the base station. Because it was the topographical features of the bathymetry at surfing sites that were required, the absolute position was not important. Even though the absolute position of the surveys (relative to a survey datum) was not imperative, tests were carried out to determine how well the estimated base station positions fit to their absolute positions for future reference.

To investigate the error of the rover relative to the base station position, rover data were recorded at a stationary point and then differentially corrected. This test was repeated four times. The corrected data points showed only a small degree of scatter, as described in Section 2.4.1 when the error of the GeoExplorer® GPS receivers was tested alone. Errors of < 1 m were commonly achieved, with the majority (> 90%) lying between 0 to 0.7 m (Fig. 2.4), well below the requirement of < 5 m.

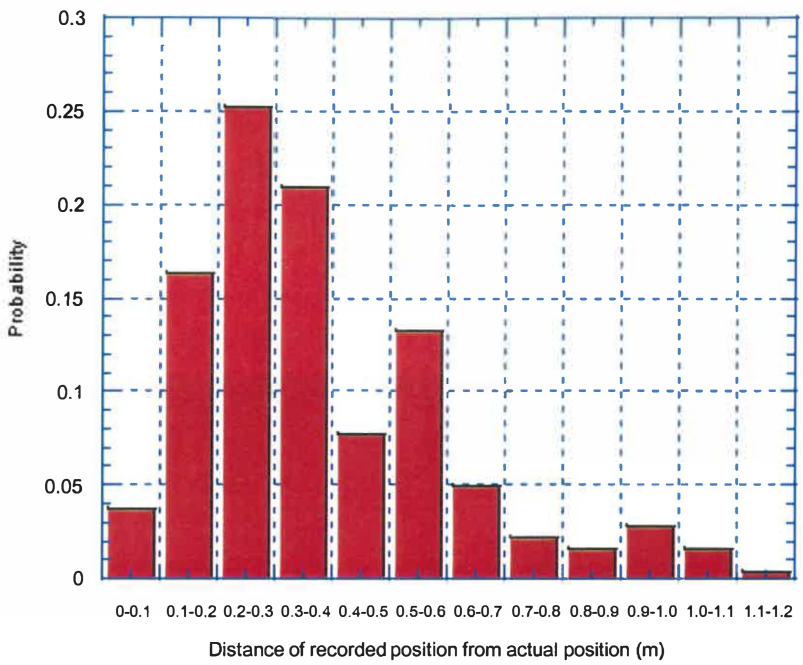


Figure 2.4. The distance of the recorded positions from 4 known positions. n = 336, mean = 0.38 m (st. dev. = 0.23), mode = 0.35 m, median = 0.33 m.

To determine the apparent error in estimating base station position by averaging the base station file after a survey, tests were carried out where base station data files were recorded at known surveyed co-ordinates. The GeoExplorer® GPS receiver, connected to the laptop PC, was placed at a known survey position at Manu Bay, Raglan (596707.55 m N, 306348.22 m E – Mount Eden Grid), and two base station files of 1.5 hrs duration were recorded. The time interval of 1.5 hrs was decided on because it approximated the duration of the smallest bathymetric survey. When these base station files were averaged and compared to the known survey position it was found that estimated positions were accurate to within 2 m.

To fully test the complete system, the University of Waikato swimming pool was utilised. This had several advantages including,

- known and easily measurable depths,

- known and easily measurable pool dimensions (and associated pool bottom markings),
- the close proximity of the Department of Earth Sciences (for liaison with technical support),
- easy access, and,
- a power supply.

Tests were carried out with the system inside an inflatable kayak and attached to a drogue-like raft (Plate. 2.1).

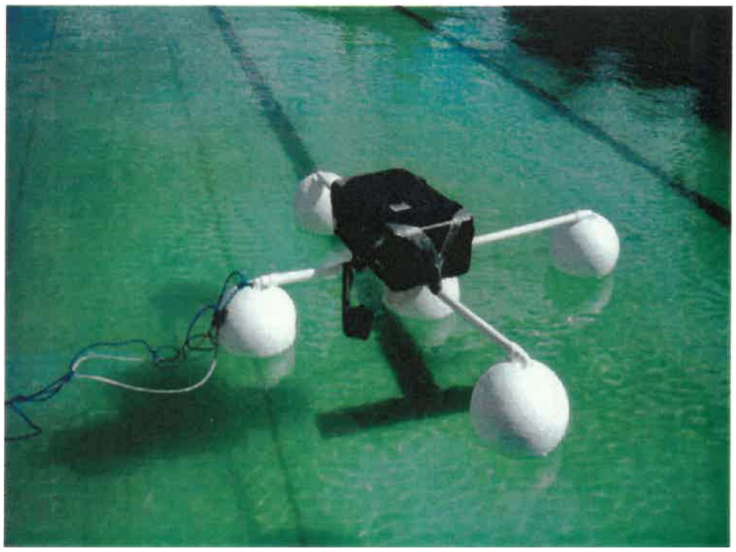


Plate 2.1. Horatio, the portable surveying system, attached to a drogue-like raft during equipment testing in the University of Waikato swimming pool.

Test surveys at the University swimming pool confirmed the survey accuracy found with the earlier tests and included depth readings that were within ±0.1 m of manually measured pool depths.

The accuracy achieved during the testing was better than that specified for the system to be successful (< 5 m), therefore Horatio could confidently be used to conduct the bathymetric surveys of world-class surfing breaks.

2.4.3 Depth Sounder Calibration

Water temperature, salinity and air pressure can all effect depth sounder measurements, therefore, it was important to calibrate the depth sounder prior to surveying. This was achieved via an inbuilt calibration function in Horatio (which is set-up to log directly to the laptop PC[2]) and requires a tape measure and a drop off into water of less than 7 m deep (e.g. a jetty).

The sounder was lowered into the water until it rested on the bottom. Voltages were then recorded from the laptop PC at 0.5 m intervals as it was brought to the surface. Voltages were next plotted against depths to produce a calibration curve and a linear trend line was fitted (Fig. 2.5). The multiplier and offset from the equation that described the association between voltage and depth are then input into Horatio prior to surveying (Appendices 2 and 3).

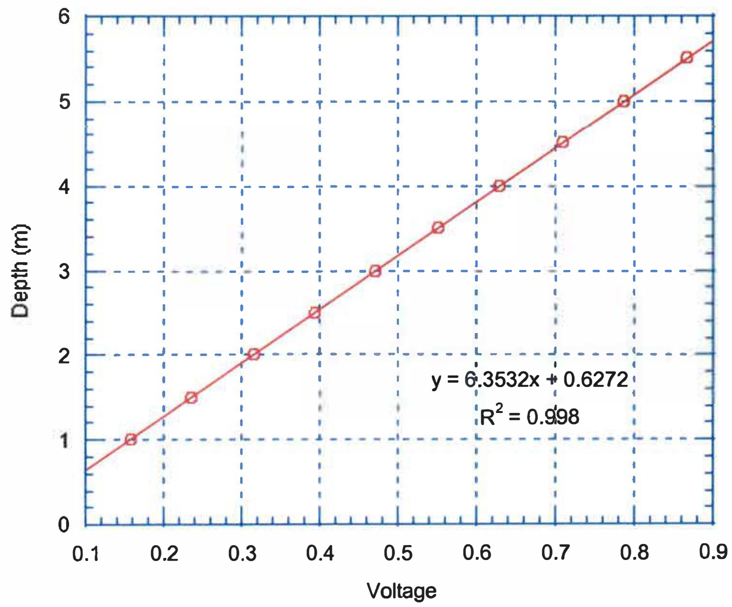


Figure 2.5. The results of a typical depth sounder calibration (multiplier = 6.3532, offset = 0.998).

[2] A Toshiba Satellite™ T2130CS laptop PC with a 486 processor was used during all fieldwork. Tattletale communication problems may arise using a laptop PC of faster processing speed.

2.5 Survey Sites

The bathymetric surveys of mostly world-class surfing breaks were conducted between September 1997 and November 1998. Surveys were conducted in several different countries including New Zealand, Australia, Indonesia, Hawaii, California and Brazil (Fig. 2.6).

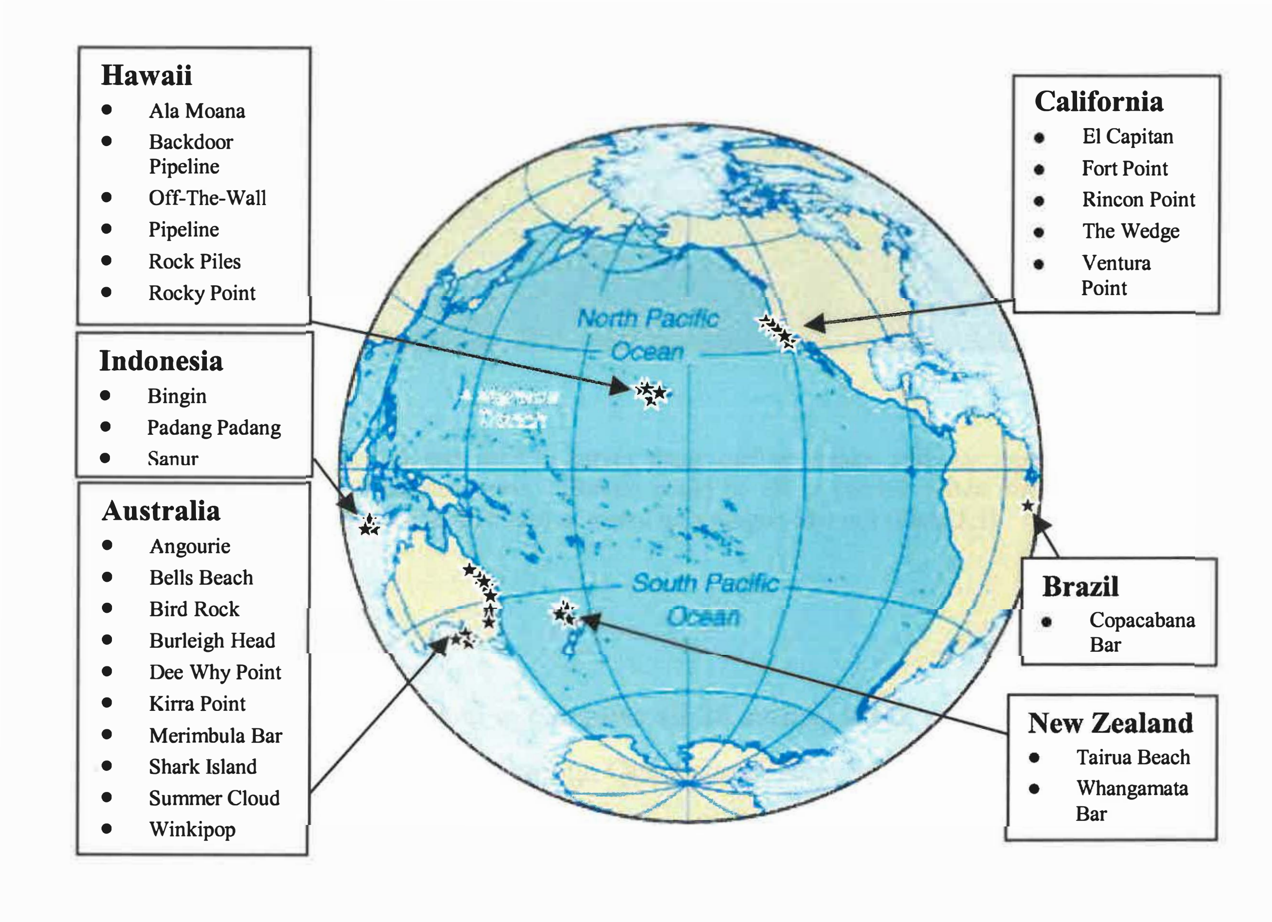


Figure 2.6. Location map of surfing break surveys – indicated by ★. (Pacific Map from www.maps.com)

The survey sites cover the geomorphic categories of coral reefs, rocky reefs, point breaks, rock ledges, river and estuarine deltas and sand beaches. Surveys were conducted using a variety of survey vessels including an inflatable kayak (Plate 2.2), a zodiac, a small fishing boat and a wet-bike. Table 2.1 lists the names, locations, base station position, survey vessel used and type of the surfing breaks surveyed.

Plate 2.2. An inflatable kayak was used to survey many surfing breaks, and was especially useful for surveying breaks in isolated areas. Horatio could be either carried within the kayak (with the depth sounder connected to the stern) or towed on a drogue-like raft (Plate 2.1).

Three separate trips were taken to complete all 28 surfing break surveys. The first trip was to Bali, Indonesia, and then through Queensland, New South Wales and Victoria in Australia, during September and November of 1997. The second trip included the North Shore and South Shore of Hawaii (April, 1998), California (May/June, 1998), Rio de Janeiro in Brazil (June, 1998) and Tahiti (June, 1998). No surveys were undertaken in Tahiti due to large swell conditions for the one-week duration of the visit (unfortunately the wind direction was onshore and so the conditions were also unfavourable for surfing). Finally, Queensland, New South Wales and Victoria in Australia were revisited in November, 1998.

Some surveys were not attempted (e.g. Waimea Bay in Hawaii, Glenewes at Port Lonsdale in Australia, Trestles in California). However, this was not due to bad access, but swell conditions that exceed a safe height. The trips were mostly timed for periods of low swell, and so even if there was swell at a particular spot, after a few days waiting period, a survey could be undertaken. In some cases surveys were undertaken during small swell conditions and video footage was used for heave compensation (Section 2.7.2).

Table 2.1. Survey locations, base station positions, survey vessel used and break type of surfing reef. Table 3.1 presents the base station position and datum used for each survey.

Break Name	Country	Vessel	Break Type
Ala Moana	Hawaii (Oahu)	Kayak	Coral/rocky reef
Angourie	Australia (New South Wales)	Kayak	Rocky point break
Backdoor Pipeline	Hawaii (Oahu)	Kayak	Coral/rock reef
Bells Beach	Australia (Victoria)	Zodiac	Rocky point break
Bingin	Indonesia (Bali)	Kayak	Coral reef
Bird Rock	Australia (Victoria)	Kayak	Rock ledge
Burleigh Heads	Australia (Queensland)	Kayak	Rock/sand point
Copacabana Bar	Brazil (Rio de Janeiro)	Small Boat	Beach break
Dee Why Point	Australia (New South Wales)	Zodiac	Rocky reef
El Capitan	USA (California)	Kayak	Rock/sand point
Fort Point	USA (California)	Kayak	Rocky point break
Kirra Point	Australia (Queensland)	Kayak	Rock/sand point
Merimbula Bar	Australia (New South Wales)	Zodiac	Estuary bar break
Off-The-Wall	Hawaii (Oahu)	Kayak	Coral/rock reef
Padang Padang	Indonesia (Bali)	Kayak	Coral reef
Pipeline	Hawaii (Oahu)	Kayak	Coral/rock reef
Rincon	USA (California)	Kayak	Rocky point break
Rock Piles	Hawaii (Oahu)	Kayak	Coral/rock reef
Rocky Point	Hawaii (Oahu)	Kayak	Coral/rock reef
Sanur	Indonesia (Bali)	Kayak	Coral reef
Shark Island	Australia (New South Wales)	Kayak	Rocky reef
Summer Cloud	Australia (New South Wales)	Zodiac	Rocky reef
Tairua	New Zealand (Coromandel)	Wet-bike	Beach break
The Wedge	USA (California)	Kayak	Beach break
Ventura Point	USA (California)	Kayak	Rocky point break
Whangamata Bar	New Zealand (Coromandel)	Wet-bike	Estuary bar break
Winkipop	Australia (Victoria)	Zodiac	Rocky point break

2.6 Survey Technique

Surveys were undertaken at, or near, high tide in low swell conditions. The detailed protocol described in Section 2.4 was followed to calibrate the depth sounder, and to set-up the base station and Horatio. In addition, a Dobie pressure sensor (developed at the Centre of Excellence) was used to record tidal changes during surveys (Section 2.7.3). Local air pressure and tide data were also collected (where possible) to correct pressure readings, and reduce survey data to lowest astronomical tide (LAT). To subsequently examine depth errors associated with the lifting of the survey vessel by passing waves, a land-based video camera, that was time synchronised with Horatio, was used to record the vessel throughout the survey.

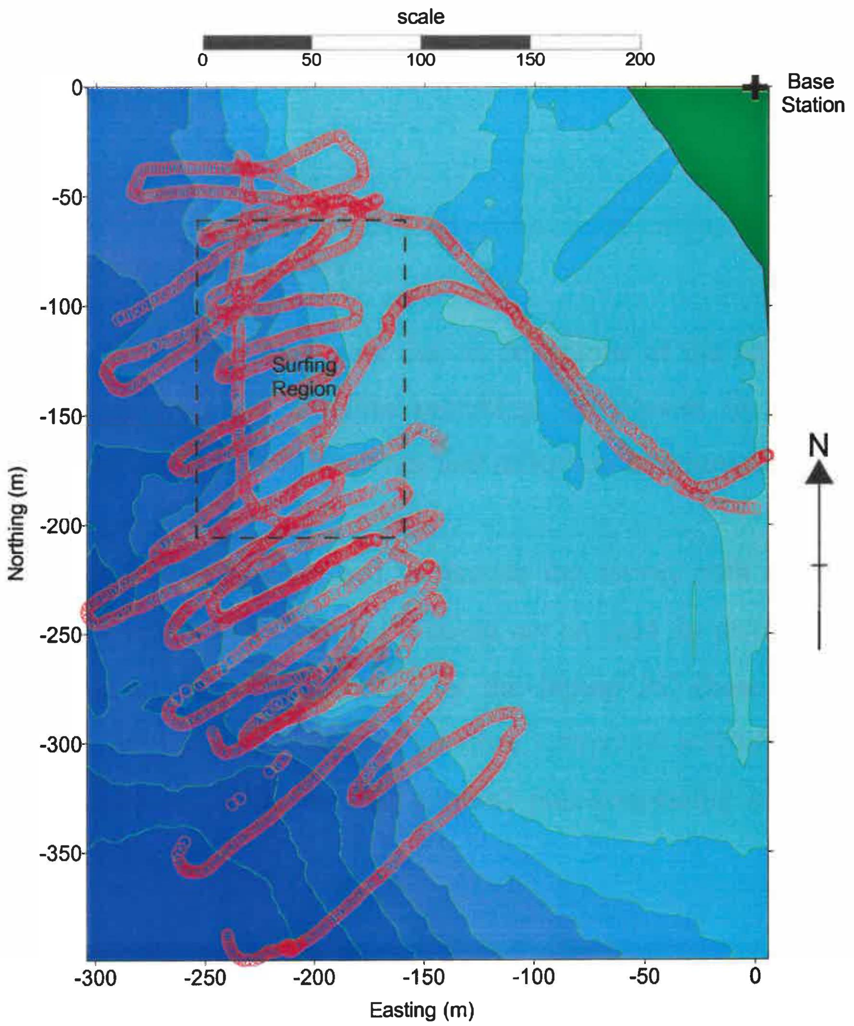


Figure 2.7. Contour map of Bingin Reef, Indonesia, showing the corrected survey run-lines in red. Surveyed 23/9/96 – northings and eastings relative to base station.

Surveys were conducted in transects approximately normal to the isobaths so that the seabed gradient could be measured with greater accuracy (e.g. Fig. 2.7). Survey duration ranged from 1.5 to 4 hours, and several surveys were repeated 2-3 times to increase the resolution. All surveys were conducted with recording intervals set at 1 s to maximise resolution.

2.7 Survey Data Correction

Post-processing of the survey data allowed accurate and reliable contour maps of each break to be produced. The data files for each surfing break required,

- survey path correction,
- tidal correction, and,
- correction for errors produced by surveying over swells and white water (heave compensation).

2.7.1 Positional Corrections

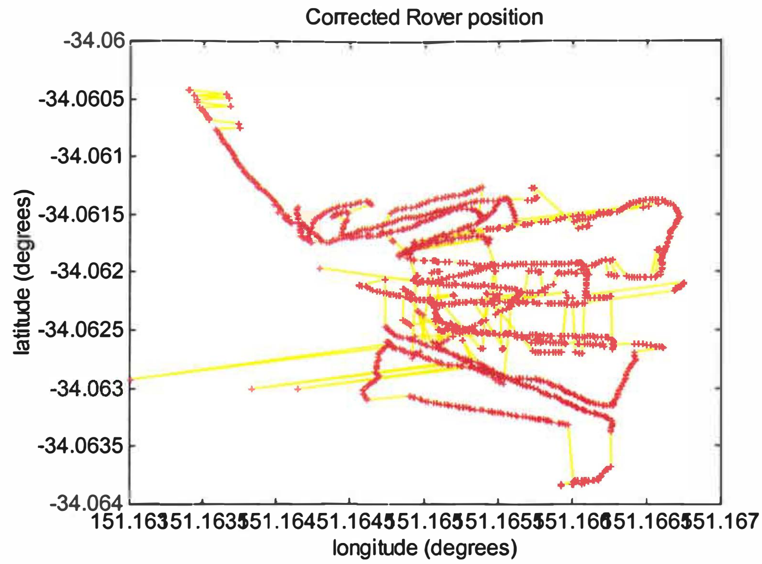
The largest errors in the data files were due to deviations of the survey path. These errors are associated with SA, satellite switching, differences in satellite selection between the base station and rover receivers, and reflection interference.

Differential correction was first applied to remove the survey path errors due to SA. The manufacturer's software (PathFinder©) could not be used for differential correction because the format of the data recorded by the laptop PC (base station) and the Tattletale logger (rover) was unsuitable. Therefore, correction software was developed, using Matlab® interactive software, that allowed post-processing of the survey data (Gorman, 1996).

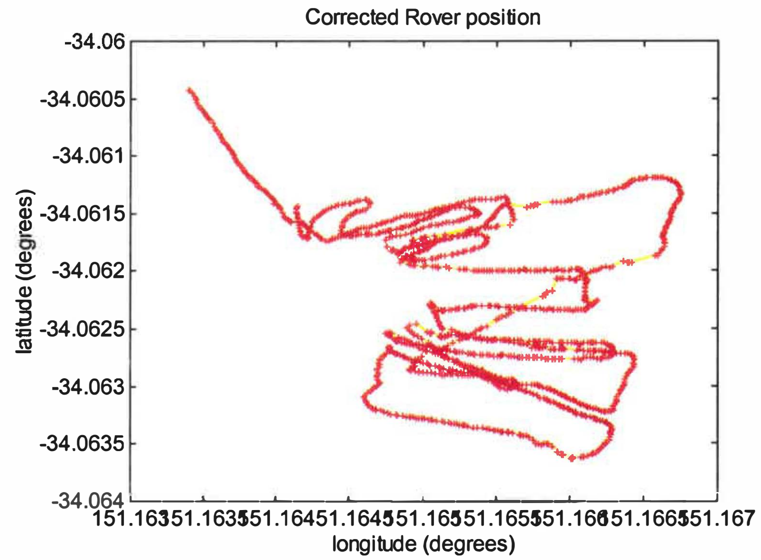
Rover data files and the associated base station data files were first edited using Microsoft Excel©. This involved 'trimming' the rover data files so that they were within the time limits of the base station data files and removing any remnant data entries where no positional information had been recorded. At this stage, the depth of the sonar transducer below the water surface was also removed from the depth records. The rover data files were corrected using MAINSHAW (Gorman, 1996) to produce log-files containing a time stamp, the corrected position and an associated depth (time, X, Y, Z) (Appendix 2). The next step was to remove path errors not caused by SA.

Satellite switching errors resulted in intermittent positional changes in the corrected survey data (Fig. 2.8a). GeoExplorer® GPS receivers can only track 6 satellites simultaneously, 4 of which are used to calculate the position. Up to 12 satellites are overhead at any one time, and more than 16 may be visible during a 4 hour survey period. The GeoExplorer® GPS receiver selects the satellites it will use to calculate its position based on the constellation of satellites that will give the highest degree of precision (Hurn, 1993). As satellites move through the sky on different trajectories, the constellations are constantly changing and the GPS receivers respond by shifting to the best constellations as they become available. In some instances, especially when the base station had a visible horizon that differed from that in the area being surveyed, the rover receiver calculated its position using a different set of satellites than the base station receiver. This resulted in survey points that were offset from the rest of the survey path - either single points (spikes) or several points together (Fig. 2.8a). This problem was exasperated by reflection of satellite signals from the sea surface (i.e. multi-path errors - Hurn, 1993), as well as the tilting of the GPS receiver due to small wave action (Z. Urbanski, pers. comm.). The drogue-like raft (Plate. 2.1) was used to minimise the tilting due to small wave action.

Some switching between satellites could be avoided by 'disarming' satellites that were not required during a survey, even though they were in position overhead. This was achieved prior to surveying using QuickPlan© software to distinguish the satellite constellations that would give the most precise positions out of all the visible satellites during the planned survey time and also be visible at both the survey and base station locations. However, due to the constantly changing satellite constellations, up to 8 satellites were required for a full survey and so some satellite switching could still occur.



A. Section of a differentially corrected bathymetric survey prior to survey path corrections.



B. Section of a differentially corrected bathymetric survey after survey path corrections.

Figure 2.8. Examples of differentially corrected bathymetric surveys before and after editing using the Matlab® program EDSHAW.

Positional errors in the differentially corrected data due to satellite switching and reflection were removed using Matlab® software. The log-file output from the Matlab® program MAINSHAW was read into an editing program EDSHAW (Gorman, 1996), so that deviations in the survey path could be deleted or, if the displacements were consistent, relocated (Fig. 2.8b). In most cases, log-files were divided into pieces prior to editing in EDSHAW to lessen the confusion of hundreds of survey points.

2.7.2 *Heave Compensation*

Once errors in the survey path had been corrected or removed, depth errors were then deleted. These errors were mainly due to passing over small waves during a survey. Some of these errors were obvious; when the sonar was lifted out of the water the depths recorded were at the maximum range (30.5 m). Other more subtle errors were removed by scrolling through the video records of surveys and deleting data points recorded while passing over small waves.

Prior to tidal correction, the survey data were converted from latitude and longitude coordinates to a metric grid. This was accomplished using a Fortran program (AMG – Black, pers. comm.) that uses the world metric grid system and also creates an additional set of co-ordinates that sets the base station position as the origin (i.e. 0, 0) (Appendix 2).

2.7.3 *Tidal Correction*

The magnitude of tidal change over most surveys was relatively minor (0.01 - 0.3 m). For the majority of surveys tidal changes were recorded using a Dobie pressure sensor. The Dobie was programmed to record water depth at a frequency of 2 Hz and deployed prior to each survey. Where possible the Dobie was deployed for a full day to check the synchrony between tide tables of a break and the actual tide. The pressure sensor data were corrected for atmospheric deviation and then averaged at 15 minute intervals to produce a tidal curve using a Fortran program (DOBIE – Black, pers. comm.). Tide tables were then used to reduce the pressure sensor data to LAT at each site.

Tidal corrections were applied to each survey log-file using a Fortran program (TIDE - Black, pers. comm.). This program applies a tidal data file produced from the reduction of the Dobie data (Appendix 2) to tidally correct the survey log-file and produce an output file. This output file contains the time stamp, easting, northing, tidally corrected depth, smoothed depth and relative gradient (between the number of points chosen) of each surveyed depth (Appendix 2).

In some early Australian surveys, tidal data were not recorded due to the loss of the pressure sensor after its third deployment in Bali, Indonesia (October 1996). For these surveys tidal curves were generated using accurate tide tables and a simple Fortran program (COSTIDE4 – Mead, unpub.), which generated sinusoidal tidal curves from the high and low tide elevations and times. These tidal curves were then used to create tidal data files (Appendix 2) to tidally correct the log-files from the early Australian bathymetry surveys.

The output files from the Fortran program TIDE were then used to create depth contour maps and bathymetry grids using the software package Surfer© (Fig. 2.7). These depth contour maps and bathymetric grids were then used to investigate how the seabed features at world-class surfing breaks consistently produce high-quality surfing waves. Identification of the form and function of the bathymetric features that comprise world-class surfing breaks is described in following chapters.

2.8 Aerial Photographs and Wave Vortex Profiles

Aerial photographs/videos and wave vortex profile photographs/videos were collected at most of the surfing breaks surveyed. Aerial photographs/video were used to measure wave peel angles (Walker, 1974a, b; Dally, 1989; Hutt, 1997) and the shape of the breaking wave vortex, or tube shape, was used to measure wave vortex parameters (Longuet-Higgins 1981; Sayce, 1997; Sayce *et al.*, 1999; Couriel, *et al.*, 1998).

Existing aerial photographs were collected from a variety of sources including, local and regional Councils, commercial aerial surveyors and published books (e.g. Readers Digest, 1986). In a few cases, flights were chartered and video and photographs were taken above breaks during surfable swell (Plate 2.3)

Plate 2.3. The author about to depart in a chartered Tiger Moth to take aerial photographs and video of Bells Beach and Winkipop in Victoria, Australia.

Images of wave vortex profiles (i.e. looking crest parallel into the breaking curve of the wave) were collected at the surfing breaks using two methods; *in situ* video recording and scanning of images from surfing magazines. During the site visits to survey the bathymetry of the surfing breaks, there were sometimes opportunities to video waves breaking from a crest parallel position using a video camera in a waterproof housing. In these cases, GPS positions of the breaking waves were also recorded using a GeoExplorer® GPS receiver in a plastic waterproof camera-case. This allowed for a precise location of the seabed gradient that the waves were breaking on to be determined from the bathymetric grids. However, the field surveys were timed to coincide with periods of low swell conditions to enable the bathymetric surveys to be undertaken. As a consequence, many surfing locations did not break during site visits, and so video of the breaking waves could not be recorded. Instead, photographs from a range of national and international surfing magazines were utilised.

Landmarks identified from aerial photographs were also surveyed at each break using the hand-held GeoExplorer® GPS receivers, so that the positions of breaking waves in the aerial photographs could be related back to the survey bathymetry. Wave peel angles and the relationship between the seabed gradient and the vortex shape of a breaking wave are described in later chapters.

2.9 Summary

In order to discover the properties of world-class surfing breaks that results in them consistently producing high-quality surfing waves, their bathymetries first had to be measured. A compact and portable, self-contained marine surveying system, nick-named Horatio, was developed for this task. A range of field tests demonstrated that the system was able to fix positions with a horizontal error of less than 3 m. 28 mostly world-class surfing breaks were surveyed in total. These breaks are located in New Zealand, Australia, Indonesia, Hawaii, California and Brazil, and include the geomorphic categories of coral reefs, rocky reefs, point breaks, rock ledges, river and estuarine deltas and sand beaches.

Once the bathymetric surveys were corrected (differential, survey path deviations, heave compensation and tidal change), depth contour maps and bathymetry grids were created. These are used in later chapters to identify the form and function of the bathymetric features that comprise world-class surfing breaks, so that similar features can be incorporated into multi-purpose reef design to enhance the amenity value by the addition of surfing. Together with aerial photographs and wave vortex information, these data represent the first ever set of world-class surfing break surveys that cover a full range of geomorphic categories.

Chapter 3

FIELD STUDIES LEADING TO THE BATHYMETRIC CLASSIFICATION OF WORLD-CLASS SURFING BREAKS

Journal of Coastal Research, Special Surfing Issue (Accepted)

Field Studies Leading to the Bathymetric Classification of World-Class Surfing Breaks

Shaw Mead† and Kerry Black‡

†Coastal Marine Group, Department of Earth Sciences. University of Waikato & Private Bag 3105, Hamilton, New Zealand

‡ASR Ltd. PO Box 13048, Hamilton, New Zealand

s.mead@asrltd.co.nz, k.black@asrltd.co.nz

ABSTRACT

Bathymetries of world-class surfing breaks were measured in order to understand seabed morphologies that produce high-quality surfing waves. Bathymetry surveys were carried out using a custom-built, portable, surveying system that was developed to enable highly accurate surfing reef surveys at remote sites worldwide. Along with peel angle and wave vortex information, the bathymetric surveys of 34 surfing locations constitute the first international database of world-class surfing breaks. A full geomorphic range was recorded that included coral reefs, rocky reefs, point breaks, rock ledges, river and estuarine deltas and sand beaches. Analysis of these bathymetries revealed meso-scale surfing reef geomorphic components that were classified as ramp, platform, wedge, ledge, focus, ridge and pinnacle, which constitute and account for the quality of world-class surfing reefs. Their function in relation to wave refraction and wave breaking is considered.

ADDITIONAL INDEX WORDS: *bathymetry surveys, reef components, refraction*

INTRODUCTION

High-quality surfing waves constitute a relatively small fraction of the large variety of wave forms that break on the coastlines of the world. Indeed surfing breaks that consistently produce world-class surfing conditions are rare. In recent years interest in creating artificial surfing breaks has increased in response to demands on the existing breaks due to higher participation in the sport (WALKER *et al.*, 1972; PRATTE, 1987; BUTTON, 1991). PITT (1997) estimates that there are at least 10,000,000 active surfers worldwide and the sport is growing everyday; surfing supports a multi-dollar industry (BARTHOLOMEW, 1997). In addition, the skills of surfers have increased significantly over the past few decades. Average surfers are performing manoeuvres on difficult waves that would have been the domain of professional surfers 15-20 years ago. This has added pressure to usage of world-class surfing breaks and a stronger demand for quality waves. The sport requires high-quality waves to progress.

There is also a growing need for environmentally-sensitive solutions to coastal protection. The amenity value of coastal construction can be greatly enhanced by incorporating multiple-use options such as coastal protection, habitat for marine organisms, surfing, diving, recreational and commercial fishing, boating and swimming safety (BLACK *et al.,* 1997). In the past artificial reefs have been utilised for coastal protection (TOYOSHIMA, 1972; PILARCZYK and ZEIDLER, 1996), ecological restoration (PRATT, 1994), fisheries enhancement (PARKER *et al.*, 1974) and recently, to enhance surfing conditions (PATTIARATCHI, 1997). However, coastal structures with more than one purpose have not been usually considered. The concept of multi-purpose reefs is not new (GRIGG, 1969; WALKER and PALMER, 1971; SILVESTER, 1975), but only now are they being developed (BLACK *et al.*, 1998a; MEAD and BLACK, 1999a).

A specific form of wave breaking is critical for the sport of surfing. Waves must be steep faced to produce high surfboard speed, but not so steep that the waves collapse (BUTTON, 1991; SAYCE, 1997; COURIEL *et al.*, 1998). In addition, waves must 'peel' as they break so that the surfer can utilise the unbroken face of the wave close the breaking part of the wave crest as it translates laterally across the face of the wave (WALKER, 1974a, b; DALLY, 1989; HUTT, 1997). It is the shape of the seabed that has the most influence on the form of breaking waves, determining both wave steepness (BATTJES,

1974; PEREGRINE, 1983; SAYCE, 1997; COURIEL *et al.*, 1998) and peel angle (WALKER, 1974a, b; HUTT, 1997). However, there has been little bathymetric investigation focusing on natural surfing breaks to elucidate how the seabed is shaped to produce waves suitable for surfing (see WALKER, 1974a, b; HUTT, 1997; SAYCE, 1997).

In order to gain an understanding of the optimum seabed morphologies required to produce high-quality surfing waves, it was necessary to measure the bathymetry of existing surfing breaks. This paper describes the fieldwork that was undertaken to produce the first ever database of international surfing break bathymetries across all geomorphologic categories. These new data were used to create bathymetric charts for visual and parametric analysis, and with the aid of numerical refraction modelling (BLACK, 1997), led to the identification and functional descriptions of meso-scale surfing reef components (MEAD and BLACK, this issue). In this paper, specific components are defined and described to develop a classification scheme for meso-scale geomorphic components of surfing reefs.

STUDY SITES AND SURVEY TECHNIQUE

Bathymetric surveys of mostly world-class surfing breaks were conducted between September 1997 and November 1998, in New Zealand, Australia, Indonesia, Hawaii, California and Brazil (Figure 3.1 & Tab. 3.1). The survey sites cover the geomorphic categories of coral reefs, rocky reefs, point breaks, rock ledges, river and estuarine deltas and sand beaches.

Existing surveys of New Zealand surfing breaks were utilised (HUTT, 1997; SAYCE, 1997, BLACK *et al.*, 1998b). However, the majority of surveys were carried out using a compact bathymetric surveying system that utilises satellite positioning (post-processed DGPS) and depth sounding mounted on a variety of vessels (small research boat, zodiac or inflatable ocean kayak) depending on the accessibility of the surfing break.

Nicknamed Horatio, the system utilises a GeoExplorer GPS receiver coupled with a Simrad Mesotech 807 depth sounder (200 kHz, 10° cone, 0.61-30.5 m range, accuracy of ±0.1 m). Data from these two instruments are recorded simultaneously by a rugged logger/control unit, which incorporates a model 5 Tattletale programmable logic chip, and signal processing circuitry. Four rechargeable 12 V batteries power the system, which is housed in a small waterproof case (531 x 328 x 213 mm). An LED mounted on the side of the case indicates surveying status (logging/not logging). The system is either towed on a drogue-like raft (Plate 3.1) or placed on a vessel using an attachment to support the sounder. Horatio is programmed prior to surveys with a portable computer and can record data at 1, 2, 3 or 4-second intervals. All surveys were conducted at 1 s recording intervals for maximum resolution. The depth sounder was calibrated prior to surveying by suspending it at known water depths.

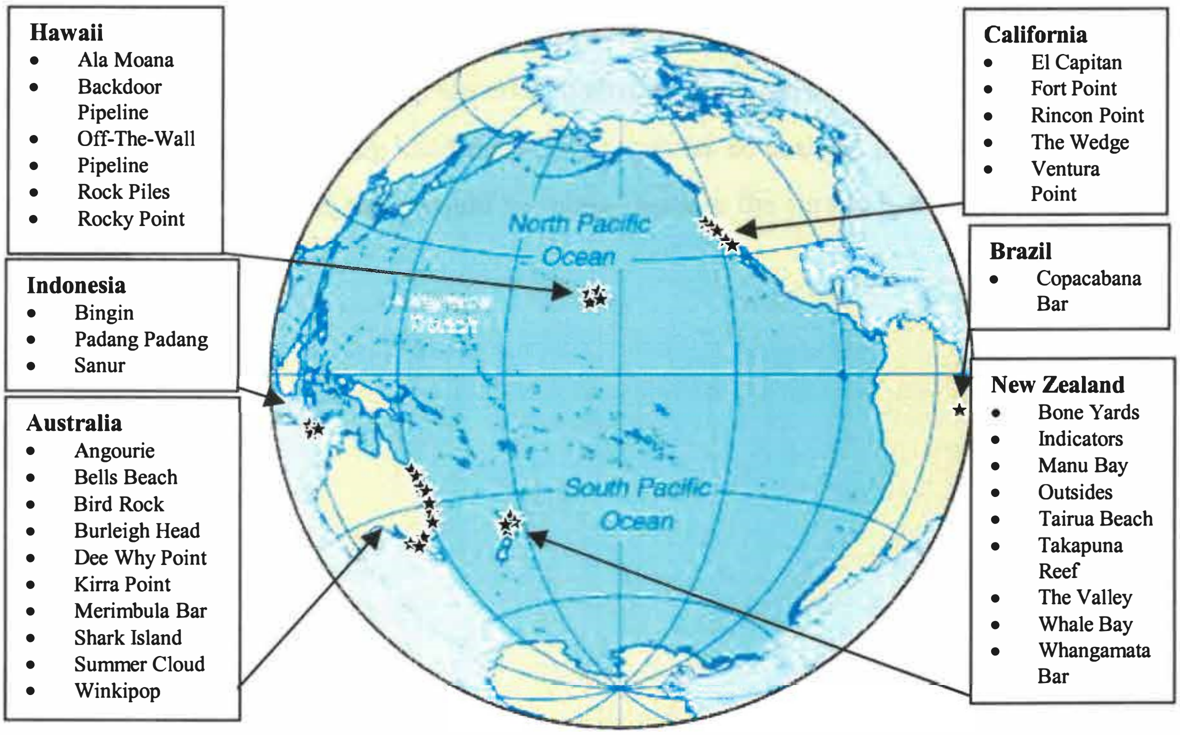


Figure 3.1. Sites of surfing break surveys (represented by ★). (Pacific Map from www.maps.com)

Surveys were undertaken at, or near, high tide in low swell conditions. A portable computer recorded base station data from a GPS receiver for the purpose of differential correction. A Dobie pressure sensor (developed at the Centre of Excellence) was used to record tidal changes during surveys. Local air pressure and tide information were also collected to correct pressure readings and reduce survey data to lowest astronomical tide (LAT). In addition, to subsequently examine depth errors associated with the lifting of the survey vessel by passing waves, a land-based video camera that was time synchronised with the survey system, recorded the vessel throughout the survey. These videos were then scrolled through and at the times when the vessel was lifted by significant waves, the associated depth records were deleted from the survey. Surveys were conducted in transects approximately normal to the isobaths so that the seabed gradient could be measured with greater accuracy. Survey duration ranged from 1.5 to 4 hours; several surveys were repeated 2-3 times to increase the resolution.

Additional information (not presented in this paper) collected at the world-class surfing breaks included aerial photographs to measure the peel angles (Walker, 1974a, b; Dally, 1989; Hutt, 1997) and the shape of the breaking wave vortex (Figure 3.2), to measure wave vortex-shape (Longuet-Higgins 1982; Sayce, 1997; Couriel, *et al.*, 1998; Sayce *et al.*, 1999). Landmarks identified from aerial photographs were also surveyed at each break using hand-held GPS receivers so that the positions of breaking waves in the aerial photographs could be related back to the survey bathymetry.

Plate 3.1. The portable surveying system, known as Horatio. The system is either towed on a drogue-like raft (as shown) or fixed to any type of vessel using a custom-built attachment.

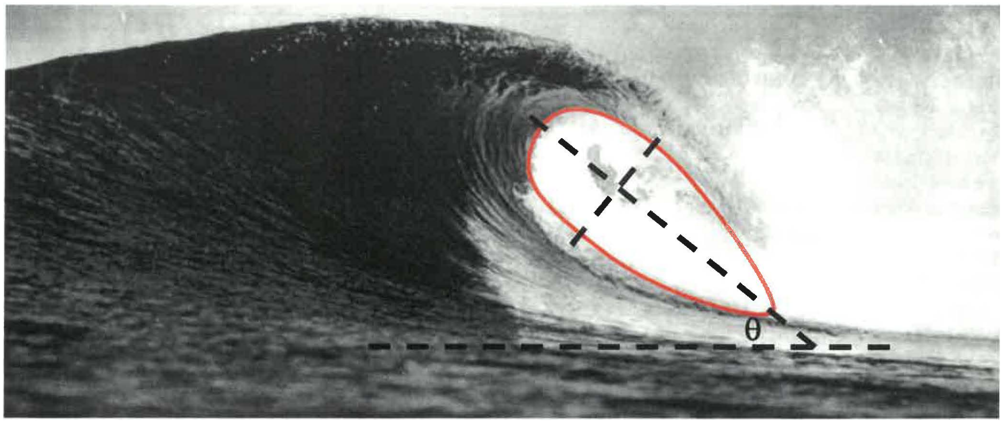


Figure 3.2. Curve fitting is applied to the forward face of a wave and used to calculate the length to width ratio and the vortex (tube) angle (BLACK *et al.*, 1997).

Table 3.1. *Survey locations and base station positions and descriptions.*

Break Name	Country	Datum	Lat. (dec.°)	Long. (dec.°)	Description
Ala Moana	Hawaii (Oahu)	Old Hawaiian, Oahu	21.66711889N	158.0551458W	Centre of circular concrete pile at start of breakwater
Angourie	Australia (New South Wales)	Australian Geodetic 1984	29.4805114S	153.360811E	Centre of top parking space at Spooky's
Backdoor Pipeline	Hawaii (Oahu)	Old Hawaiian, Oahu	21.66794416N	158.0553414W	Pipeline beach site, located from concrete cinder box in Ehukia Park (R041818A)
Bells Beach	Australia (Victoria)	Australian Geodetic 1984	38.36822806S	144.2818244E	Centre of carpark in front of MR plaque
Bingin	Indonesia (Bali)	WGS-84	8.807208611S	115.1147186E	Left corner of wall, at bottom Rondavel on cliff top
Bird Rock	Australia (Victoria)	Australian Geodetic 1984	38.349605S	144.3040672E	Centre of parking space closest to viewing platform
Bone Yards	New Zealand (Raglan)	NZ Geodetic 1949	595314.90N	304039.00E	Top of post at Manu Bay (Hutt 1997)
Burleigh Heads	Australia (Queensland)	Australian Geodetic 1984	27.9266325S	153.4019389E	Southern end of roof peak at 24 Clam St, Runaway Bay
Copacabana Bar	Brazil (Rio de Janeiro)	SAD 69, Brazil IBGE	22.98555139S	43.18777208W	Centre of large concrete pile on end of jetty, Western end of Copacabana Bay
Dee Why Point	Australia (New South Wales)	Australian Geodetic 1984	33.75321325S	151.2969887E	Centre of first carpark on the seaward side of the SLC.
El Capitan	USA (California)	North American 1983	34.45823871N	120.0218226W	Centre of tree stump at end of path across the stream on the point
Fort Point	USA (California)	North American 1983	37.81102016N	122.4766944W	Metal spike in concrete wall at set back of chain railing
Kirra Point	Australia (Queensland)	Australian Geodetic	27.9266325S	153.4019389E	Southern end of roof peak at 24 Clam St.,

		1984			Runaway Bay
Break Name	**Country**	**Datum**	**Lat. (dec.°)**	**Long. (dec.°)**	**Description**
Indicators	New Zealand (Raglan)	NZ Geodetic 1949	595314.90N	304039.00E	Top of post at Manu Bay (Hutt 1997)
Manu Bay	New Zealand (Raglan)	NZ Geodetic 1949	595314.90N	304039.00E	Top of post at Manu Bay (Hutt 1997)
Merimbula Bar	Australia (New South Wales)	Australian Geodetic 1984	36.89755253S	149.91431E	Centre of carpark directly in front of beach access
Off-The-Wall	Hawaii (Oahu)	Old Hawaiian, Oahu	21.66794416N	158.0553414W	Pipeline beach site, located from concrete cinder box in Ehukia Park (R041818A)
Outsides	New Zealand (Raglan)	NZ Geodetic 1949	595314.90N	304039.00E	Top of post at Manu Bay(Hutt 1997)
Padang Padang	Indonesia (Bali)	WGS-84	8.813758888S	115.1038561W	2m back from solid rock in centre of cliff viewing point
Pipeline	Hawaii (Oahu)	Old Hawaiian, Oahu	21.66794416N	158.0553414W	Pipeline beach site, located from concrete cinder box in Ehukia Park (R041818A)
Rincon	USA (California)	N-am. 1983	34.37382498N	119.4750077W	10m normal to property walls, at boundary of brick and plaster wall
Rock Piles	Hawaii (Oahu)	Old Hawaiian, Oahu	21.66794416N	158.0553414W	Pipeline beach site, located from concrete cinder box in Ehukia Park (R041818A)
Rocky Point	Hawaii (Oahu)	Old Hawaiian, Oahu	21.67357567N	158.0492477W	Centre of large lava rock in front of break (photo)
Sanur	Indonesia (Bali)	WGS-84	8.67553060S	115.2644722E	Centre of foot of breakwater at northern end of Sanur
Shark Island	Australia (New South Wales)	Australian Geodetic 1984	34.06154083S	151.1543450E	Western corner of Gerrale St
Summer Cloud	Australia (New South Wales)	Australian Geodetic 1984	35.17211389S	150.691625E	Centre of carpark directly opposite access track
Tairua	New Zealand (Coromandel)	NZ 1949 geodetic	36.98881808S	175.8558933E	Top of second post to the north of the protection fence at the northern beach access
Takapuna	New Zealand (Auckland)	NZ 1949 geodetic	Mount Eden Grid	Mount Eden Grid	Surveyed by the Port of Auckland for a consulting contract
The Valley	New Zealand (Raglan)	NZ Geodetic 1949	595314.90N	304039.00E	Top of post at Manu Bay (Hutt 1997)
The Wedge	USA (California)	N-am. 1983	33.59358059N	117.8813422W	Centre of breakwater adjacent to lifeguards tower
Ventura Point	USA (California)	N-am. 1983	34.27367085N	119.3033811W	Large driftwood located from concrete retaining wall in carpark (R052301C)
Whale Bay	New Zealand (Raglan)	NZ Geodetic 1949	595314.90N	304039.00E	Top of post at Manu Bay (Hutt 1997)
Whangamata Bar	New Zealand (Coromandel)	NZ Geodetic 1949	37.20246348S	175.8788748E	Centre of post at base of sand dune
Winkipop	Australia (Victoria)	Australian Geodetic 1984	38.36822806S	144.2818244E	Centre of carpark in front of MR plaque

A GeoExplorer receiver recording internally can store data for only $1^1/_4$hr at 5 s intervals. Thus, the data were recorded to a computer to allow longer survey time and improve resolution. Tests with Horatio and the base station set-up, both configured to record at 1 sec intervals, found that surveys could be continued for up to 4.5 hours before data storage capacity of the model 5 tattletale logger was reached.

Survey transects at surfing breaks are optimally spaced at intervals no greater than 10 m, and so an error of <5 m was required. Field tests with the system, showed that it was possible to achieve greater accuracy than the manufacturer's specification. Two types of error were considered: (1) the relative error between the base station and the rover, and (2) the absolute error of the base station position. For the purpose of these surveys the most important type of error is the relative error, that is the difference between the recorded rover position and its true position relative to the base station. The absolute position of the base station relates to the survey datum that the positions were recorded in (Table 3.1). Because we are interested in the shape of the bathymetry at surfing sites, the absolute position is not important.

To investigate the error of rover relative to the base station position, rover data were recorded at a stationary point and then corrected by subtracting the bases station fixes. The corrected data points were found to be clumped in a tight scatter around the true position of the rover. Errors of <1 m were commonly achieved, with the majority (>90%) lying between 0 to 0.7 m (Figure 3.3) well below the requirement of <5 m.

Surveys were sometimes conducted in isolated areas, and so exact co-ordinates of the base station position would have been difficult to obtain for the purpose of absolute position, even if this was considered necessary. Instead, base station positions were mostly estimated by averaging the base station data files recorded during surveys (a brief description of these locations is given in Table 3.1). Calibration tests, where base station data files were recorded at known surveyed co-ordinates, found that estimated positions were accurate to within 2 m when base station files of >1.5 hrs duration were averaged.

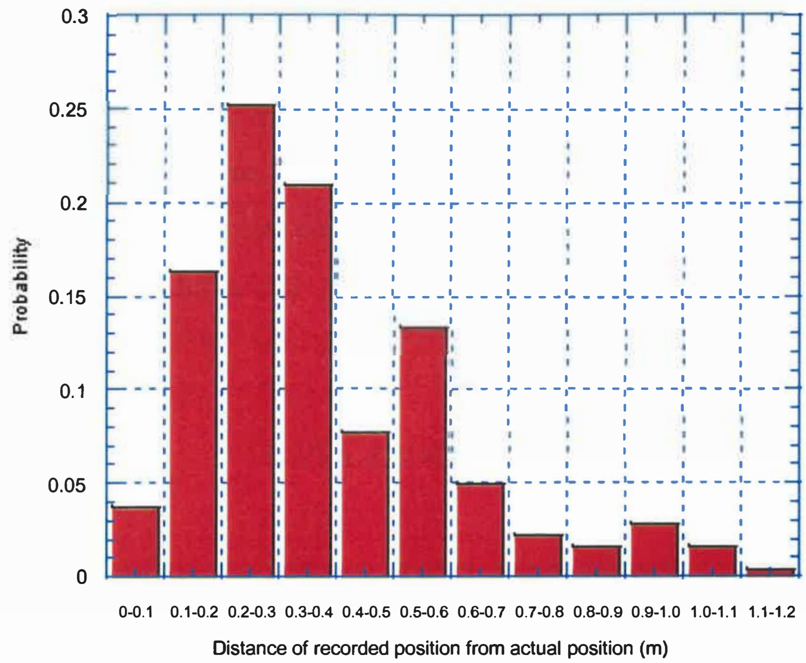


Figure 3.3. The distance of the recorded positions from 4 known positions. n = 336, mean = 0.38 m (st.dev .= 0.23), mode = 0.35 m, median = 0.33 m.

GeoExplorer GPS receivers can only track 6 satellites simultaneously, 4 of which are used to calculate position. There are often up to 12 satellites overhead at any one time, and more than 16 may be visible during a 4-hour survey period. The GPS receiver selects the satellites it will use to calculate its position based on the constellation of satellites that will give the highest degree of precision (HURN, 1993). As satellites move through the sky on different trajectories, the constellations are constantly changing and the GPS receivers respond by shifting to the best constellations as they become available. In some instances, when the base station had a visible horizon that differed from that in the area being surveyed, the rover receiver calculated its position using a different set of satellites than the base station receiver. This resulted in survey points that were offset from the rest of the survey path - either single points (spikes) or several points together. This problem was increased by reflection of satellite signals from the sea surface (multipath errors - HURN, 1993) and the tilting of the GPS receiver due to small wave action (Z. URBANSKI, pers. comm.).

Some switching between satellites could be avoided by 'disarming' satellites that were not required during a survey, even though they were in position overhead. This was achieved prior to surveying using QuickPlan® software to distinguish the satellite constellations that would give the most precise positions out of all the visible satellites during the planned survey time and also be visible at both the survey and base station locations. However, due to the constantly changing satellite constellations, up to 8 satellites were required for a full survey and so some satellite switching could still occur.

DATA PROCESSING

When the GeoExplorer GPS receiver is communicating to an external device, such as the PC or tattletale logger in this case, the format of the recorded data is unsuitable for post-processed differential correction using the manufacturer's software (Trimble®). Therefore, correction software was developed, using Matlab® interactive software, to allow post-processing of the survey data (GORMAN, 1996). Further processing included conversion of longitudes and latitudes to a metric grid, removal of depth sounding errors and tidal correction to LAT.

Rover data files and the associated base station data files were edited using Microsoft Excel© prior to correction in Matlab®. This involved 'trimming' the rover data files so that they were within the limits of the base station data files and removing any remnant data entries where no positional information had been recorded. The rover data files were corrected to produce log-files containing a time stamp, the corrected position and an associated depth (time, x, y, z).

Errors in the survey path were removed using Matlab® software (GORMAN, 1996) that displays the corrected log-file. Deviations in the survey path could be deleted or, if the displacements were consistent, relocated. Once errors in the survey path had been removed or corrected, depth-recording errors were then deleted. These errors were mainly due to passing over small waves during a survey. Some of these errors were obvious; when the sonar was lifted out of the water the depths recorded were at the maximum range (30.5 m). Other more subtle errors were removed by scrolling through the video records of surveys and deleting data points recorded while passing over small waves.

The next step was to convert the positional data from latitude and longitude to a metric grid. This was accomplished using a Fortran program that uses the world metric grid system and also creates an additional set of co-ordinates that sets the base station position as the origin (i.e. 0, 0).

Finally, tidal corrections were applied using a second Fortran program. Tide data recorded with a Dobie pressure sensor were corrected for atmospheric deviation and then averaged at 15 min intervals to produce a tidal curve. Astronomical tide data were used to reduce the data to LAT at each site. In some early Australian surveys, tidal data were not recorded due to the loss of the pressure sensor after its third deployment in Bali, Indonesia (October 1996). Accurate tide tables were available in Australia. A simple Fortran program was written to generate sinusoidal tidal curves from the high and low tide levels and times in the tables. This tide information was then used to tidally correct the early Australian bathymetry surveys.

IDENTIFICATION OF MESO-SCALE REEF COMPONENTS

Survey data were used to create regular bathymetry grids with Surfer6© software. Bathymetry maps were created with the grids, and landmark surveys could then be overlaid to give a clearer indication of the break's location (e.g. Figure 3.4). Isobath normal seabed profiles, wave orthogonal seabed profiles and wave peel angles in relation to isobaths were extracted and have been used for the design of artificial surfing reefs (BLACK *et al.*, 1998a; MEAD and BLACK, 1999a). To identify the meso-scale features that constitute world-class surfing breaks the most useful methods of analysis were visual classification of reef components and numerical refraction modelling (WBEND – BLACK & ROSENBURG, 1992; BLACK, 1997) to discern component functions (MEAD & BLACK, this issue).

[The following italicised section is not included in the peer-reviewed paper, but has been added here for clarification of the process followed to extract the components from the bathymetry surveys] *Numerical modelling grids were created by rotating* *bathymetry data, creating regular grids and converting these to mid-depth (*.md) bathymetry grids for use in WBEND. Model simulations of a range of wave height and directions and tidal phases were then carried out and the changes to wave orthogonal directions and break point locations were examined to assess the impact of the underlying bathymetry and estimate peel angles for comparison with the aerial photographs of each break. In this way the surfing break models were verified, the meso-scale components were identified and a classification system was developed.*

In order to run WBEND, the bathymetry grid must be orientated with the land on the right hand side because waves are input from the left and run from left to right. In most cases, this required rotation of the bathymetry survey data prior to gridding. This was accomplished using a set of specific formulas and the software package SURFER© surface mapping system (Golden Software, Inc.). Once rotated, the Kriging method of interpolation was selected for grid creation. Kriging is a geostatistical gridding method that has proven useful and popular in many fields (Golden Software, Inc., 1996). This method produces visually appealing contour and surface plots from irregularly spaced data (e.g. Fig. 3.4). Kriging attempts to express trends that are suggested in the data, so that, for example, high points might be connected along a ridge, rather than isolated by bull's-eye type contours (Golden Software, Inc., 1996). Kriging is an exact interpolator, i.e. this method of gridding honours data points exactly when the data point coincides with the grid node being interpolated. Validation tests comparing survey data with grids created using Kriging have shown that the method is very accurate and that errors associated with surveys are based on the accuracy of the depth soundings (Mathew et al., 2000).

WBEND has three types of boundary condition that can be used: the probability file, the spectrum file and the sediment transport contour file (Appendix 4). The sediment transport contour file is needed when WBEND is used in sediment transport mode; this was not required to investigate the form and function of meso-scale surfing reef components. Probability files and spectrum files are wave files that can be used to input individual waves or a whole spectrum of waves respectively. Probability files (monochromatic waves) were used for the model simulations of surfing break bathymetries. The initial wave files were made up of 3-12 waves, which were a combination of 3-4 wave heights (1, 2, 3 and 4 m) and 1-3 wave directions; the period *was estimated as the peak period that would be expected during a swell at each break (9 to 18 s). Input wave angles were between -50° and +50° relative to the bathymetry grid. Wave angle is defined relative to the left or east of the grid and is positive anti-clockwise (Cartesian axes). The wave heights and directions were simulated for high-, mid- and low-tides.*

The numerical wave refraction model WBEND (Wave BENDing) (Black and Rosenberg, 1992) has been applied to a broad range of physical environments and has been calibrated and shown to be accurate on many occasions. Moreover, the model has been successfully validated and used as one of the primary design tools for the surfing reef designed for the Gold Coast (Black et al., 1998). WBEND has been validated against surfing reef measurements (e.g. Hutt, 1997; Mead et al., 1998; Mead and Black, 1999b), laboratory data (Black and Rosenberg, 1992) and in open coast conditions (Black et al., 1997, 1998a, b; McComb et al., 1997). However, calibration of the numerical models of the surfing reefs could not be achieved in the absence of direct wave measurements. Consequently, the friction coefficient in the WBEND information file was set at 0.09 after consulting similar studies that utilised WBEND (Beamsley, 1996; Hutt, 1997; Black et al, 1998a, b; McComb, 1998, Bradshaw, 1991; Dell et al., 1985). The aerial photographs were used to validate the models by comparing the wave crests and peel angles at surfing breaks with the modelling results. In addition, orthogonal seabed gradients, which were later used to develop a method of predicting wave breaking intensity (Mead and Black, 2000 – Chapter 6) were recorded for the predominant wave directions at each break.

The final test was to critically examine each of the 34 surfing break bathymetries and classify all of the meso-scale reef components at each break into one of the new categories.

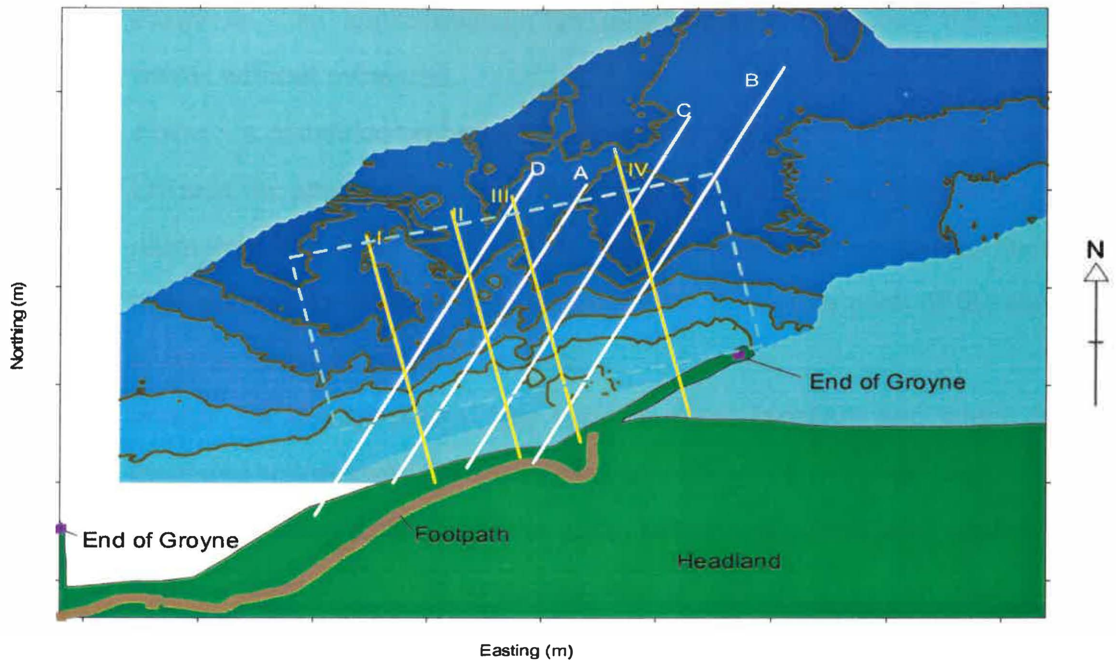


Figure 3.4. Bathymetry map of Kirra Point surfing break in Queensland, Australia, with surveyed landmarks overlaid. (Surveyed October, 1997)

Several recurring meso-scale morphologies were identified from the surfing break bathymetries. The components were classified using surfing terminology as ramp, platform, focus, wedge, ledge, ridge and pinnacle (Figure 3.5). As the meso-scale components of a surfing break control wave refraction and allow waves to peel at surfable speeds (see WALKER, 1974a, b; DALLY 1989; HUTT, 1997), component descriptions are based on the components' shape and isobath orientation, and the component alignment relative to the 'favoured orthogonal direction' of incoming waves. The favoured orthogonal direction is defined here as the wave alignment that produces the best quality surfing wave at each break. If the waves are not aligned around the favoured orthogonal direction they will either peel too fast or too slow to be useful for high-performance surfing. The brief definitions of surfing reef components are,

(1) ***Ramp*** - a seaward-dipping seabed that refracts incoming waves towards the favoured wave orthogonal direction (Figure 3.5a).

(2) ***Platform*** - an approximately horizontal region of seabed that translates waves without refraction.

(3) ***Focus*** - a distended seabed ridge aligned so that wave orthogonals converge towards the apex of the ridge. It acts to cause height convergence and may ultimately lead to a "take-off peak" where surfers can commence their ride, or a 'section' in the wave that breaks earlier than other parts of the wave due to its increased height (Figure 3.5b).

(4) ***Wedge*** - a sloping seabed that initiates wave breaking and which refracts incoming waves away from the favoured orthogonal direction (Figure 3.5d).

(5) ***Ledge*** – a sharp discontinuity in depth below a platform with gradient >1:4, which causes the waves to steepen and plunge quickly with little time for refraction to occur (Figure 3.5e).

(6) ***Ridge*** - a seabed ridge on a wedge or ledge aligned so that the offshore isobaths are at a greater angle to the favoured orthogonal direction than the preceding isobaths of the wedge or ledge, and so that the inshore isobaths do not cause convergence along the apex of the ridge. A ridge causes a local increase in seabed gradient and leads to a "hollow" wave section with a steeper wave face and faster peel angle (Figure 3.5f).

(7) ***Pinnacle*** - an isolated region of shallow bathymetry that causes the wave to locally rear up and steepen (e.g. a shallow rock, pinnacle or coral-head) (Figure 3.5c).

Figure 3.5. (Following 2 pages) Reef components that comprise the bathymetry at world-class surfing breaks. Isobaths of components become shallower in the direction of wave propagation (up the page). The large arrows represent the 'favoured orthogonal direction' and the small arrows represent transformations to the wave orthogonals. Schematic diagrams are accompanied by an example of a reef component from a measured bathymetry. Note, the platform has not been included here because it is essentially a flat component that does not refract waves that pass over it.

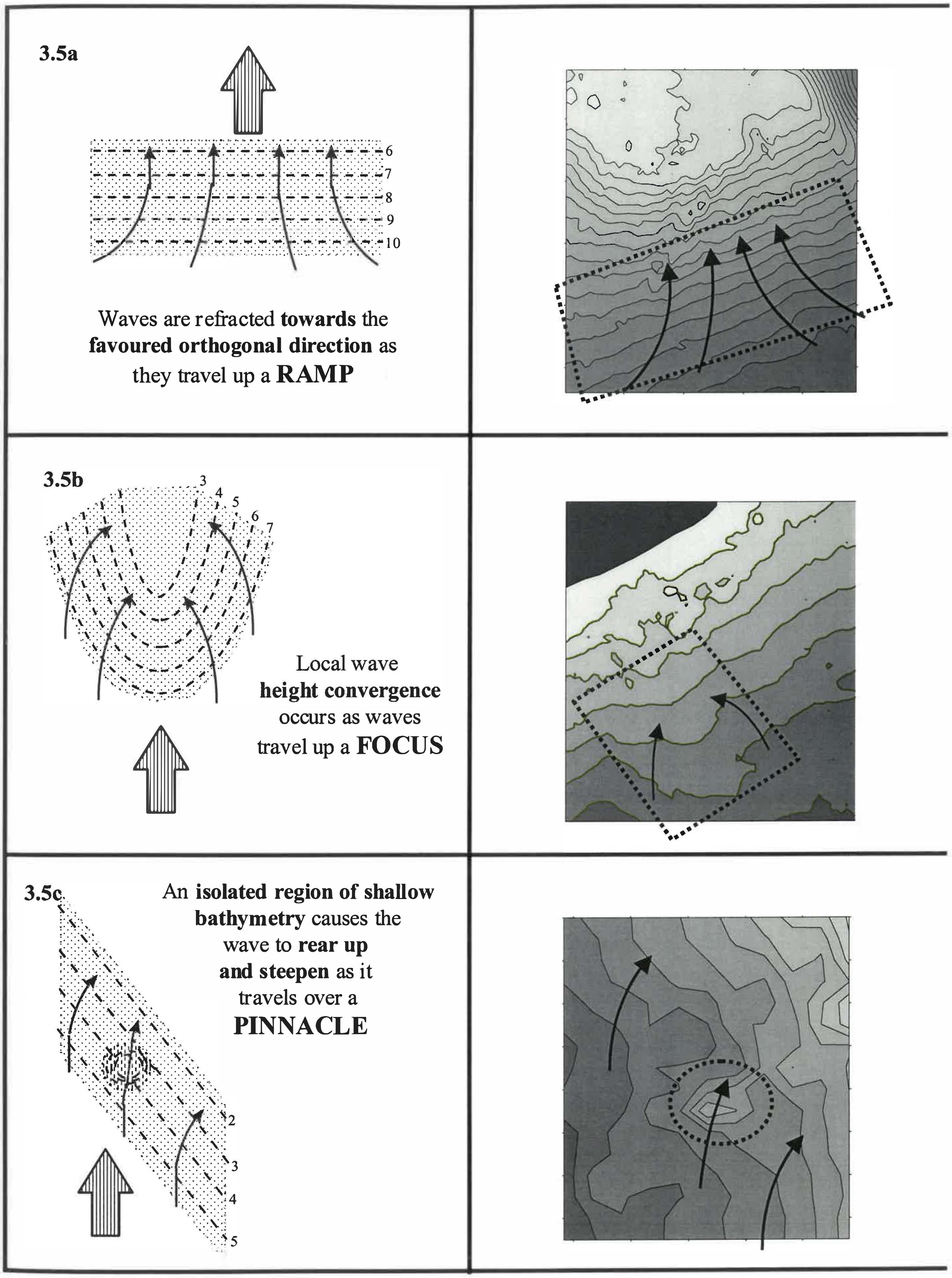


Figure 3.5. (Caption above)

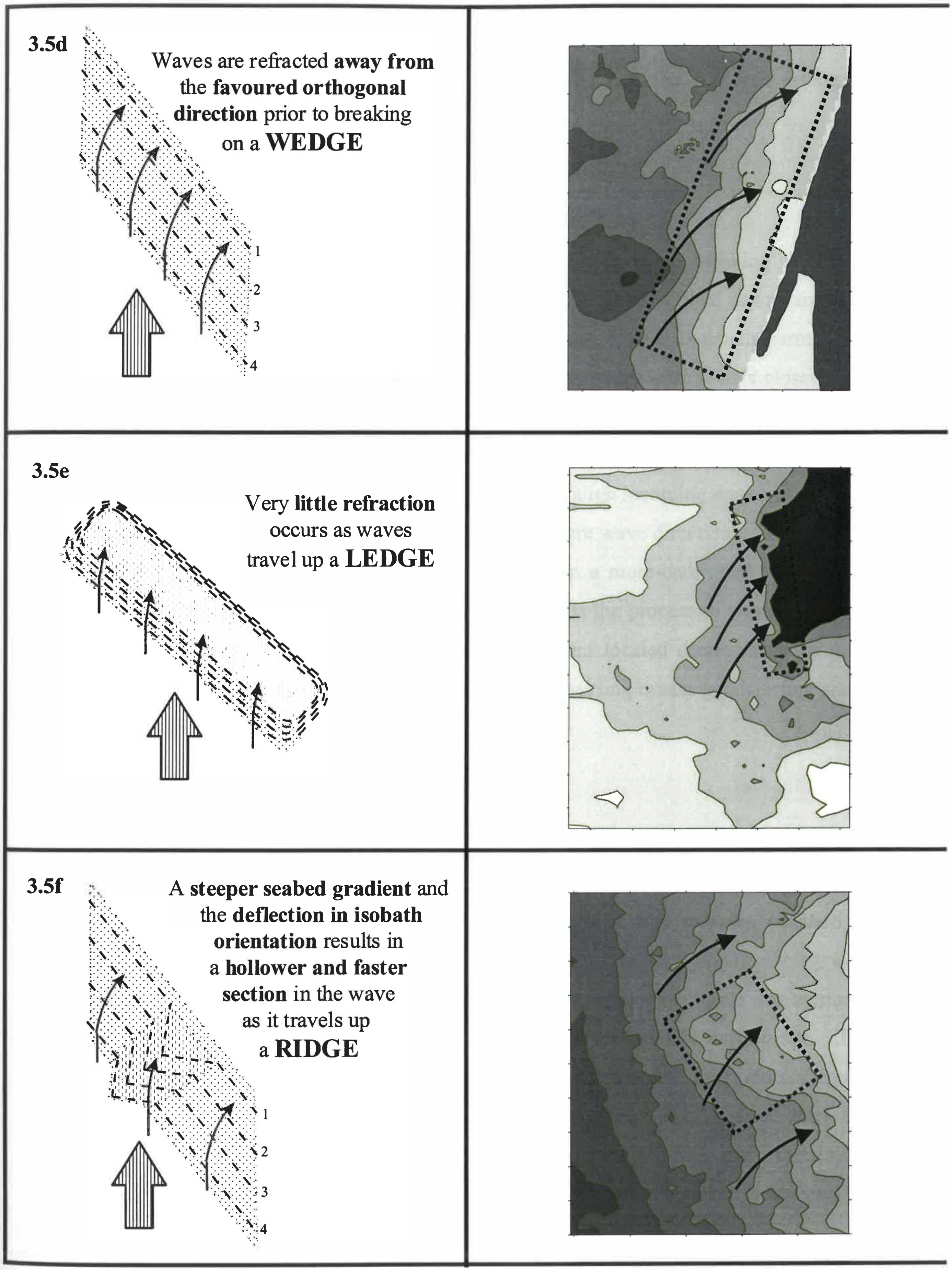


Figure 3.5. (Caption above)

We will now describe the morphology of each component and the effects they have on waves with respect to wave transformation and the favoured orthogonal direction in greater detail.

Ramp

The ramp's primary function is to align waves prior to breaking on another morphological component, usually a wedge. The planar ramp is tilted downward in the offshore direction and refraction tends to align incoming wave orthogonals normal to its isobaths. For a surfing break, this process also aligns wave orthogonals closer to the favoured orthogonal direction (Figure3.5a). Waves propagating shoreward from a variety of offshore directions will all be refracted towards the favoured orthogonal direction by varying amounts. Thus, the ramp acts to align incoming waves by reducing directional spread compared to the spectrum of offshore wave directions. Alignment of waves to the favoured orthogonal direction results in a more-controlled surfable peel angle at the break point. In addition, the ramp begins the process of wave steepening due to shoaling. The ramp is an offshore component located deeper than the usual maximum breaking depth for waves at each specific surfing break; good surfing waves do not break on a ramp.

Platform

The platform is essentially a flat, horizontal, plane, which has very little effect on the path of the wave orthogonals. The platform's function is to maintain the wave orthogonals at the alignment established by a ramp or, in less common situations, a focus. In this situation the platform links components together without altering wave orientation and thus maintains a surfable wave peel angle. Platforms are optimally situated at a depth just below the breaking depth for a particular surfing site. This enables offshore waves to be aligned as close as possible to the favoured orthogonal direction before breaking on inshore components. Waves of greater than this 'maximum wave height' will break on the platform, resulting in a wave that breaks almost simultaneously along the crest, known as a 'close-out'. Close-out waves peel too fast to be of any use for surfing.

Platforms are also associated with ledge components. They define the upper limit of the ledge, and their function in this case is to allow sufficient water depth for waves to break above the ledge. If a ledge continues upwards to shallow depths or even above water level, waves will surge or collapse on its steep gradient (BATTJES, 1974; PEREGRINE, 1983) and be impossible to surf.

Focus

A focus is a distended sea bed ridge aligned so that wave orthogonals converge towards the apex of the ridge when the wave is aligned close to the favoured orthogonal direction (Figure 3.5b). If the ridge is orientated so that the isobaths on either side cause waves to refract away from the apex of the ridge, convergence of wave orthogonals will not occur and ridge will not function as a focus. Convergence of wave orthogonals on a focus forms a 'peak', which is a local increase in wave height. Simultaneously, the wave steepens even further as water depth decreases on top of the focus until breaking occurs at the peak in the wave. The peak created by the focus breaks earlier than any other part of the wave and so can define the start of the surfing ride, or the 'take-off zone'. An additional benefit of the focus with respect to the take-off zone is the decrease of effective seabed gradient that is defined along the orientation of the wave travel path. The oblique angle between the focus isobaths and the wave orthogonals (Figure 3.5b) causes the effective seabed gradient to become less steep. This results in reduced wave steepness at the break point that makes it easier for a surfer to successfully take-off.

Although the peak created by a focus can form a take-off zone, a peak may also occur at any point along the surfing ride. These peaks create what is termed a 'section' in a wave, which is a locally faster peeling area of the wave. The local increase in wave height caused by the focus breaks earlier than the rest of the wave and so creates the section similar to that caused by peakiness in the actual swell (HUTT, 1997). Peaks in waves created by a focus may break on the focus, or they can break on other reef components inshore, depending on the depth and scale of the focus. This is discussed in more detail by MEAD and BLACK (this issue).

While a focus may be good at producing a peak in a wave, at the same time the very process of focusing can be extracting energy from the adjacent parts of the wave. If a focus is too large this can result in a much reduced wave height after the initial peak and can also increase wave peel angle to such an extent that the peel rate is too slow for good surfing. This has become very evident during the process of artificial reef design (BLACK *et al.*, 1998a, MEAD and BLACK, this issue).

Wedge

A wedge is similar to a ramp in shape (a planar component, tilted downward in the offshore direction). However, its orientation, depth and function are distinctly different (Figure 3.5d). A wedge is oriented at an angle to the favoured orthogonal direction, it is at a depth shallow enough to break waves and it refracts waves away from the favoured wave orthogonal. A wedge is commonly the main wave breaking component at a surfing break.

In many cases a wedge is an indent or outcrop in a coastline, although a wedge may be entirely a feature of the local bathymetry (e.g. an offshore reef). Waves initially aligned by a ramp component are subsequently refracted away from the favoured orthogonal direction by a wedge. The amount of refraction that occurs on a wedge prior to breaking determines the peel angle. To maintain a surfable peel angle, the wedge must be aligned at the correct angle to the favoured orthogonal direction with respect to the depth of the wedge and the height of the waves that break on it. Waves must peel at an angle along the crest for surfing, but refraction tends to align wave crests parallel to the isobaths. If waves are refracted too much before breaking on the wedge, the peel angle is decreased past surfable limits; waves begin to close-out. This occurrence is related to wave height. As wave height decreases the amount of refraction prior to breaking increases. Thus a surfing break can have a range of peel angles for a certain swell direction that are dependent on wave height. Large waves will peel along a wedge at a higher (slower) peel angle than smaller waves. Mead and Black (this issue) describe configurations of meso-scale reef components that can control and minimise this effect on peel angle.

Ledge

A ledge may be thought of as a very steep wedge that has a platform extending shoreward from its top edge (Figure 3.5e.). Like a wedge, surfing waves break along a ledge. Its orientation to the favoured orthogonal is critical to the peel angle. Very little refraction can occur on a ledge prior to breaking because it is very steep. Waves hit the ledge and break with no time to align to its contours. This means that waves must be oriented close to the favoured orthogonal direction prior to breaking. Therefore ledges work better in shallow water where maximum alignment (refraction) can occur prior to encountering the ledge. A shallow depth also means that waves shoal to near critical steepness before reaching the ledge and breaking onto the platform above it.

Gradients of >1:4 have been specified in the definition of a ledge because waves of common surfing height (1-4 m) and period (>8 s) have been predicted to collapse or surge on gradients steeper than this (GALVIN, 1968; BATTJES, 1974; PEREGRINE, 1983; BUTTON, 1991)). However, even though the very steep gradient of the ledge should result in waves that surge or collapse, if it is topped by a platform that allows for sufficient water above the top edge of the ledge, waves will break with a form suitable for surfing (i.e. plunge). This is because the ledge does not continue above the still water level and so the water on top of the platform acts as a 'source' for offshore directed water movement during wave breaking. Ledges in relatively shallow water (i.e. the ledge face is only 2-3 m vertically) may also allow waves to break without collapsing or surging because the wave has already shoaled to a near critical breaking point. However, shallow water ledges will have a small range of surfable wave heights; larger waves will break beyond the ledge and may not be surfable. The prerequisite for water above a ledge can also mean that it is very susceptible to fluctuations in the tide.

Ridge

A ridge component modifies a small area of a breaking wave. This component rests on top of a wedge or ledge with the isobaths of its offshore side aligned almost perpendicular to the favoured orthogonal direction and presents the wave with both a steeper seabed gradient and an offshore deflection of the isobath orientation (Figure 3.5f). Consequently, there is a perceptible change in the wave as it breaks over the ridge. This section of the wave breaks steeper, due to the increase in seabed gradient

(BATTJES, 1974; PEREGRINE, 1983; SAYCE, 1997; COURIEL *et al.*, 1998; SAYCE *et al.*, 1999), and faster due to the decrease in the local peel angle caused by the offshore deflection of the isobaths. A ridge is similar to a focus in shape, however, it is aligned so that it does not cause convergence along its apex. The section of a wave will often break in an extreme plunging manner, know as a tube-section, creating a more exciting ride and requiring a higher skill level to surf (Plate 3.2).

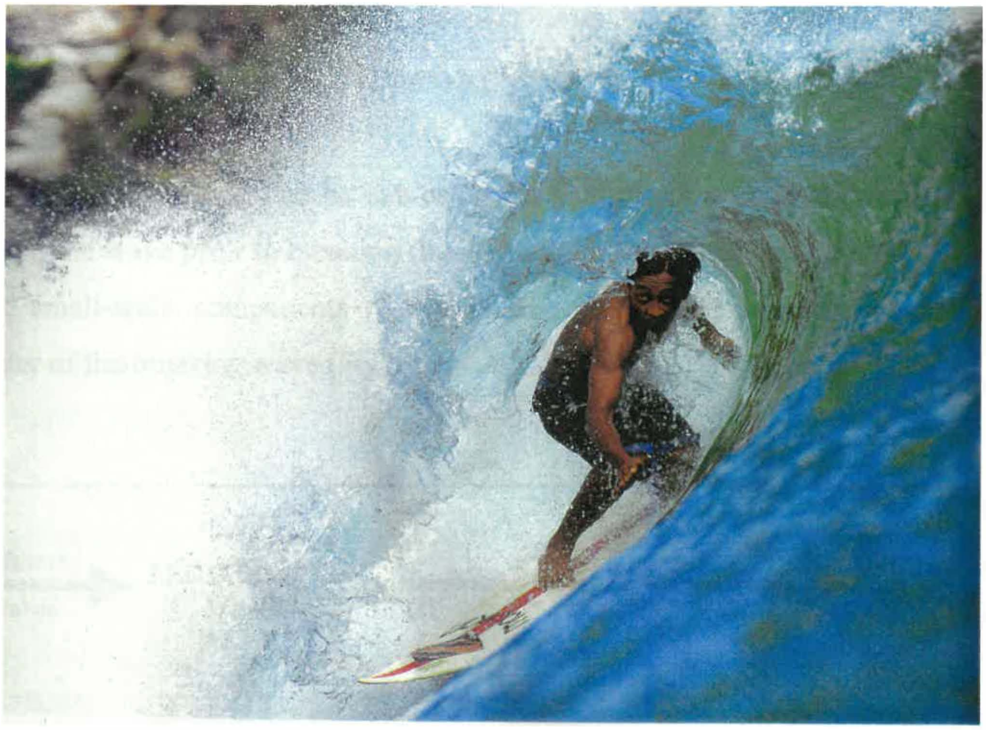


Plate 3.2. Surfing inside the vortex of a breaking wave, under the plunging lip of a wave, is known as riding in the 'tube' and takes a high level of skill. (Photo MTVZ – In: Uluwatu. Tadevan Holdings Pty Ltd. 1998)

Pinnacle

A pinnacle, like a ridge, modifies a small area of a breaking wave. Pinnacles also create sections in a wave, however, they are usually more abrupt and effect a relatively smaller area than those produced by ridges (Figure 3.5c). In addition, while ridges are mostly along the main length of the ride, pinnacles can also define the take-off zone in a similar way that a focus does. The shallow bathymetry of a pinnacle at the take-off zone creates a peak that breaks earlier than other parts of the wave. This allows a surfer time to stand up and line up the ride ahead, and therefore leads to a higher chance of successfully catching and riding a wave. Pinnacles located on the wedge further along the peeling wave may act to create a short section similar to that of a ridge or, if the pinnacle rises up to very shallow depths, may cause a section of wave to collapse. In the case where a pinnacle causes the wave to collapse, the surfer must either try to surf low on the wave around this area or 'float' over the top of this section, depending of the individual skill level. Like a ridge, a pinnacle creates a more exciting and challenging surfing wave.

COMPONENT SCALE

Components can also be sub-categorised by function as those which (1) pre-condition the wave prior to breaking (by aligning and shoaling) and (2) break the wave. In (2), small-scale components resting on the larger-scale components modify the character of the breaking wave (Figure 3.6 & Tab. 3.2).

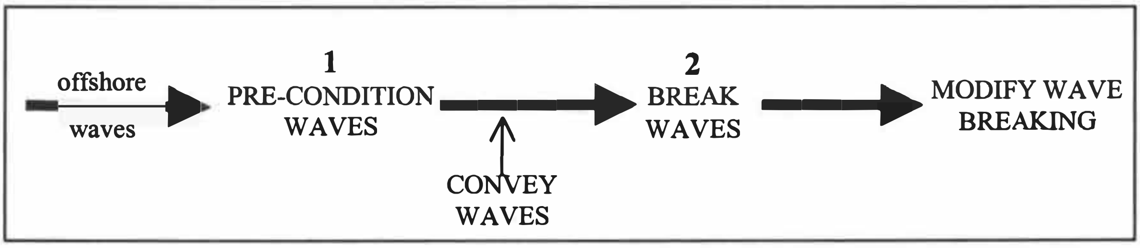


Figure 3.6. The functional order of surfing reef building blocks. Refer to Table 3.2 for reef components in each category.

Table 3.2. *Functions of surfing reef components.*

Component	Function	Details
Ramp, Focus	1. Pre-condition waves	- Pre-condition for other components
Platform		- Convey waves without change
Wedge, Ledge	2. Break waves	- Break waves for surfing
Ridge, Pinnacle		- Modify breaking waves

The functional order of components results in a size range from larger offshore components that align waves prior to breaking, to the smaller inshore component that only modify a small section of the wave. Each component has a specific function and performs this function within its own scale range (Figure 3.7). While some components may perform their function over a wide range of scales, others are relatively restricted. For example, a ramp may orientate waves towards the favoured orthogonal direction along a whole section of coast, or it may act on a relatively smaller scale, catering to one specific break. Wave refraction begins when the water depth is equal to 0.25-0.5 the wave length (KOMAR, 1976), and so a ramp can start functioning in relatively deep water with respect to a surfing break. This leads to a range in scale for a ramp from as small as 100 m^2 and up to square kilometres. However, a pinnacle greater than several meters across would be impossible to successfully surf; the sections would be too long to negotiate. The upper size limit of a pinnacle is set by the maximum distance that a surfer can travel to successfully negotiate the section that the pinnacle creates. Speed can not be indefinitely maintained when passing below a collapsing section due to the low steepness of the wave face at the base, or when floating over the white-water of the broken section. The same is true if a section created by a pinnacle breaks in a plunging form; there is a limit to how far a surfer can negotiate when the crest is breaking simultaneously along a section. If it is too long, the section becomes a close-out.

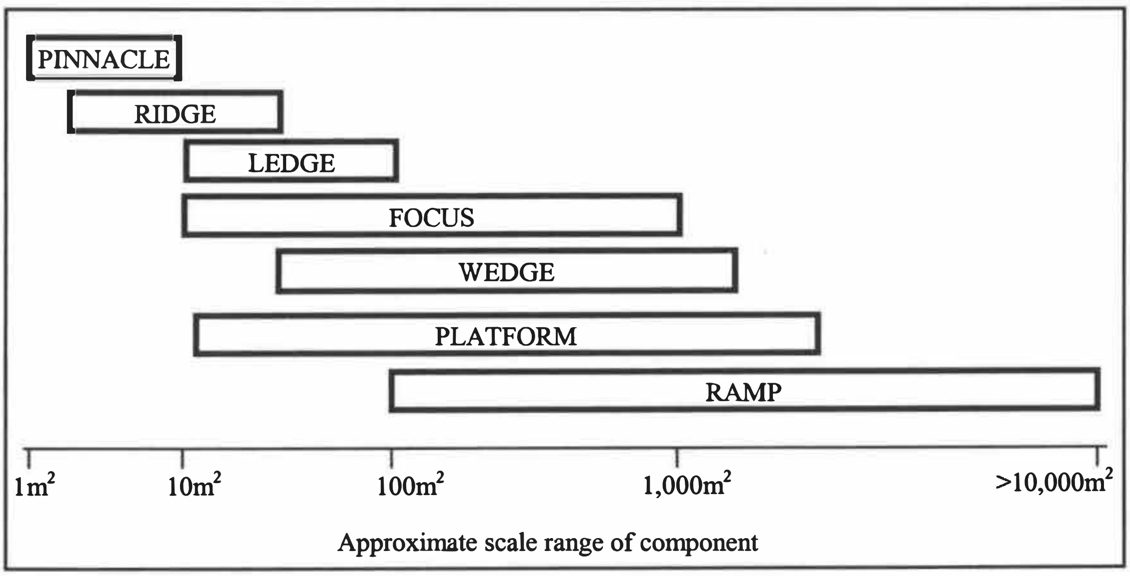


Figure 3.7. The functional scales of surfing reef components.

[Table 3.3 and the italicised text below not included in the peer-reviewed paper, but has been added here to summarise and quantify the meso-scale reef components identified from the bathymetry surveys]. *Table 3.3 summarises the function, size and shape/alignment of the meso-scale reef components. All of the reef components identified at each break in the dataset of surfing reef bathymetries fit within the limits of the categories. The categories in Table 3.3 refer to,*

1. *the functional order of components as presented in Figure 3.6 and Table 3.2.*
2. *the size range of components as presented in Figure 3.7 – note, a large wedge or headland (discussed in Chapter 4 and Table 4.1) is a combination of a wedge and a ramp (both pre-condition and break waves) and therefore has a size range that is an amalgamation of the two.*
3. *contour normal seabed gradient of each individual component.*
4. *component alignment refers to the contour normal axis of a component relative to the favoured orthogonal direction.*

Table 3.3. Summary table of meso-scale reef components – refer to notes 1-4 above for clarification of the factors included in the table.

Component	Function[1]	Size[2]	Contour Normal Gradient[3]	Component Alignment[4]
Ramp	Pre-condition	100->10,000 m^2	1:40-1:80	0-90°
Platform	Convey	10-3,000 m^2	>1:80	0-20°
Focus	Pre-condition	10-1,000 m^2	1:10-1:80	40-90°
Wedge	Break	50->2,000 m^2	1:4-1:40	30-80°
Ledge	Break	10-1,000 m^2	1:1-1:4	25-60°
Ridge	Break	5-50 m^2	1:4-1:40	0-50°
Pinnacle	Break	1-10 m^2	<1:0.25-1:1	NA

Further discussion of component functional scale is given in the companion paper in this issue, where common location and orientation of reef components at world-class surfing breaks are described (MEAD and BLACK, this issue). Surf breaks are made up of a number of reef components in specific configurations, which are holistically connected through the process of refraction (MEAD and BLACK, 1999b). Consequently, the orientation of wave orthogonals prior to breaking has a large influence on the peel angle at the breakpoint. In the right configurations, meso-scale reef components act to maintain surfable peel angles. These data are proving invaluable for the design and incorporation of artificial surfing reefs into coastal construction (BLACK *et al.*, 1998A; MEAD and BLACK, 1999a).

CONCLUSION

The bathymetric surveys of world-class surfing sites represent the major component of the first international surfing break database. These bathymetries reveal that natural world-class surfing reefs are comprised of several meso-scale reef components. Classification and functional description of the meso-scale reef components has led to a better understanding of seabed morphology of surfing breaks as well as an understanding of the functional scale of components. This information is essential for the design of man-made surfing reefs and points to the necessity of sophisticated configurations of reef components rather than simple one or two component configurations.

In conjunction with numerical modelling, the database of surfing breaks can be applied to reef design for a variety of site specific conditions (existing bathymetry, wave climate, etc.). However, before this new information on surfing reef morphology can be applied to reef design, an understanding of how reef components are combined to produce world-class surfing breaks is required.

ACKNOWLEDGEMENTS

This study formed part of the larger Artificial Reefs Program, which aims to enhance amenity value along New Zealand's coastline. The program is evaluating multiple use options for artificial reefs, with a particular emphasis on surfing. The Program is supported by the Centre of Excellence in Coastal Oceanography and Marine Geology (within the National Institute of Water and Atmospheric Research (NIWA) and the Coastal Marine Group at the University of Waikato), the Foundation for the Research Science and Technology, Opus International Consultants, and Rip Curl (NZ) Ltd. Technical support from John Radford (University of Waikato), Richard Gorman (NIWA) and Zig Urbanski (Geosystems) led to the development of Horatio. Angela Mead provided invaluable field assistance and support.

REFERENCES

BARTHOLOMEW, W., 1997. Quality of Surfing Lifestyle. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

BATTJES, J. A., 1974. Surf Similarity. *Proceedings 14th Coastal Engineering Conference*, ASCE, pp. 466-480.

BEAMSLEY, B., 1996. Shoreface Wave Height Reinforcement and Frictional Dissipation Off Waihi Beach, with Emphasis on Seabed Characteristics and Numerical Modelling. Unpublished MSc Thesis, Earth Sciences Department, University of Waikato.

BLACK, K. P., 1997. *Wave refraction model WBEND.* Occasional Report, Centre of Excellence in Coastal Oceanography and Marine Geology, Department of Earth Sciences, University of Waikato, New Zealand.

BLACK, K. P. and M. A. ROSENBURG, 1992. Semi-empirical Treatment of Wave Transformation Outside and Inside the Breaker Line. *Coastal Engineering,* 16: 313-345.

BLACK, K. P.; ANDREWS, C.; GREEN, M.; GORMAN, R.; HEALY, T.; HUME, T.; HUTT, J. ; MEAD, S., and SAYCE, A., 1997. Wave Dynamics and Shoreline Response On and Around Surfing Reefs. *Proceedings of the 1^{st} International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

BLACK, K. P.; HUTT, J. A. and MEAD, S. T., 1998a. *Narrowneck Reef Report 2: Surfing Aspects*. Technical Report prepared for the Gold Coast City Council, June, 1998.

BLACK, K. P.; HUTT, J. A. and MEAD, S. T., 1998b. *Takapuna Boat Ramp: Surfing Impact Assessment and Reef Feasibility Study.* Report for North Shore City Council, October, 1998.

BRADSHAW, B. E., 1991. Nearshore and Inner Shelf Sedimentation on the East Coromandel Coast. New Zealand. Unpublished MSc Thesis, University of Waikato, New Zealand.

BUTTON, M., 1991. Laboratory Study of Artificial Surfing Reefs. Bachelor of Engineering, Department of Civil and Environmental Engineering, University of Western Australia, 1991.

COURIEL, E. D., P. R. HORTON and D. R. COX, 1998. *Supplementary 2-D Physical Modelling of Breaking Wave Characteristics*. WRL Technical Report 98/14, March, 1998.

DALLY, W. R., 1989. Stochastic Modelling of Surfing Climate. *Proceedings The 22^{nd} Coastal Engineering Conference*, ASCE, Vol. 1, pp. 516-529.

DELL, P. M., T. R. HEALY and C. S. NELSON, 1985. A Prelminary Investigation of Sediments on the East Coast Coromandel Inner Shelf and Implications for Cross-shelf Sediment Transport. *Proceedings 7th Australasian Conference on Coastal and Ocean Engineering*, Christchurch, New Zealand.

GALVIN, C. J., 1968. Breaker-Type Classification on Three Laboratory Beaches. *Journal of Geophysical Research*, Vol. 73, No. 12, June, 1968.

GORMAN, R., 1996. Software. National Institute of Water and Atmospheric Research, Hamilton, New Zealand.

GRIGG, R., 1969. *Artificial Reefs: A Plan For Multiple Use*. Surfer Magazine, January, 1969.

HURN, J., 1993. Differential GPS Explained. Trimble Navigation Ltd.

HUTT, J. A., 1997. Bathymetry and Wave Parameters Defining the Surfing Quality of Five Adjacent Reefs. Unpublished Thesis, University of Waikato, New Zealand. Pp. 170.

KOMAR, P. D., 1976. Beach Processes and Sedimentation. Prentice-Hall Inc., New Jersey.

LONGUET-HIGGINS, M. S., 1982. Parametric Solutions For Breaking Waves. *Journal of Fluid Mechanics*, 121, 403-424.

MCCOMB, P.J., BLACK, K.P., ATKINSON, P.N., HEALY, T.R. and BELL, R.G., 1997. High-resolution wave transformation on a coast with complex bathymetry. *Pacific Coasts and Ports '97,* Christchurch, 7-11 September 1997.

MEAD, S., BLACK, K. and HUTT, J., 1998. Surfing Reef Morphological Components Combine To Create World-Class Surfing Breaks. *2nd Annual International Artificial Surfing Reef Symposium*. San Diego. April, 1998.

MEAD, S. T. and BLACK, K. P., 1999a. A Multi-Purpose, Artificial Reef at Mount Maunganui Beach, New Zealand. *Coastal Management Journal* 27(4), 355-365.

MEAD, S. T. and BLACK, K. P., 1999b. Configuration of Large-Scale Reef Components at a World-Class Surfing Break: Bingin Reef, Bali, Indonesia. *Proceedings Coasts & Ports '99*, Vol. 2:438-443.

PARKER, Jr.; R. B. STONE, R. O.; BUCHANAN C. C., & STEIMLE, JR., F. W., 1974. *Fishery Facts-10: How to Build Marine Artificial Reefs*. NOAA. US Government Printing Office, Washington D.C. 47p.

PATTIARATCHI, C., 1997. Design Studies for an Artificial Surfing Reef at Cable Station, Western Australia. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

PEREGRINE, D. H., 1983. Breaking Waves on Beaches. *Ann. Rev. Fluid Mech.*, 15, 149-178.

PILARCZYK, K. W. and ZEIDLER, R. B., 1996. *Offshore Breakwaters and Shore Evolution Control*. A. A. Balkema, Rotterdam. 560p.

PITT, B. A. 1997. Surfing into the 21st Century - Harbord Reef. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

PRATT, J. R., 1994. Artificial habitat technology and ecosystem restoration: managing for the future. *Bulletin of Marine Science* 55(2-3), 268-275.

PRATTE, T. P., 1987. Ocean Wave Recreation. *Proceedings of Coastal Zone '87*, ASCE, Seattle, Washington, 1987.

SAYCE, A., 1997. Transformation of Surfing Waves Over Steep and Complex Reefs. Unpublished Thesis, University of Waikato, New Zealand.

SAYCE, A., K. P. BLACK and R. GORMAN, 1999. Breaking Wave Shape on Surfing Reefs. *Proceedings Coasts & Ports '99*, Vol. 2, 596-603.

SILVESTER, R., 1975. Synthetic Surfing Sites. University of Western Australia, Nedlands, Western Australia.

TOYOSHIMA, O., 1972. *Detached Breakwaters*. *In:* Coastal engineering for practising engineers, K. W. Pilarczyk ed. Chapter 8, 118p.

WALKER, J. R. & PALMER, R. Q., 1971. A General Surf Site Concept. LOOK Laboratory TR-18, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii, 1971.

WALKER, J. R.; PALMER, R. Q.; & KUKEA, J. K., 1972. Recreational Surfing on Hawaiian Reefs. *Proceedings 13th Coastal Engineering Conference*, 1972.

WALKER, J. R., 1974a. Recreational Surf Parameters. LOOK Laboratory TR-30, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii, 1974.

WALKER, J. R., 1974b. Wave Transformations Over a Sloping Bottom and Over a Three-Dimensional Shoal. PhD. Dissertation, University of Hawaii, 1974.

Chapter 4

FUNCTIONAL COMPONENT COMBINATIONS CONTROLLING SURFING WAVE QUALITY AT WORLD-CLASS SURFING BREAKS

Journal of Coastal Research, Special Surfing Issue (Accepted)

Functional Component Combinations Controlling Surfing Wave Quality at World-Class Surfing Breaks

Shaw Mead† and Kerry Black‡

†Coastal Marine Group, Department of Earth Sciences. University of Waikato & Private Bag 3105, Hamilton, New Zealand

‡ASR Ltd. PO Box 13048, Hamilton, New Zealand

s.mead@asrltd.co.nz, k.black@asrltd.co.nz

ABSTRACT

Bathymetric measurements on natural world-class surfing breaks around the Pacific Rim and Indonesia revealed the presence of repeating combinations of meso-scale reef components. Several common configurations of large-scale reef components were identified. Numerical modelling was utilised to investigate how the common configurations function and led to the development of their functional descriptions. It was found that the specific combinations of reef components at these surfing sites consistently produce high-quality surfing waves. The reef component combinations have a holistic character; relative sizes and placement of the components determines the overall quality and length of the surfing break. Refraction and wave attenuation on a succession of components maintains surfable wave peel angles. Designs of artificial surfing reefs must apply these holistic principles in order to produce high-quality surfing facilities that optimise the characteristics of specific sites.

ADDITIONAL INDEX WORDS: *surfing reefs, bathymetry, refraction, numerical modelling.*

INTRODUCTION

There are a variety of properties that put world-class surfing breaks in a category of their own, but it is the seabed shape that has the largest influence on the form of a breaking wave and therefore the quality of a surfing break. However, until now, knowledge of surfing reef character was minimal (WALKER and PALMER, 1971; WALKER *et al.*, 1972; WALKER, 1974; HUTT, 1997). Recent studies of the seabed morphology at world-class surfing breaks have found that they are more complex than originally thought (BLACK *et al.*, 1997a; BLACK *et al.*, 1998a; MEAD and BLACK, 1999a; Mead & BLACK, this issue). In order to incorporate surfing reefs into coastal development and protection projects (BLACK *et al.*, 1997b; BLACK *et al.*, 1998a; BLACK *et al.*, 1998b; BLACK, 1998; MEAD and BLACK, 1999b; BLACK *et al.*, 1999; JACKSON *et al.*, 1999), an understanding of the function of bathymetric components of natural reefs is essential.

Knowledge of the relationship of seabed geomorphology to surfing wave quality and form remains in its infancy (BUTTON, 1991; SAYCE, 1997; COURIEL *et al.*, 1998; SAYCE *et al.*, 1999; MEAD and BLACK, 2000). Moreover, the process of refraction and its consequences with respect to wave quality at surfing sites has not been previously considered at small-scales, although past studies have considered refraction in broad terms (WALKER and PALMER, 1971, MOFFAT and NICHOL, 1989; LYONS, 1992; HUTT, 1997; RAICHLE, 1998). This paper continues the investigation into seabed morphology at world-class surfing breaks; data acquisition and the classification of meso-scale reef components at surfing breaks are presented in a companion paper in this issue. Here, we describe how meso-scale reef components combine to create world-class surfing breaks.

PEEL ANGLE

To fully comprehend the importance of reef component combinations on surfing wave quality, it is important to clearly understand how wave peel angles relate to surfing waves. High-performance surfing depends on steep-faced waves, which are produced by steep seabed gradients (BATTJES, 1974; PEREGRINE, 1983; SAYCE, 1997; COURIEL *et* *al.*, 1998; SAYCE *et al.*, 1999; MEAD and BLACK, 2000), and fast peel angles (DALLY, 1990; HUTT, 1997). The steep face provides downhill slopes similar to that required for skiing. The peel angle determines surfing wave "speed" as the surfer travels laterally ahead of the breaking section on the unbroken wave face. Refraction changes the direction of wave propagation causing wave crests to align more parallel with the seabed contours (KOMAR, 1976). This is important for surfing because it alters the peel angle (WALKER, 1974). The closer aligned the crest lines and the isobaths become, the greater velocity the surfer must attain to successfully ride the wave (WALKER *et al.*, 1972).

The peel angle is defined as the angle between the trail of the broken white water and the crest of the unbroken part of the wave as it propagates shoreward (WALKER, 1974). Peel angles range between 0 and 90°, with small peel angles resulting in fast surfing waves and large angles in slow surfing waves (DALLY, 1990; HUTT, 1997). There is a limit to how small the peel angle can get before it becomes impossible for a surfer to stay on the unbroken wave face, ahead of the breaking section; when this is no longer possible the wave is termed a 'close-out'. On the other hand, as the peel angle increases towards the maximum of 90°, peel speed is reduced until it becomes too slow to be considered good for surfing.

On straight coasts with parallel contours, refraction often aligns the wave crests at the breakpoint nearly parallel to the isobaths, resulting in waves that break almost simultaneously along the crest (close-out). This isobath alignment relative to the wave orthogonal direction makes the waves impossible to surf and, in combination with inappropriate seabed gradients, is one of the main reasons why only relatively few quality surfing breaks exist along the world's coastlines. The meso-scale reef components of a surfing break combine to control wave refraction and allow waves to peel at surfable speeds.

Table 4.1. *List of international surfing breaks surveyed for seabed investigations, the components that each break is comprised of and a description of wave breaking characteristics (wave steepness and peel speed).*

Break Name & Location		Components	Wave Characteristics
Ala Moana	Hawaii	ramp, wedge, pinnacle	steep & fast
Angourie	Australia	large wedge, ledge, ridge, pinnacle	mod. steep & fast; steep/hollow section
Backdoor	Hawaii	ramp, focus, wedge, pinnacle	v. steep/hollow & v.fast
Bells Beach	Australia	large wedge, ridge	mod. steep & fast; steep/hollow section
Bingin	Indonesia	ramp, platform, focus, wedge, ridge	v. steep/hollow & fast; v. fast section
Bone Yards	New Zealand	large wedge, pinnacle, ridge	mod. steepness & peel speed; fast section
Bird Rock	Australia	ramp, ledge, platform	fast, steep/hollow
Burleigh Heads	Australia	platform, large wedge, ridge	steep & fast; v. steep/hollow sections
Copacabana Bar	Brazil	ramp, wedge	low to mod. steepness, slow to mod. peel
Dee Why Point	Australia	ramp, ledge, wedge, pinnacle	v. steep/hollow & fast
El Capitan	California	large wedge, focus, pinnacle	steep/hollow & fast; v. steep & fast sections
Fort Point	California	large wedge, pinnacle, ridge	mod. to steep/hollow, mod. to fast sections
Indicators	New Zealand	large wedge, ridge	mod. to steep/hollow, mod. to fast sections
Kirra Point	Australia	platform, large wedge, ridge	steep & fast; v. steep/hollow sections
Manu Bay	New Zealand	large wedge, ridge	low to v. steep/hollow & fast section
Merimbula Bar	Australia	ramp, wedge	fast to v. fast and steep to v. steep/hollow
Off-The-Wall	Hawaii	ramp, wedge, pinnacle	v. steep/hollow & v. fast
Outsides	New Zealand	large wedge, pinnacle, ridge	mod. to v. steep/hollow, mod. to fast sections
Padang Padang	Indonesia	ramp, focus, wedge, pinnacle	v. steep/hollow & v. fast
Pipeline	Hawaii	ramp, large focus, pinnacle	v. steep/hollow & v. fast
Rincon	California	large wedge, ridge, pinnacle	mod. to v. steep/hollow, mod. to fast sections
Rock Piles	Hawaii	ramp, wedge, pinnacle	v. steep to hollow & fast to v. fast
Rocky Point	Hawaii	ramp, wedge, pinnacle	v. steep to hollow & fast to v. fast
Sanur	Indonesia	ramp, platform, wedge, ridge, pinnacle	steep to v. steep/hollow & fast to v. fast sections
Shark Island	Australia	ramp, focus, wedge	v. steep/hollow & v. fast
Summer Cloud	Australia	ramp, focus, wedge	steep to v. steep/hollow & fast to v. fast sections
Tairua	New Zealand	ramp, wedge	low to mod. steepness, slow to moderate peel
Takapuna Reef	New Zealand	platform, wedge, ledge, platform, pinnacle	low to hollow, slow to v. fast
The Wedge	California	ramp, wedge	v. steep/hollow & v. fast

Break Name & Location		Components	Wave Characteristics
The Valley	New Zealand	large wedge, ridge	steep to v. steep/hollow &

			fast to v. fast sections
Ventura Point	California	large wedge, ridge, pinnacle	mod. to v. steep, slow to fast sections
Whale Bay	New Zealand	large wedge, ridge, pinnacle	mod. to steep, slow to mod. peel
Whangamata Bar	New Zealand	ramp, wedge	mod. to steep, slow. to mod. peel; fast section
Winkipop	Australia	large wedge, platform, ridge	steep to v.steep/hollow, fast to v. fast sections

COMMON REEF COMPONENT CONFIGURATIONS AT WORLD-CLASS SURFING BREAKS

Decomposition of surfing break bathymetry measurements recorded in New Zealand, Australia, Indonesia, Hawaii, California and Brazil (Table 4.1) led to the classification of meso-scale reef components that constitute world-class surfing breaks (MEAD & BLACK, this issue). These reef components were isolated by their specific shapes as well as their different functions and were classified as ramp, platform, focus, wedge, ledge, ridge and pinnacle (Fig. 4.1). As the meso-scale components of a surfing break control wave refraction and allow waves to peel at surfable speeds (see WALKER, 1974; DALLY 1990; HUTT, 1997), component descriptions are based on the component shape and isobath orientation, and the component alignment relative to the 'favoured orthogonal direction' of incoming waves. The favoured orthogonal direction is defined as the wave alignment that produces the best quality surfing waves at each break. If the waves are not aligned around the favoured orthogonal direction they will either peel too fast or too slow to be useful for high-performance surfing. Full definitions of these components are given in the companion paper in this issue.

During the classification of individual reef components, it was found that not only were there common components at many surfing breaks (MEAD & BLACK, this issue), but that certain combinations of these components were also recurring. The most common component combinations are illustrated in Figure 4.2. Each common combination is represented by three related diagrams. The first is an example of a measured surfing break bathymetry. The second is a numerical model output of wave refraction over the same bathymetry. The third is an idealised schematic of the component combination where the more complex bathymetry of the natural reef has been simplified to the dominant components. By considering the changes to wave orthogonal direction caused by reef components using the numerical model WBEND (BLACK, 1997), the functions of these various features (Fig. 4.1) and the utility of some of the common combinations (Fig. 4.2) were explored.

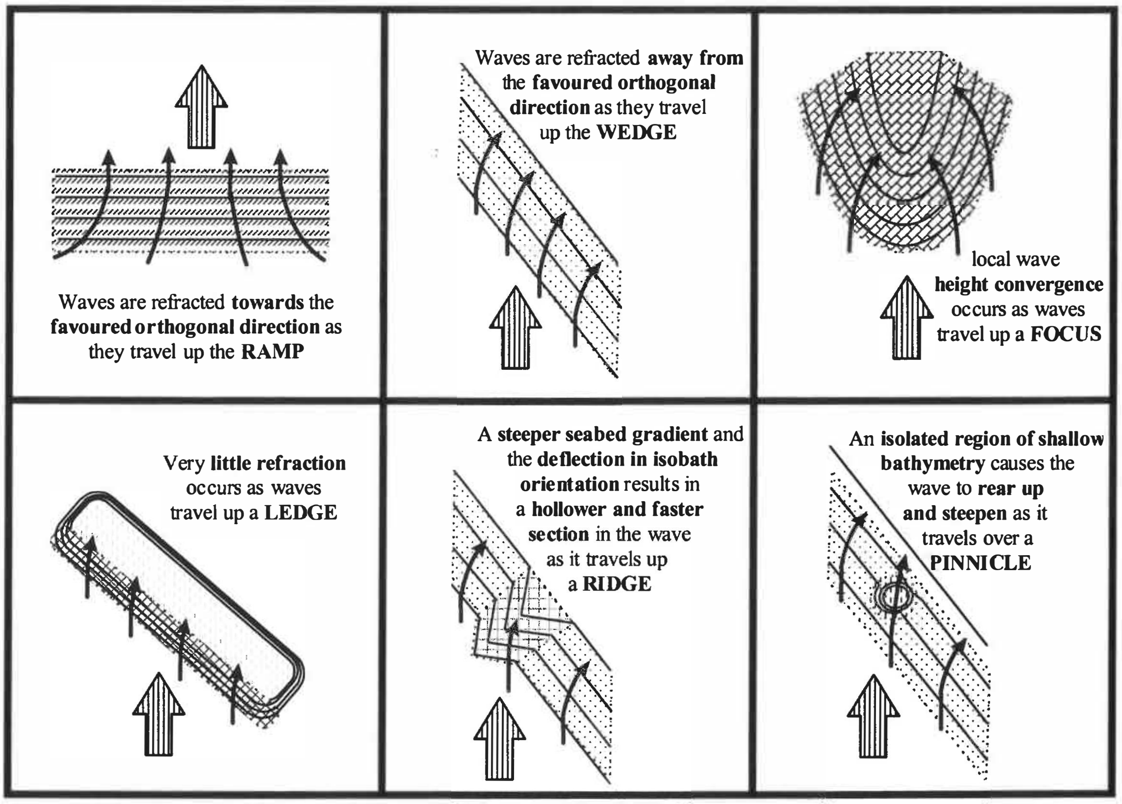


Figure 4.1. Reef components that comprise the bathymetry at world-class surfing breaks. Isobaths of components become shallower in the direction of wave propagation (up the page). The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. Note, the platform has not been included here because it is essentially a horizontal component that does not refract waves that pass over it.

WBEND is a 2-dimensional numerical wave refraction model (BLACK, 1997). It applies a fast, iterative, finite-difference solution of the wave action equations to solve for wave height, wave period, breakpoint location, long shore sediment transport, bottom orbital currents and near-bed reference concentration of suspended sediments. The most relevant outputs for surfing wave characteristics are wave refraction and shoaling, as they affect peel angle and wave height distribution at the breakpoint along the reef.

Figure 4.2. (Following 2 pages) Common combinations of reef components found at world-class surfing breaks. For each set of three diagrams, from left to right, the first is an example of a measured surfing break bathymetry; the second is a numerical model output of refraction of waves over the particular surfing break bathymetry; and the third is an idealised schematic of the component combination - the multi-faceted bathymetry of natural surfing reefs has been simplified to highlight the dominant components. The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. Isobaths of components become shallower in the direction of wave propagation (up the page), and break point is represented by ☆. Note, the model bathymetry has been rotated so that wave input is from the left-hand side.

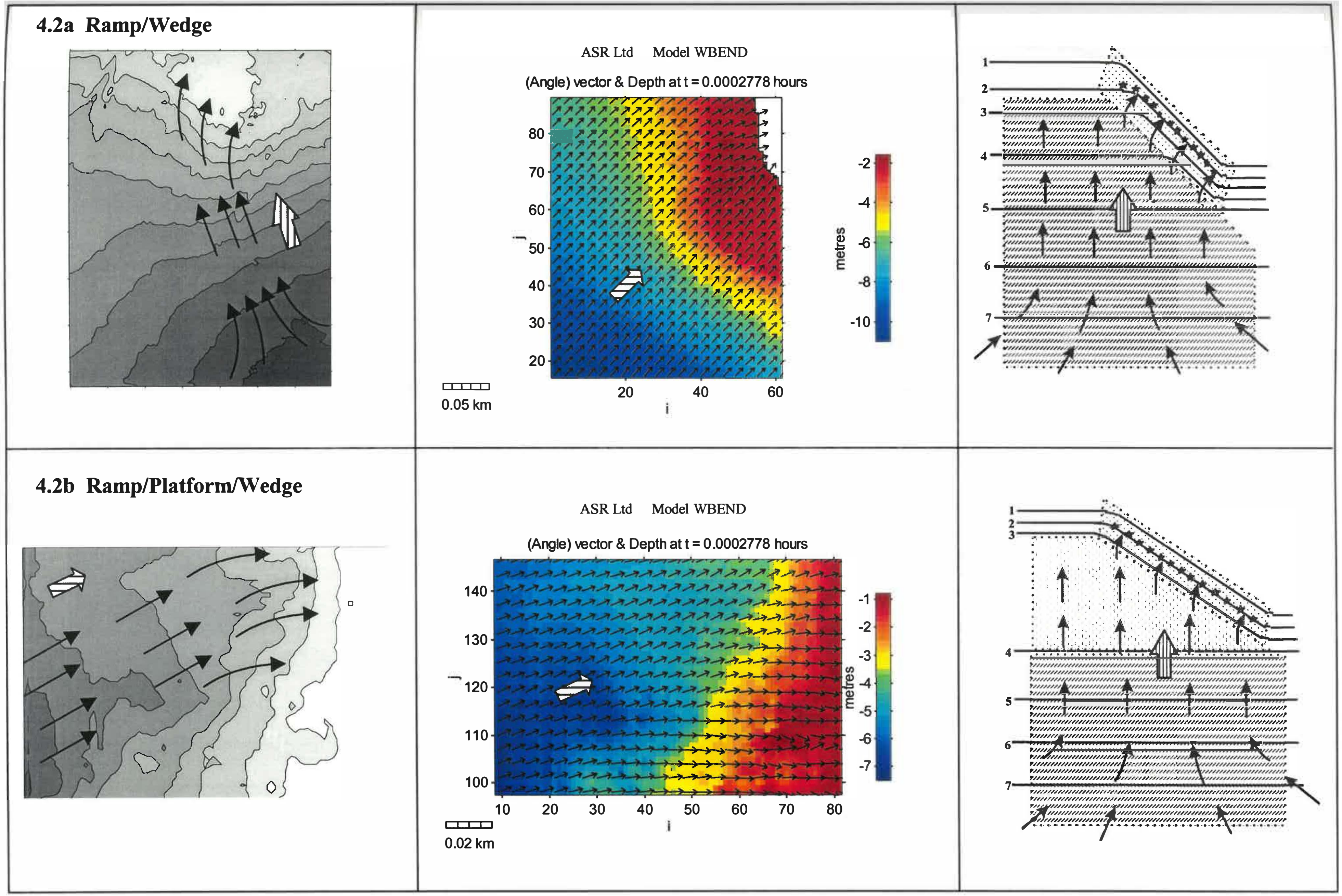


Figure 4.2. (Caption above)

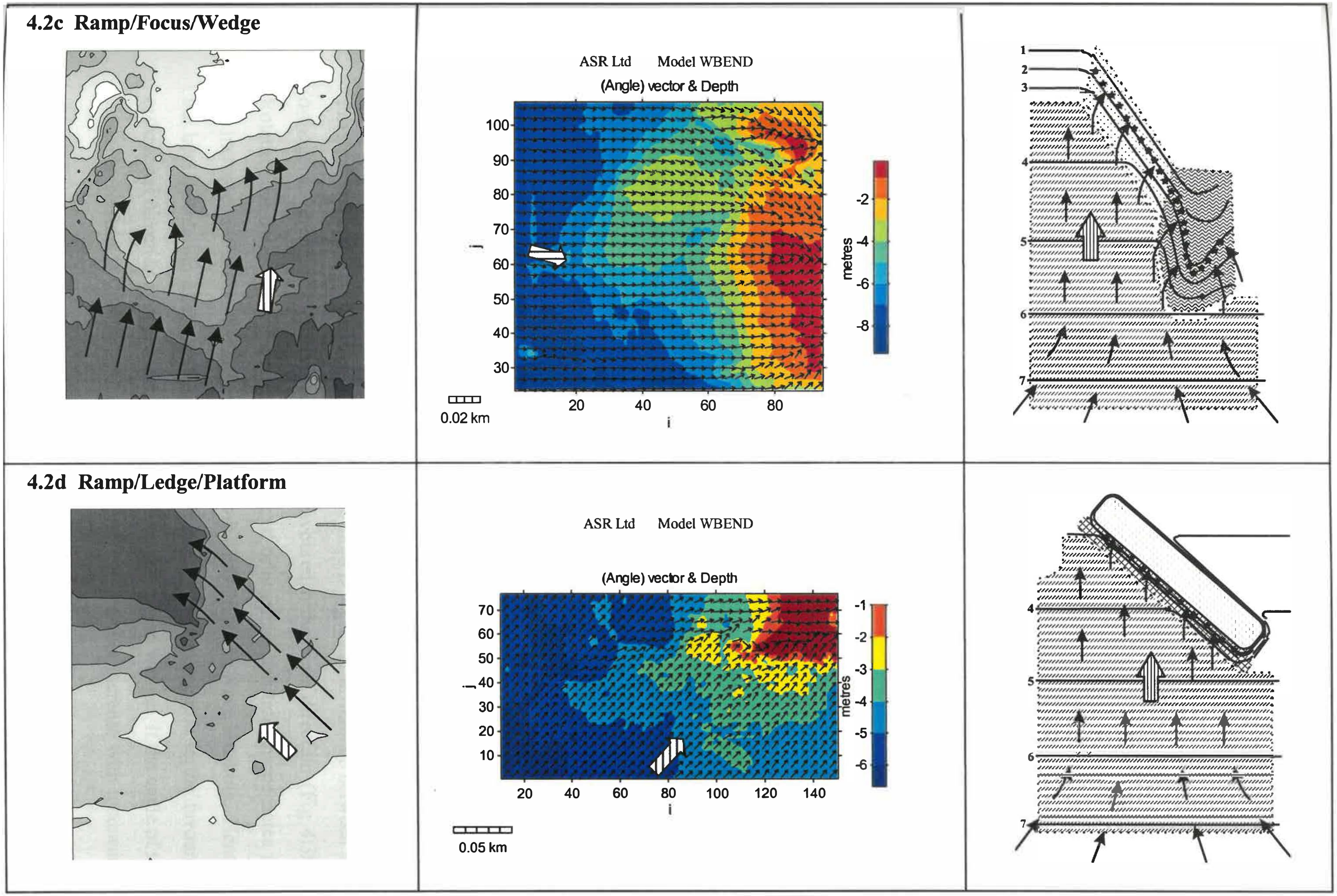


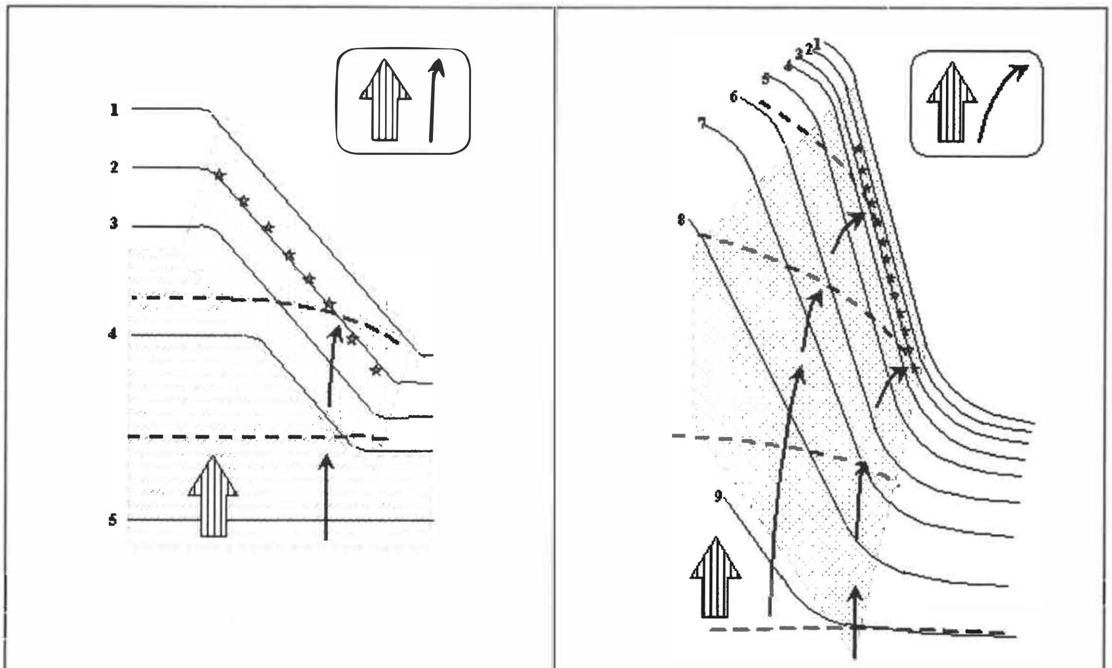
Figure 4.2. (Caption above)

The Ramp/Wedge Configuration

The most common configuration of reef components is the ramp/wedge combination (21 cases were identified, including large wedge configurations – discussed below), where a ramp aligns waves to break on an overlying wedge (Fig. 4.2a). As the waves propagate shoreward, they first encounter the ramp. Numerical modelling indicated that refraction on the ramp aligns wave orthogonals closer to the favoured orthogonal direction. Thus, the ramp acts to orient incoming waves by reducing directional spread compared to the spectrum of offshore wave directions. In addition, the ramp begins the process of wave steepening due to shoaling.

Incoming waves next encounter the wedge as they enter shallower water. Waves that were aligned to the favoured orthogonal direction by the ramp are subsequently refracted away from the favoured orthogonal direction by the wedge (Fig. 4.2a). The degree of refraction that occurs on the wedge prior to breaking must be such that a surfable peel angle is maintained. This is dependent on depth of the offshore toe of the wedge, which consequently effects the wedge alignment (MEAD and BLACK, 1999a). At a shallow depth, only a small amount of refraction can occur prior to wave breaking. Thus orthogonal direction at the break point is only slightly different to the favoured orthogonal direction (Fig. 4.3a). As a consequence, the peel angle is not strongly influenced by refraction on the wedge, just by the incident angle determined by the ramp and the isobath orientation of the wedge.

Modelling results of a number of breaks with the ramp/wedge component combination show that as the depth of a wedge increases, the amount of refraction occurring on the wedge prior to breaking increases. As a result, the wedge must be rotated at a greater angle to the favoured orthogonal direction in order to maintain a surfable peel angle at breaking. Consequently, there is a greater difference between the orthogonal direction at break point and the favoured orthogonal direction (Fig 4.3b). Rotating the wedge more parallel to the favoured orthogonal direction compensates for the increased refraction that occurs on the deeper wedge prior to wave breaking. Hence, the best orientation of the wedge for quality surfing waves in relation to the favoured orthogonal direction is dependent on the depth and size of the wedge. If the angle of the wedge's isobaths to the favoured orthogonal direction does not increase with increasing depth and size, the wave will be refracted beyond a surfable peel angle at the break point and result in waves that close-out (MEAD and BLACK, 1999a).



4.3a. The difference between the favoured orthogonal direction and the wave orthogonal direction at break point is small when the wedge is at a shallow water depth.

4.3b. The difference between the favoured orthogonal direction and the wave orthogonal direction at break point is relatively larger when the wedge size increases.

Figure 4.3. Schematic diagrams of wedge orientation changes required to maintain a surfable peel angle at break point with increasing size/depth of the wedge. The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. The dashed lines represent wave crests. Note the small difference between the favoured orthogonal direction and the direction of the wave orthogonal at break point in 4.3a (shallow water wedge), compared to the relatively large difference between these directions in 4.3b (large deep water wedge or headland).

The Ramp/Platform/Wedge Configuration

A modification of the ramp/wedge configuration is the incorporation of a platform component between the ramp and the wedge (Fig. 4.2b). In this configuration the ramp and platform pre-condition the waves prior to breaking on the wedge. The ramp performs the same task as described above, aligning waves to the favoured orthogonal direction and initiating wave steepening. At the top of the ramp, waves then pass across the platform with little additional refraction and onto the wedge beyond (Fig. 4.2b). In essence, the horizontal platform allows the wedge to be aligned at an angle that is rotated shoreward relative to the crest of the ramp without altering wave orientation. The wave aligning function of the ramp is maximised by terminating the ramp at a relatively shallow horizontal platform. In addition, the depth of the wedge remains constant along its length because it is located above the horizontal platform. This minimises any differences in wave orthogonal direction (and therefore peel angle) due to differential refraction up a wedge as occurs when a ramp and wedge are not separated by a platform (Fig. 4.2a). Thus, the platform links two fundamental components and, by eliminating refraction, maintains the wave orthogonals at the alignment established by the ramp. Because orthogonal alignment is not changed by the platform in this configuration of reef components, the length of the break can be increased without a subsequent shoreward rotation of the wedge, as is required if the depth of the wedge is increased in the absence of a platform, as described above.

An advantage of the ramp/platform/wedge configuration is that peel angle remains relatively constant over a range of wave heights; little refraction occurs on the shallow wedge before breaking. MEAD and BLACK (1999a) demonstrated how the ramp/platform/wedge combination at Bingin in Indonesia functions to produce waves with consistent peel angles over a range of wave heights and swell directions. However, because the platform is located at the top of the ramp in relatively shallow water depth, the larger waves can break on the platform (close-out). Therefore, this combination of components is effectively limited to a maximum wave height, as was found during the numerical modelling when larger wave heights were input. If the platform was to be located in deeper water to accommodate larger wave heights, a similar scenario as described above for the large ramp/wedge combination would occur, refraction would be increased on the wedge prior to breaking during small wave conditions, resulting in close-out conditions.

The Ramp/Focus/Wedge Configuration

Another common modification to the ramp/wedge combination is the ramp/focus/wedge (Fig. 4.2c). The ramp functions as usual, aligning the waves to the favoured orthogonal direction. The newly aligned wave crests next detect the focus, where refraction acts to locally increase the wave height by bending the wave onto the focus as it travels shoreward along the focus apex. Simultaneously, the wave steepens even further as water depth decreases on top of the focus until breaking occurs on the peak. The peak created by the focus breaks earlier than any other part of the wave and so defines the start of the surfing ride, or the 'take-off' zone.

An additional benefit of the focus is the decrease of effective seabed gradient, which is defined along the orientation of the wave travel path. The oblique angle between the focus isobaths and the wave orthogonal causes the effective seabed gradient to lessen (Fig. 4.2c). This results in decreased breaking intensity at the break point, making it easier for a surfer to take-off successfully. A good example of this 'softening' of the take-off is Shark Island in New South Wales, Australia (Fig. 4.2c bathymetry example). Shark Island reef is world-famous for the extreme form of plunging waves that break on it, producing wide hollow 'tubes' that are surfed by experienced board-riders. These extremely hollow waves break along a very steep wedge. However, the take-off prior to the wedge is relatively easier to negotiate. In the words of a surfer who frequently surfs at this break … "Places like Shark Island have a little section where you take-off that's kind of easy and then you backdoor the gnarly part." (BILDERBACK, 1994). It is the presence of the focus at Shark Island, as was identified in the bathymetry and subsequent numerical modelling, that decreases the breaking intensity at the take-off.

The Ramp/Ledge/Platform Configuration

A less common surfing reef component is the ledge in the ramp/ledge/platform combination (Fig. 4.2d). Although ledges themselves may be fairly common along some coastlines, very few produce surfable waves. For a ledge break to be a successful surfing location, there are several prerequisites including wave direction, ledge depth, water depth above the ledge and ledge alignment. Hence, they rarely work as surfing breaks in nature. Wave alignment to the favoured orthogonal direction is again performed by the ramp. Orientation of the ledge must be such that the waves aligned by the ramp break along it at a surfable angle. For this reason a ledge works most consistently in fairly shallow waters so that the ramp can decrease wave direction spread to within a small range prior to breaking. The shallow location of the ledge also allows wave shoaling to proceed to a near critical stage before breaking on the ledge. The pre-alignment of waves is important for a ledge because very little alignment (refraction) can occur on the ledge, due to the abrupt nature of the rise in the seabed; waves break before they can adjust.

Because water depth changes with the tide, ledges are often tide-dependent. If the top of the ledge is close to or above the water level, waves surge or collapse on its very steep face (BATTJES, 1974). A good example of a ramp/ledge/platform surfing break is Bird Rock in Victoria, Australia (Fig. 4.2d bathymetry example). At Bird Rock when the tide is low, waves surge and collapse along the edge of the emerged ledge and platform, and bigger waves close-out on the ramp offshore. However, as the tide rises and sufficient water covers the Bird Rock ledge and platform, waves shoal and align on the ramp and then break fast and hollow along the edge of the ledge.

Ridges and Pinnacles

Ridge and pinnacle components were not considered in the common reef combinations above because they are smaller scale components that do not affect the general character of a surfing break. However, these components are commonly found at many breaks (Table 4.1) and they do locally affect the character of a breaking wave that encounters them.

Ridges and pinnacles are both components that modify small areas of a breaking wave. Their effect on breaking waves is localised and usually associated with enhancing wave breaking for the performance of a single surfing manoeuvre. Ridge and pinnacle components produce faster, hollower breaking areas of a wave, known as 'sections'. Sections on a surfing wave create a more exciting ride and require a higher skill level to surf, often producing the highly prized 'tube-ride' where the surfer rides under the plunging jet of a wave. A detailed discussion of these component's functions is given by MEAD & BLACK (this issue).

GENERAL DISCUSSION

An important factor to consider with respect to component configuration of surfing reefs is scale. This is especially important when point or headland breaks are considered. Notably, headlands are actually large wedges. Headlands are often associated with large terrestrial outcrops on otherwise straight coasts (e.g. Raglan Point in New Zealand, Fig. 4.4). Headland breaks have wedges extending to great depths and, because the wedge is in relatively deep water (say 10 m), it must therefore be orientated at a large angle to the favoured orthogonal direction (Fig. 4.3b). This is shown to be an essential characteristic of a headland break by Black *et al.* (this issue) in the design of the Gold Coast Reef. On large headlands, the waves need to approach the headland such that the orthogonal is directed essentially straight down the length of the headland, otherwise wave refraction can cause the wave to close-out.

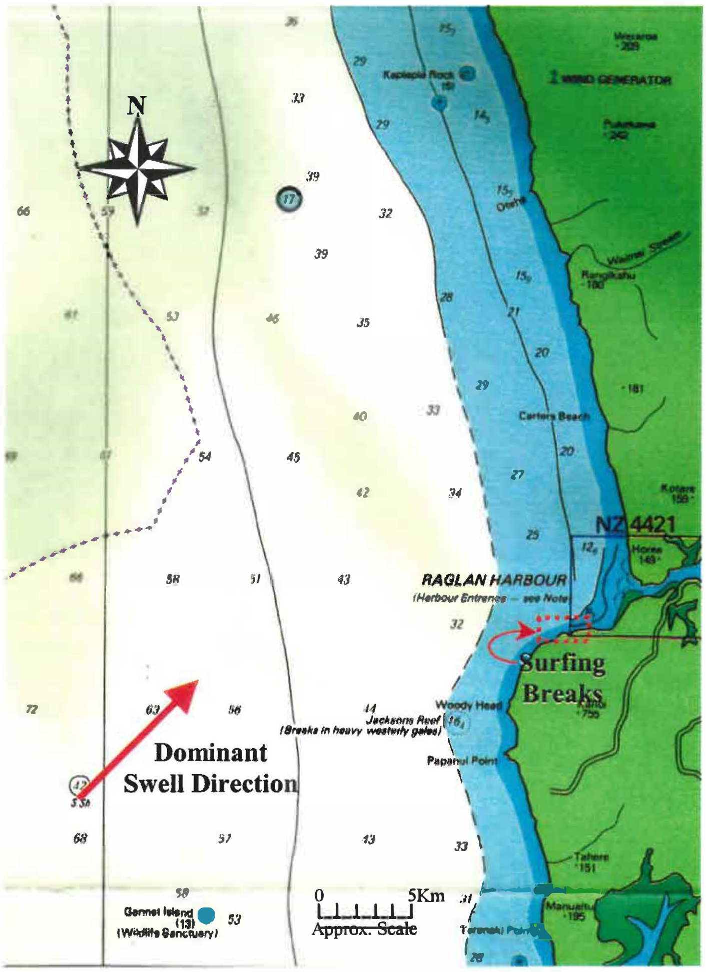


Figure 4.4. Raglan headland on the west coast of North Island, New Zealand (Nautical chart NZ43, RNZN Hydrographic Office). The dominant swell and wind directions are from the southwest. The main surfing breaks at Raglan are orientated away from the dominant swell direction, towards the north.

The 'refraction compensation' achieved by the rotation of the large wedges to a position more parallel to the wave orthogonal direction at headland breaks is sometimes found at small offshore island and reef breaks (Plate 4.1). In this case, the isobaths of the large-scale wedge continually bend away from the favoured orthogonal direction as they follow the topography of the island or reef, and so refraction is compensated and a surfable peel angle results. With the headland or island surfing break there is often a close-out section, before the peel angle is surfable, where the isobaths are initially near parallel to the wave crest (i.e. the far end of the headland or the side of an island facing the incoming swell) (Plate 4.1).

Plate 4.1. Aerial view of an island surfing break, where the wedge (reef edge) is continually bending away from the approaching waves, which compensates for refraction and produces surfable peel angles over a very long distance. Note the region at the top of the photo, where wave peel angles are very low and unsurfable where the island faces the swell direction and waves are closing out. (Photo Dick Hoole – In: Uluwatu. Tadevan Holdings Pty Ltd. 1998)

One of the consequences of the refraction mechanism, which may explain why surfers seek headlands (often called 'point-breaks') for surfing, is that refraction is strongly dependent on wave period. This means that the longer period waves refract more and can therefore reach parts of the coast that are not orientated towards the dominant swell direction, i.e. the sheltered side of large headlands. For example, the dominant swell direction at Raglan, New Zealand (Fig. 4.4), a large headland on the North Island's west coast, is from the southwest, but the main surfing breaks are orientated away from the dominant swell direction, towards the north. The dominant swell orientation is important for a headland to function well as a surfing break. Indeed, swells that approach Raglan headland from the northwest are rarely good for surfing because refraction around the headland does not occur and so shorter period waves can also approach the break 'confusing' the larger components of a swell. The orientation of a headland can produce long peeling surfing waves and also acts as a wave filter, refracting the longer period waves into the break while letting other shorter period waves travel past up the coast. As discussed above, the large wedges of headlands must be rotated away from the favoured orthogonal direction to compensate for refraction of waves beyond surfable peel angles. As a consequence, point-breaks often have better surfing conditions than coasts that are oriented towards the dominant swell direction. Orientation of all sizes of wedges must be properly considered during artificial reef design, as wedges are the main component on which surfing waves break.

Differences in wave height can also have a similar outcome on peel angle as that found by differences in the depth/size of the wedge. Large waves break earlier (in deeper water) than small waves and therefore have less time to refract away from the favoured orthogonal direction (MEAD and BLACK, 1999a). For this reason, some breaks may produce close-out conditions when a small swell is present, but fast surfable waves once the swell reaches a critical size (e.g. Kirra Point in Queensland, Australia – BLACK *et al.*, 1998a). HUTT (1997) identified this process at Raglan in New Zealand and referred to the difference between the small wave height and the large wave height as refraction breaks vs headland breaks, indicating that far less refraction occurred when the wave height was large. The difference between the offshore wave direction and the wave direction at break point was shown to be 15° and 40°, for a 4 m and 1 m wave heights, respectively (HUTT, 1997).

At a small wave height, wave refraction on the wedge prior to breaking considerably reduces the peel angle, while at large wave heights far less refraction occurs on the wedge prior to breaking and so peel angle increases. This increase of peel angle due to increased wave size is typical of many surfing breaks and raises the question of whether or not it is an advantage to have a slower peeling wave as the wave size increases. There are two views that can be taken. On one hand, a bigger wave intuitively leads to faster board speed and therefore smaller (faster) peel angles can be successfully negotiated. On the other, in order to utilise the whole face of big waves a higher (slower) peel angle may be required to accommodate the increased distance that must be travelled. This is a complex question to answer because the steepness of the breaking wave face on a specific seabed gradient is dependent on the waves height and period (GALVIN, 1968; DALLY, 1989); wave face steepness increases with increasing period and decreases with increasing height. In addition, bathymetry gradients usually change with increasing depth and so different height waves will break on different seabed gradients; this may be compounded by shifts in the breaker zone due to tidal cycles. Another complication is the speed of the waves themselves. Wave speed is relative to water depth and therefore bigger waves are travelling faster at the break point than smaller waves. In effect, at a specific peel angle, the surfer is travelling faster on bigger waves. More investigation into the speed attained by surfers (such as DALLY, this issue) and the maximum section of a breaking wave that can be successfully ridden with respect to the wave height and period, and the bathymetry over which the waves are breaking, will shed more light on this question in the future.

Scale has also been found to be important when focuses are considered. Some surfing breaks are essentially a large focus, for example Pipeline in Hawaii. In these cases, the deeper part of the focus aligns wave crests, which are also height reinforced into a peak as they move up the focus before breaking, as described above. Wave peeling is mainly a consequence of the height reinforcement into a peak and the consequent loss of wave height from adjacent parts of the wave. This results in a very pronounced wave height gradient from the peak formed along the apex of the focus, reducing down from the peak along the wave crest (Plate 4.2). Because wave breaking is dependent on water depth, the highest part of the wave, the peak, breaks earliest in deeper water and then along the reducing height gradient caused by the focusing as it encounters shallower water depths. While the large focus does have the advantage of greatly increasing wave height, it is susceptible to closing out in small wave conditions due to increased refraction prior to breaking (as described above) and also provides a relatively short ride due to the extraction of energy from adjacent parts of a wave.

Plate 4.2. Pipeline on Hawaii's North Shore is a good example of a large focus break. In this picture the height reduction along the wave crest due to energy extraction from the adjacent wave crest is very obvious. (Photo ASL Vol. 73, Oct. 1994).

The study presented here has greatly increased the understanding of the make-up and function of the bathymetry at natural high-quality surfing breaks. Isolating and describing the large-scale reef components (MEAD and BLACK, this issue) and how specific components combinations function to produce world-class surfing breaks represents a major advantage for incorporation of surfing into coastal construction. While some of the principles discussed above have already been applied to the design of artificial surfing reefs (e.g. BLACK *et al*, 1998a), this study has expanded upon them and we now have a wider range of options to draw upon. The numerical modelling of natural reef component configurations, as well as the manipulation of reef component configurations (MEAD and BLACK, 1999a), has well shown that refraction links reef components, and so a holistic approach must be taken when developing reef design. These studies have shed light on many aspects of surfing reef bathymetry and function and made it clear that design of artificial surfing breaks must take many different factors into consideration and take a holistic approach due to the interconnectivity of various components and the effects of component size. For instance, incorporating a focus into a surfing break can not only define the take-off zone, but also increase the wave height and lessen the difficulty required to catch a wave. However, as BLACK *et al.* (1998a) found, the focussing must be directed so as not to disrupt the rest of the surfing break by extracting too much wave energy from the adjacent wave crest and thereby divorcing itself from the rest of the wave.

The inter-dependent relationship between the favoured orthogonal direction, combination of reef components, component size and the peel angle must all be considered during surfing reef design in conjunction with specific site factors such as wave climate, existing bathymetry, etc., and the purpose for which the reef is being designed for whether it be coastal protection, a port wall, primarily a new surfing break or any manner of coastal development that may incorporate artificial reef technology. With a good understanding of reef component combinations and individual component functions it may now be possible to create surfing reef combinations that may not necessarily occur naturally to provide high-quality surfing conditions. The demand for new surfing reefs will continue to grow and the potential for multi-purpose artificial reefs will develop along with the need for environmentally-sensitive solutions to coastal protection and recreational usage of our beaches.

CONCLUSION

It is the specific combination of the meso-scale reef components at a surfing break that determine its overall quality and consistency. Because the process of refraction links components together, reef component combinations have a holistic nature. The analysis and numerical modelling of the database of world-class surfing reefs presented here has led to a much better understanding of the holistic nature and function of particular reef components and their common combinations. These principles must be taken into account and applied during the design of artificial surfing reefs.

ACKNOWLEDGEMENTS

This study formed part of the larger Artificial Reefs Program, which aims to enhance amenity value along New Zealand's coastline. The program is evaluating multiple use options for artificial reefs, with a particular emphasis on surfing. The Program is supported by the Coastal Marine Group at the University of Waikato and ASR Ltd.

REFERENCES

BATTJES, J. A., 1974. Surf Similarity. *Proceedings 14th Coastal Engineering Conference*, ASCE, 466-480.

BILDERBACK, 1994. Mr Lucky Does Australia. Australian Surfing Life, Ed. Tim Baker, Volume 73, October 1994.

BLACK, K. P., 1997. *Wave refraction model WBEND. Occasional Report, Centre of Excellence in Coastal Oceanography and Marine Geology, Department of Earth Sciences, University of Waikato, New Zealand.*

BLACK, K. P, 1998. *Narrowneck Reef Report 3: Sediment Transport. Technical Report prepared for the Gold Coast City Council, July, 1998.*

BLACK, K. P.; ANDREWS, C.; GREEN, M.; GORMAN, R.; HEALY, T.; HUME, T.; HUTT, J.; MEAD S., and SAYCE, A., 1997a. Wave Dynamics and Shoreline Response On and Around Surfing Reefs. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

BLACK, K. P.; GORMAN, R. M.; STEPHENS, S.; BEAMSLEY, B. J.; HEALY, T. R.; BELL, R. G., and OLDMAN, J. W., 1997b. *Port Gisborne Dredging Development AEE. Prepare for Port Gisborne Ltd., by Centre of Excellence in Coastal Oceanography and Marine Geology, Department of Earth Sciences, University of Waikato and National Institute of Water and Atmospheric Research.*

BLACK, K. P.; HUTT J. A., & MEAD, S. T., 1998a. *Narrowneck Reef Report 2: Surfing Aspects. Technical Report prepared for the Gold Coast City Council, June, 1998.*

BLACK, K. P.; HUTT J. A., & MEAD, S. T., 1998b. *Takapuna Boat Ramp: Surfing Impact Assessment and Reef Feasibility Study. Report for North Shore City Council, October, 1998.*

BLACK, K.P.; MEAD, S. T.; MCCOMB, P.; JACKSON, A., and ARMSTRONG, K., 1999. *New Plymouth City Foreshore Redevelopment: Reef and Beach Feasibility Study. Prepared by the Centre of Excellence in Coastal Oceanography and Marine Geology, for the New Plymouth District Council, March 1999.*

BUTTON, M., 1991. Laboratory Study of Artificial Surfing Reefs. Bachelor of Engineering, Department of Civil and Environmental Engineering, University of Western Australia, 1991. Pp.107

COURIEL, E. D., P. R. HORTON and D. R. COX, 1998. *Supplementary 2-D Physical Modelling of Breaking Wave Characteristics. WRL Technical Report 98/14, March, 1998. Pp. 27.*

DALLY, W. R., 1989. Quantifying Beach 'Surfability'. *Proceedings Beach Technology Conference*, Tamp, Florida, February, 1989.

DALLY, W. R., 1990. Stochastic Modelling of Surfing Climate. *Proceedings, Coastal Engineering Conference*, ASCE, Vol. 1, 516-529.

GALVIN, C. J., 1968. Breaker-Type Classification on Three Laboratory Beaches. *Journal of Geophysical Research*, Vol. 73, No. 12, June, 1968.

HUTT, J. A., 1997. Bathymetry and Wave Parameters Defining the Surfing Quality of Five Adjacent Reefs. Unpublished Thesis, University of Waikato, New Zealand.

JACKSON, A.; BLACK, K. P.; TOMLINSON, R.; MEAD, S. T.; MATHEW, J.; HUTT J. A., and SKELLY, D., 1999. *Recommendations for Noosa Main Beach Restoration and Protection. Report for Noosa Council, August, 1999.*

KOMAR, P. D., 1976. *Beach Processes and Sedimentation.* Prentice-Hall Inc., New Jersey.

LYONS, M., 1992. Design of an Artificial Surfing Reef. Bachelor of Engineering, Department of Civil and Environmental Engineering, University of Western Australia, 1992. Pp. 73.

MEAD, S. T., and BLACK, K. P., 1999a. Configuration of Large-Scale Reef Components at a World-Class Surfing Break: Bingin Reef, Bali, Indonesia. *Proceedings Coasts & Ports '99*, Vol. 2, 438-443.

MEAD, S. T., and BLACK, K. P., 1999b. A Multi-Purpose, Artificial Reef at Mount Maunganui Beach, New Zealand. *Coastal Management Journal* 27(4), 355-365.

MEAD, S. T., and BLACK, K. P., 2000. Predicting the Breaking Intensity of Surfing Waves. International Coastal Symposium (ICS2000) Rotorua, New Zealand. Special Issue of *Journal of Coastal Research* (in press).

MOFFAT & NICHOL, 1989. *The Patagonia Surfing Reef Feasibility Study. Report prepared for The Surfrider Foundation, Huntington Beach California, by Moffat & Nichol, Engineers, Long Beach, California. Job No. 2521, September, 1989. Pp. 39.*

PEREGRINE, D. H., 1983. Breaking Waves on Beaches. *Ann. Rev. Fluid Mech.*, 15, 149-178.

RAICHLE, A. W., 1998. Numerical Predictions of Surfing Conditions at Mavericks, California. *Shore & Beach*, April, 1998, 26-30.

SAYCE, A. J., 1997. Transformation of Surfing Waves Over Steep and Complex Reefs. Unpublished Thesis, University of Waikato, New Zealand.

SAYCE, A.; BLACK, K. P., and GORMAN, R., 1999. Breaking Wave Shape on Surfing Reefs. *Proceedings Coasts & Ports* '99, Vol. 2, 596-603.

SILVESTER, R., 1975. 1975. Synthetic Surfing Sites. University of Western Australia, Nedlands, Western Australia.

WALKER, J. R. and PALMER, R. Q., 1971. *A General Surf Site Concept. LOOK Laboratory TR-18, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii.*

WALKER, J. R.; PALMER, R. Q., and KUKEA, J. K., 1972. Recreational Surfing on Hawaiian Reefs. *Proceedings 13th Coastal Engineering Conference*, ASCE, Vol. 3.

WALKER, J. R., 1974. *Recreational Surf Parameters. LOOK Laboratory TR-30, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii.*

Chapter 5

CONFIGURATION OF LARGE-SCALE REEF COMPONENTS AT A WORLD-CLASS SURFING BREAK: BINGIN REEF, BALI, INDONESIA

Coasts and Ports '99 Conference Proceedings Vol. 2, 438-443

Configuration of Large-Scale Reef Components at a World-Class Surfing Break: Bingin Reef, Bali, Indonesia.

S. T. Mead and K. P. Black

Centre of Excellence in Coastal Oceanography and Marine Geology.

Department of Earth Sciences at The University of Waikato and

National Institute of Water and Atmospheric Research,

P.O. Box 11-115, Hamilton, New Zealand.

Phone: 64 7 856 7026 Fax: 64 7 856 0151 E-mail: asrltd@clear.net.nz

SUMMARY Bathymetric surveys of world-class surfing breaks have revealed large-scale reef components that holistically combine to produce high-quality surfing waves. Individual breaks are comprised of several of these components, or building blocks, often in recurring combinations that are linked by wave refraction. Here, 2-dimensional numerical wave refraction modelling is used to demonstrate the utility and connectivity of the specific combination of reef components at Bingin in Bali, Indonesia. Refraction modelling of the existing bathymetry at Bingin was in close agreement with field measurements and highlighted how the reef components function to produce consistent, high-quality waves. Wave breaking remained at a similar angle to the wave crest (~35°) over a range of wave heights and directions in the main area of surfing. A defined take-off zone was a persistent feature, which is a result of wave-focusing over a large-scale reef component. Also very obvious in the model simulations, was the fast-breaking, steeper faced, part of the wave at Bingin, that is produced by a smaller scale reef component positioned on top of a larger feature. When the reef components that comprise Bingin were manipulated, and sometimes omitted, in most cases, the consequent changes to wave refraction produced waves that broke with less than world-class characteristics. The most common result was that waves broke too fast for surfing, or 'closed-out. In some cases this could be overcome be re-orientating components at angles greater than those that exist at Bingin. However, this resulted in greater changes to peel angles with changing wave height and directions than normally experienced at Bingin. Re-positioning or omitting smaller reef components had less effect on wave breaking, but these changes still down-graded the quality of the wave for surfing.

1 INTRODUCTION

Artificial surfing reefs, whether incorporated into works for coastal protection (1, 2) or port developments (3), or specifically for amenity enhancement (4), are now becoming a feasible option for coastal construction. In New Zealand, the Artificial Reefs Program (ARP) was established to investigate alternative solutions to coastal construction that will mitigate environmental impacts as well as increase amenity values (5). Specifically, the ARP aims to enhance the coastal amenity value of the shoreline by evaluating multiple use options (coastal protection, habitat for marine organisms, surfing, diving, recreational and commercial fishing, boating and swimming safety) for incorporation into coastal structures.

As well as studies relating to the wave dynamics of surfing (6, 7) and the response of the shoreline in the lee of offshore reefs (8), the ARP has compiled a database of world-class surfing breaks to support the design of artificial offshore reefs that incorporate the amenities such as surfing and provide the coast with a predictable area of protection. The database contains the bathymetries, peel angles and wave breaking shape of some 34 surfing breaks from around the Pacific and Indonesia. Analysis of the database revealed recurring morphologies at surfing breaks.

These morphologies, or large-scale reef components, control wave refraction and allow waves to peel at surfable speeds. High-performance surfing requires fast peel angles. The peel angle determines surfing wave "speed" as the surfer travels ahead of the breaking section on the unbroken wave face. Strictly, the peel angle is defined as the angle between the trail of the broken white water and the crest of the unbroken part of the wave as it propagates shorewards (9). Small peel angles refer to fast surfing waves and large angles to slow surfing waves. Refraction modelling of breaks in the database of world-class surfing reefs has found that peel angles at these breaks are maintained by the configurations of the large-scale reef components. Here, we focus on Bingin Reef in Indonesia and demonstrate the utility and connectivity of the specific combination of reef components that comprise this surfing break.

2 COMPONENT CONFIGURATION FROM THE SURFING BREAK DATABASE

Analysis of the database revealed recurring large-scale seabed shapes at surfing breaks. These distinct units link together to form the shape of the full reef and control wave refraction, wave breaking and peel angles. Seven large-scale reef components have been classified from the database, using descriptive terminology. These are ramp, platform, focus, wedge, ledge, ridge and pinnacle. The ramp, platform and focus components pre-condition the wave (by aligning and shoaling), while the wedge, ridge, ledge and pinnacle components break the wave. Pre-conditioning of wave orthogonals results in wave alignment that produces a surfable peel angle when the waves break on the wave-breaking components.

Quality of the break depends on the arrangement of the components, which determines the wave direction or peel angle at the breakpoint. We term the wave orthogonal direction resulting from alignment by the pre-conditioning components as the 'favoured orthogonal direction'. If the waves are not aligned around the favoured orthogonal direction they will either peel too fast ('close-out') or too slow to be useful for high-performance surfing.

3 METHODS

3.1 Bingin Reef Survey

Bingin Reef is situated at the northern end of Bukit Peninsula, on the island of Bali in Indonesia. It is one of a series of coral reef breaks along the Bukit Peninsula that receive deep ocean swells from the south to south west during the southern hemisphere winter. Bingin Reef is world-renowned for consistently producing very high quality waves that break fast and hollow along the edge of the steep reef face for up to 90 m.

The bathymetry at Bingin was measured with satellite positioning (post-processed DGPS) and depth sounding equipment in a custom-built, compact surveying system mounted on an inflatable ocean kayak. High-density soundings, recorded at 1 s intervals along transects that were mostly isobath normal and generally <10 m apart, were used to generate bathymetric charts that revealed the shape and structure of Bingin reef. Wave breaking was videoed from the cliff top above the break while a surfable swell was present. During video recording, wave data was recorded by a Dobie pressure sensor.

3.2 Numerical modelling

The 2-dimensional numerical wave refraction model, WBEND (10), was used to model wave transformation over the variable topography of Bingin Reef. The model applies a fast, iterative, finite-difference solution of the wave action equations to solve for wave height, wave period, breakpoint location, longshore sediment transport, bottom orbital currents and near-bed reference concentration of suspended sediments. The most relevant outputs for surfing wave characteristics are wave refraction and shoaling, as they affect peel angle and wave height distribution at the breakpoint along the reef.

Table 5.1. Wave inputs for model simulations with measured Bingin Reef bathymetry.

Wave Hts (m)	Wave Angles (°T)	Period (s)
1-5 (1 m steps)	170-240 (10° steps)	16

The model results were found to be in close agreement with the field measurements when wave inputs similar to those recorded during the survey were simulated (1.8 m (H_{10}), 16 s period). The model showed fast peel angles of ~35° along the main length of the break. Observations of higher peel angles (slower) and increased wave height at the take-off and a faster peeling section across the ridge were also obvious in the model. The model was then used to simulate a larger variety of wave input angles and heights over the measured Bingin bathymetry (Table 5.1).

4 RESULTS

4.1 The arrangement and function of components at Bingin Reef

Examination of Bingin Reef's bathymetry reveals that it is comprised of the five large-scale reef components in the configuration depicted in Figure 5.1.

At Bingin, as waves propagate shoreward, they first encounter the ramp (Fig. 5.1). Refraction on the ramp aligns wave orthogonals closer to the favoured orthogonal direction. Thus, the ramp acts to orient incoming waves by reducing directional spread compared to the spectrum of offshore wave directions (Fig. 5.1). In addition, the ramp begins the process of wave steepening due to shoaling.

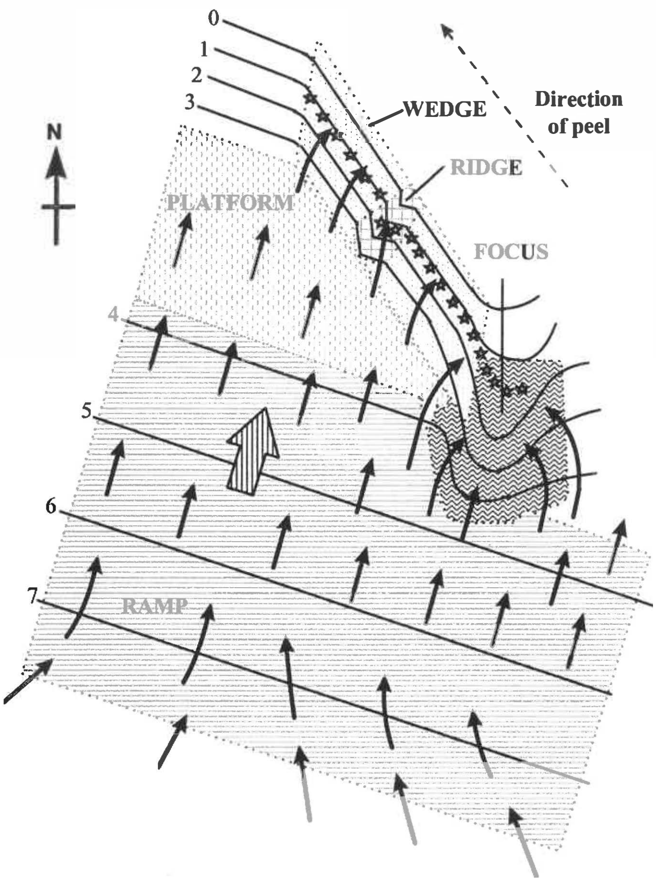


Figure 5.1. The configuration of large-scale reef components at Bingin Reef, Bali, Indonesia. The large arrow represents the favoured orthogonal direction, the smaller arrows represent the alignment of wave orthogonals as they pass over the various components. Stars indicate breakpoint for a 1 m wave at mid-tide. Depth contours approximate the measured Bingin Reef bathymetry.

The newly-aligned wave crests next detect the focus, where refraction acts to locally increase the wave height by bending the wave onto the focus as it travels shorewards along the focus apex (Fig. 5.1). Simultaneously, the wave steepens further as water depth decreases on top of the focus until breaking occurs. The peak in the wave height created by the focus breaks earlier than any other part of the wave, and so defines the start of the surfing ride, or the 'take-off' zone.

As the incoming wave enters shallower water at Bingin it peels to the left by breaking along the wedge (Fig. 5.1). The wedge subsequently refracts waves that were aligned to the favoured orthogonal direction by the ramp. The degree of refraction that occurs on the wedge prior to breaking leads to a surfable peel angle which is maintained at the break point along the wedge.

Beyond the focus, the ramp and wedge are separated by a horizontal platform. The wave orthogonal directions on the platform remain unchanged as there is minimal refraction on this horizontal feature (Fig. 5.1). As such, a relatively constant peel angle, set up by the wave orthogonal direction on the ramp, is maintained along the length of the Bingin wedge.

A ridge midway down the wedge creates an anomaly in the straight isobaths of the wedge (Fig. 5.1). The isobaths of the ridge cause a local increase in sea bed gradient and a reduction in the peel angle. This results in a locally-faster, steeper section of the wave that produces a 'tube-section'. Surfers often ride underneath the breaking crest of the tube-section in order to reach the next section of the wave.

4.2 Numerical Modelling

The most important finding of the numerical modelling of the measured Bingin bathymetry was the high stability of the wave peel angle at Bingin over a variety of wave heights and offshore directions. Wave peel angles consistently measured ~35°. Peel angles were only slightly higher as input angles tended towards the south (180°). In the take-off zone, where the focus creates a local peak, the peel angle is higher (40-55°).

Several other aspects of the break were confirmed with the model simulations. It was found that there is a maximum surfing wave height due to closing out on the platform. Waves of 4 m and higher closed-out at all input directions. As the wave input direction tended towards the south west (225°) wave height at breaking increased. At these input angles, waves travel relatively straight up the ramp and so less height is lost by refraction.

Also obvious in the model simulations was the faster-breaking part of the wave at Bingin in the 'tube-section' that is produced by the ridge component positioned on the wedge (Fig. 5.1). The length of this section was found to increase with increasing wave height. This was also observed in the video footage, and is due to the shape of the ridge, which is wider in deeper water (Fig. 5.1).

In the following sections, we manipulate and omit reef components to investigate how the peel angle is affected.

5 COMPONENT MANIPULATION

To allow manipulation of the large-scale components that comprise Bingin Reef, computer software was written which enabled components to be generated in a purely idealised form and oriented to create new reef bathymetries for modelling with WBEND (e.g. Fig. 5.2). This meant that Bingin's bathymetry could be reduced to a fundamental set of large-scale reef components. All of the reef components at Bingin Reef were reduced to the idealised form shown in Figure 5.2, except the ridge. It must be noted that the ridge is an important component of the break bathymetry, as it adds an extra dimension to the break in the form of a tube-section that is highly valued by surfers. However, the ridge is a small-scale component and omission of this component has little effect on the peel angle over the majority of the break. Therefore it was omitted during the component manipulations. Notably, re-location of this component to another position along the wedge would degrade the quality of the surfing break. Due to the break's relatively short length, the ridge must be placed centrally to enable entry to and exit from the tube-section.

Wave inputs with of heights 1-3 m and a broad spread of directions were simulated. Directions were +50° to -10° relative to the model grid, which corresponds to swells from 10° east of south through to WSW. A wave period of 16 s was adopted; long periods characterise the best surfing swells in Bali. Mid-tide was used for all model simulations (~1 m above datum).

The first test bathymetry consisted of all the reef components at Bingin Reef with the exception of the ridge, named Bingin A (Fig. 5.2). Although idealised, Bingin A with all of the fundamental components showed very similar results to the model runs with the measured bathymetry at Bingin. Resulting peel angles along the wedge were ~35° for all input heights and directions and the peak created by the focus had peel angles of 40-55°.

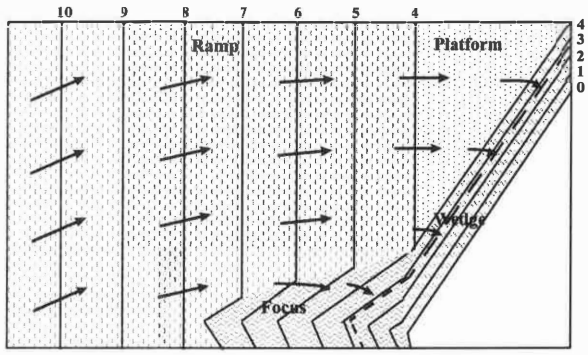


Figure 5.2 Bingin A - Idealised component bathymetry of Bingin Reef. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m above datum). Wave input was +20° relative to the model grid.

Next, the platform was removed from the component configuration (Bingin B, Fig. 5.3). Without the platform, peel angles decrease below those normally present on Bingin Reef and essentially close-out. This is mainly due to the replacement of the platform with the ramp. Because the ramp continues to shoal beyond the 4 m isobath of the missing platform, the wedge is also almost replaced by the ramp inshore (Fig. 5.3). As a result, waves >1 m break mainly on the ramp instead of the wedge with a greatly reduced peel angle. Only a small part of the surfing break still functions like the original Bingin configuration; the focus still created a defined take-off zone with a surfable peel angle of 40-55°. However, this section of the break is <20 m long, which is too short to be categorised as a world-class surfing break.

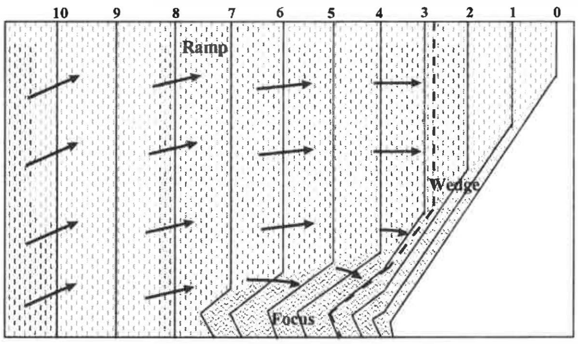


Figure 5.3 Bingin B - Idealised component bathymetry of Bingin Reef with the platform omitted. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m above datum). Wave input +20° relative to model grid.

To compensate for the loss of depth due to the removal of the platform, the wedge was moved further offshore into deeper water (Bingin C, Fig. 5.4). The focus was removed in this case for simplicity. As a result of the increase in depth above the wedge, more refraction now occurs on the wedge itself prior to breaking. Because of the increased refraction, the wave crests become more parallel to the wedge isobaths and the peel angle decreases, resulting in a wave that breaks too fast to be surfable, or closes out. This phenomenon is more evident at small wave heights because smaller waves break further shoreward and allow more refraction to occur. As wave height is increased, the peel angle increases but the waves are still unsurfable for many surfers and are lower than those normally experienced at Bingin Reef.

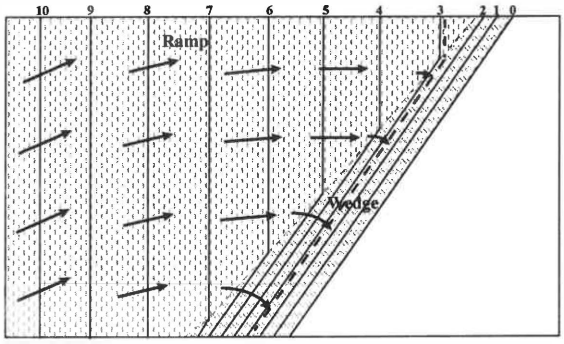


Figure 5.4 Bingin C - Idealised component bathymetry of Bingin Reef with the platform and focus omitted and the wedge moved to a greater depth. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m). Wave input +20° relative to model grid.

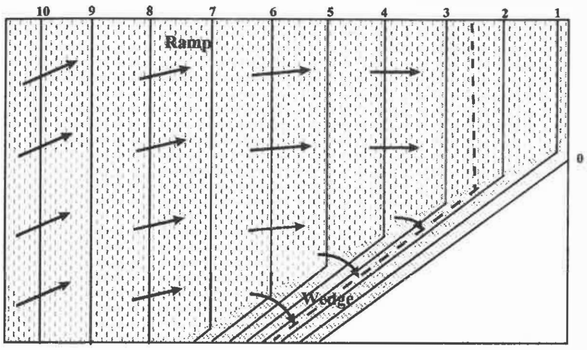


Figure 5.5 Bingin D - Idealised component bathymetry of Bingin Reef with the platform and focus omitted and the wedge in deeper water and rotated. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m). Wave input +20° relative to model grid.

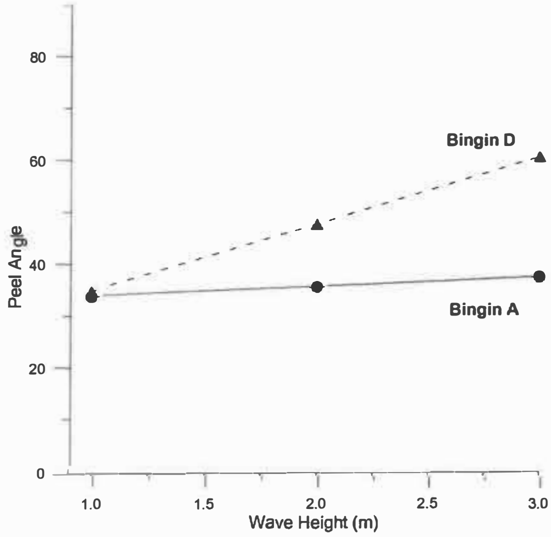


Figure 5.6 Changes in wave peel angle with respect to wave height for Bingin A (idealised bathymetry of existing Bingin Reef) and Bingin D (idealised bathymetry of Bingin Reef with no platform component and a rotated wedge at greater depth). Wave input +20° relative to model grid.

In order to alter the peel angle on the wedge of Bingin C to an angle that is able to be surfed, it had to be rotated more parallel to the wave orthogonal; i.e. at a greater angle to the ramp (Bingin D; Fig. 5.5). The focus was also removed in this case for simplicity.

On Bingin D, peel angles are high enough for the wave to remain surfable; at 1 m the peel angle is similar to the existing peel angle at Bingin (~35°). However, as wave height increases so does peel angle.

In Figure 5.6, the changes in wave peel angle with changes in wave heights are compared between Bingin A and Bingin D. The greater variability in peel angle of the configuration without the platform is clear. Peel angles in Bingin D markedly increase with increasing wave height. Peel angles can be increased to a range that are considered surfable by rotating the wedge but, at larger wave heights, they are significantly greater than those that normally occur at Bingin and are mostly too high (slow) for the break to remain world-class are.

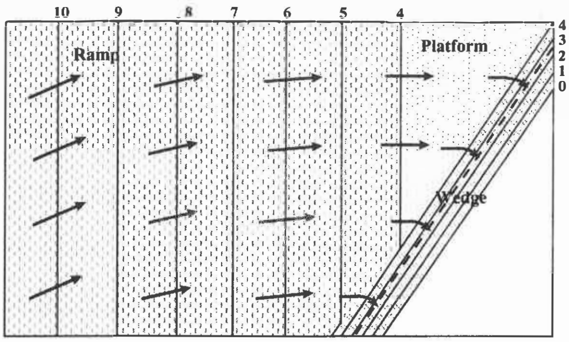


Figure 5.7 Bingin E - Idealised component bathymetry of Bingin Reef with the focus omitted. Arrows represent wave orthogonals. The dashed line represents breakpoint of a 2 m wave at mid-tide (~1 m). Wave input +20° relative to model grid.

The last configuration investigated was Bingin E, in which the focus was removed from the Bingin A configuration (Fig. 5.7). While the wave still breaks along the wedge at the existing Bingin angle of ~35° for a range of wave heights and directions, there is no longer a defined take-off zone. The absence of the slower peel angle and increased height of the wave in the take-off zone decreases the chances of successfully catching the wave, and encourages surfers to take-off further along the wave.

Without the defined take-off zone, there is inevitably an increase in 'dropping-in', an undesirable situation where a surfer catches the wave further down the wave from the area of peeling even though another surfer is already riding the wave close to the peel and therefore has priority. The surfer that 'drops-in' along the wave relies on the wave to break too fast for the surfer with priority, who is left behind in the white water and unable to continue the ride.

6 CONCLUSION

Many observed surfing wave characteristics of Bingin Reef in Bali (Indonesia) were confirmed with numerical model simulations of measured bathymetry and a series of idealised morphologies. Not only for its speed and hollow waves, Bingin Reef proved to be a world-class surfing break because of the stability of the wave peel angle over a variety of wave heights and offshore directions. Although there are many other factors such as wave steepness, speed of ride, length of ride, height of wave, prevailing winds, etc., that add to a surfing break's reputation, consistency of a break is a very important factor.

Bingin Reef's reputation as a break that consistently produces world-class surfing waves stems from the ramp-platform-wedge configuration of the large-scale reef components that constitute the break's bathymetry. Omission or reorientation of components invariably down-graded its surfing characteristics. After removing the platform, surfable peel angles could only be achieved by moving the wedge component offshore and rotating it at a greater angle to the ramp. However, peel angles of the modified configuration were mostly greater than those that normally occur at Bingin and were too high (slow) for the break to remain world-class. Moreover, a high variation in peel angles occurred with changes in wave height, which resulted in quality waves over a narrower range of conditions. The bathymetry of the natural world-class surfing reef at Bingin is much more sophisticated than a simple (one or two component) configuration.

7 ACKNOWLEDGEMENTS

J. Radford at the University of Waikato for development of the bathymetric surveying equipment.

8 REFERENCES

1 Black K. P., J. A. Hutt and S. T. Mead, 1998. Narrowneck Reef, Report 1: Surfing Aspects. Report to the Gold Coast City Council, March, 1998.

2 Black, K. P., 1998. Narrowneck Reef, Report 3: Sediment Transport. Report to the Gold Coast City Council, March, 1998.

3 Black, K. P., R. M. Gorman, S. Stephens, B. J. Beamsley, T. R. Healy, R. G. Bell and J. W. Oldman, 1997. Port Gisborne Dredging Development AEE. Prepare for Port Gisborne Ltd., by Centre of Excellence in Coastal Oceanography and Marine Geology, Department of Earth Sciences, University of Waikato and National Institute of Water and Atmospheric Research.

4 Pattiaratchi, C., 1997. Design Studies for an Artificial Surfing Reef at Cable Station, Western Australia. Proceedings of the 1st International Surfing Reef Symposium, Sydney, Australia. March, 1997.

5 Black, K. P., C. Andrews, M. Green, R. Gorman, T. Healy, T. Hume, J. Hutt, S. Mead and A. Sayce, 1997. Wave Dynamics and Shoreline Response On and Around Surfing Reefs. Proceedings of the 1st

International Surfing Reef Symposium, Sydney, Australia. March, 1997.

6 Hutt, 1997. Bathymetry and Wave Parameters Defining the Surfing Quality of Five Adjacent Reefs. Unpublished MSc Thesis. Centre of Excellence in Coastal Oceanography and Marine Geology, Earth Sciences Department, University of Waikato.

7 Sayce, 1997. Transformation of Surfing Waves On Steep and Complex Reefs. Unpublished MSc Thesis. Earth Sciences Department, University of Waikato.

8 Andrews, C. J., 1997. Sandy Shoreline Response to Submerged and Emerged Breakwaters, Reefs or Islands. Unpublished MSc Thesis. Centre of Excellence in Coastal Oceanography and Marine Geology, Earth Sciences Department, University of Waikato.

9 Walker, J. R, 1974. Recreational Surf Parameters. LOOK Laboratory TR-30, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii, 1974.

10 Black, K. P., 1997. Wave refraction model WBEND . Occasional Report, Centre of Excellence in Coastal Oceanography and Marine Geology, Department of Earth Sciences, University of Waikato, New Zealand

Chapter 6

PREDICTING THE BREAKING INTENSITY OF SURFING WAVES

Journal of Coastal Research, Special ICS 2000 Issue (Accepted)

Predicting the Breaking Intensity of Surfing Waves

Shaw Mead† and Kerry Black‡

†Coastal Marine Group, Department of Earth Sciences. University of Waikato & Private Bag 3105, Hamilton, New Zealand

‡ASR Ltd. PO Box 13048, Hamilton, New Zealand

s.mead@asrltd.co.nz, k.black@asrltd.co.nz

ABSTRACT

A method for predicting and describing the breaking intensity of plunging surfing waves has been developed. This method uses the orthogonal seabed gradient to predict the wave vortex lenght to width ratio, which was found to be the best indicator of wave breaking intensity. The subtle differences in the vortex shape of plunging waves on different seabed gradients can now be described much better than with simplistic indicators, such as the Irribarren number. Description of the shape of plunging waves, or the tube-shape, is critical for defining quality surfing waves. These quantitative predictions of tube shape will be incorporated into artificial surfing reef design.

ADDITIONAL INDEX WORDS: *vortex ratio, seabed gradient, tube shape, Irribarren number*

INTRODUCTION

Of the four breaker types (GALVIN, 1968; PEREGRINE, 1983; BATTJES, 1988), spilling and especially plunging, waves are required for surfing (WALKER, 1974). Collapsing and surging breakers occur at the water's edge or where very steep seabed gradients come close to the water's surface. Such waves cannot be surfed because they lack a steep smooth face (Plate 6.1) and/or they break at the water's edge, i.e. a surf zone through which breaking waves propagate does not exist.

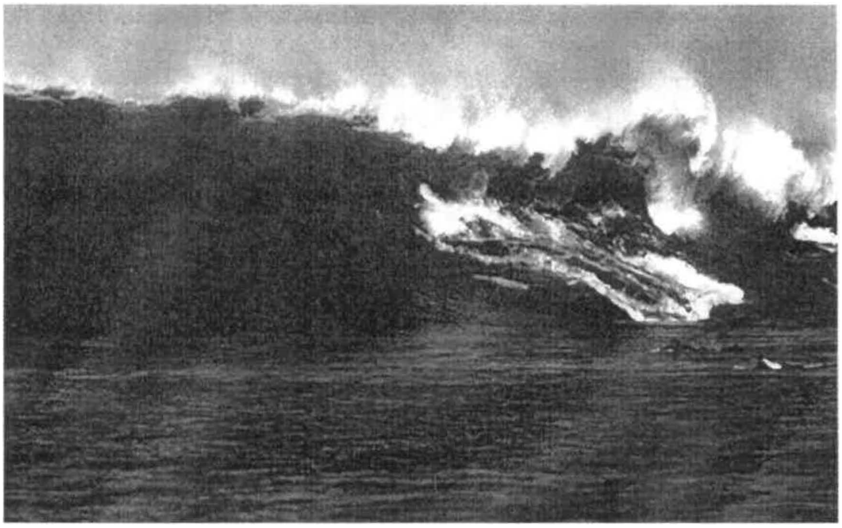


Plate 6.1. A wave collapsing as it breaks above the very steep seabed of Todo Santos reef in Mexico (after Sayce, 1997).

Indeed, surfing requires a steep unbroken wave face to create board speed for performing manoeuvres. In particular, good surfing waves break in a 'peeling' manner, where the breaking region of the wave translates laterally across the wave crest (DALLY, 1990; HUTT, 1997). It is the area close to the breaking crest of the peeling wave, sometimes known as the 'pocket', which has the steepest face and therefore offers the most speed for surfing (Plate 6.2). For detailed discussion of peel angles of surfing waves see WALKER, 1974; DALLY, 1990; BLACK *et* al., 1997; HUTT, 1997; MEAD and BLACK, 1999a; HUTT *et al.*, 2000.

Plate 6.2. The steep wave face close to the peeling crest of the wave, known as the pocket, offers the most speed for surfing.

While both spilling and plunging waves are utilised for surfing, the face of a spilling wave is relatively gently sloping and therefore provides low board speed in comparison to the steeper-faced plunging wave. As a consequence, spilling waves are not preferred for surfing, except by beginners in the early stages of learning. Of the four categories of breakers (spilling, plunging, collapsing and surging), it is plunging waves that are sought by surfers. The steep face of a plunging wave provides the high downhill speed needed to perform manoeuvres, not unlike that required for skiing. In addition, the open vortex of the plunging wave provides the opportunity to perform surfing's ultimate manoeuvre, the tube ride, where the surfer rides under the breaking jet of the wave (Plate 6.3).

Plate 6.3. A surfer riding under the jet of a breaking wave; the tube ride.

Surfers are usually able to distinguish between the vortex shape of waves at different breaks. Most experienced surfers can be shown a picture of a plunging wave profile (i.e. viewed crest parallel, into the vortex of the breaking waves – Plate 6.3) and be able to name the surfing break that the wave is breaking at. This ability to identify the location of surfing waves does not rely on water-colour, background landmarks or repeated photographic angles. It is the subtle differences in the shape of the face of the breaking wave, the vortex or tube shape, that allows the distinction to be made. As is implied by the sequence of breaker types (spilling though to surging), there is a transition between them and so it follows that within a category there is also a sequence, e.g. from gentle plunging to extreme plunging. This has previously been termed breaking intensity (SAYCE, 1997; SAYCE *et al.*, 1999).

The range of breaking intensity of surfing waves is reflected by the different terms used by surfers to describe surfing waves. As mentioned above, spilling waves are usually not preferred for surfing due to the difficulty in generating board speed on the gently sloping wave face. Surfers often term spilling waves as 'fat' or 'gutless', which indicates the lack of speed/power that can be generated on them while surfing. There are many descriptive terms that surfers use to describe plunging waves such as 'tubing', 'hollow', 'pitching' and 'square'. However, exactly what is meant by a specific term, and how this relates to the wave's breaking intensity, is subjective and often depends on the experience of a surfer. A definitive description of wave breaking intensity is required to relate the subtleties of surfing waves in a way that can be universally understood. Thus, it is critical to have a highly-refined definition of the wave breaking intensity and to define the actual shape of the plunging wave profiles.

Several factors affect the category that waves fall into when breaking (spilling, plunging, collapsing or surging), such as wave height and period (IRRIBARREN and NOGALS, 1947 – cited SAYCE, 1997; DALLY, 1989), and wind strength and direction (GALLOWAY *et al.*, 1989; MOFFAT and NICHOL, 1989; BUTTON, 1991). However, it is the underlying bathymetry that influences the shape of breaking waves the most (PEREGRINE, 1983; BATTJES, 1988; SAYCE, 1997). The transition of breaker shape, from spilling through to surging, is mainly a result of increasing seabed gradient. On low gradient seabeds, waves break with a spilling form. As seabed gradients increase, breaker form tends towards plunging, and finally to collapsing or surging waves on very steep gradients (BATTJES, 1988).

Here, surfing wave profile (vortex shape) information from a database of mostly world-class surfing breaks is used in conjunction with the local seabed gradients to quantify breaking intensity as a predictive tool for surfing reef design. This study investigates the curvature of a breaking wave in comparison with the underlying bathymetry of well-known surfing reefs around the Pacific Rim and Indonesia. The methods used are similar to those developed by SAYCE (1997) and SAYCE *et al.* (1999) to fit a cubic curve to the face of plunging waves (LONGUET-HIGGINS, 1982). However, the previous authors had limited information about seabed gradients, and so the present analysis is the first to relate wave vortex parameters to seabed slopes at a wide selection of world-class surfing breaks. The seabed gradients used to develop the method of predicting wave-breaking intensity described here range between 1:8 and 1:40 and relate to plunging, or 'tubing' surfing waves.

THE IRRIBARREN NUMBER

Existing methods that have been used to describe wave breaking characteristics employ a non-dimensional parameter, such as the Irribarren number (IRRIBARREN and NOGALS, 1947 – cited SAYCE, 1997; DALLY, 1989), the surf scaling parameter (GUZA and INMAN, 1975 – cited SAYCE, 1997) or the surf similarity parameter (BATTJES, 1974). These methods take into account all forms of wave breaking (spilling through to collapsing). All are based on wave steepness (H_b/L_∞) and a single value of beach slope, β. For example, DALLY (1989) defines the Irribarren number (ξ_b) as,

$$\xi_b = \frac{\beta}{\sqrt{H_b / L_\infty}} \qquad (6.1)$$

where β is the beach slope. Once ξ_b is calculated, it is used to classify the breaker type, with higher values indicating higher intensity breaking and each breaker type classified within a range of values (e.g. $0.5 < \xi_b < 3.3$ indicates plunging waves). However, while these methods give an indication of breaker intensity, previous studies of surfing wave shape have found that they do not well differentiate the transition between breaker categories (BUTTON, 1991; SAYCE, 1997; COURIEL *et al.*, 1998; SAYCE *et al.*, 1999). In addition, these values do not describe the actual shape of plunging/surfing wave profiles, or tube shape, which is imperative for describing surf quality. A better method of wave shape definition is required for surfing waves.

CUBIC CURVE FITTING

LONGUET-HIGGINS (1982) showed that a cubic curve gave a good description of the forward face of a plunging wave viewed in profile, i.e. parallel to the crest (Figure 6.1). The parametric form of the cubic curve is

$$\left.\begin{aligned} x/a &= 3\mu^2 - 1/3, \\ y/b &= -\mu^3 + 2\mu \end{aligned}\right\} \qquad (6.2)$$

where μ is the free parameter on the curve given in parametric form, x and y are spatial co-ordinates relative to the axis of symmetry and a and b are length scale parameters (Figure 6.2). The LONGUET-HIGGINS (1982) cubic curve intersects the x-axis when μ = 0 and +/-√2, that is at vertex and node points x/a=-1/3 and 17/3, respectively, the latter point being a double point on the curve (Figure 6.2). Hence the loop of the cubic curve has an aspect ratio of:

$$\frac{Length}{Width} = \frac{\Delta x/a}{\Delta y/b} = 2.75 \qquad (6.3)$$

where the maximum width is approximately 1/3rd of the of the way from the vertex to the node points. Subsequent work with cubic curve-fitting to the forward face of the wave has shown that the aspect ratio of the vortex of surfing waves is often not close to LONGUET-HIGGINS (1982) value of 2.75 and can range between 1.73 and 4.43 (SAYCE, 1997; COURIEL *et al.*, 1998; SAYCE *et al.*, 1999).

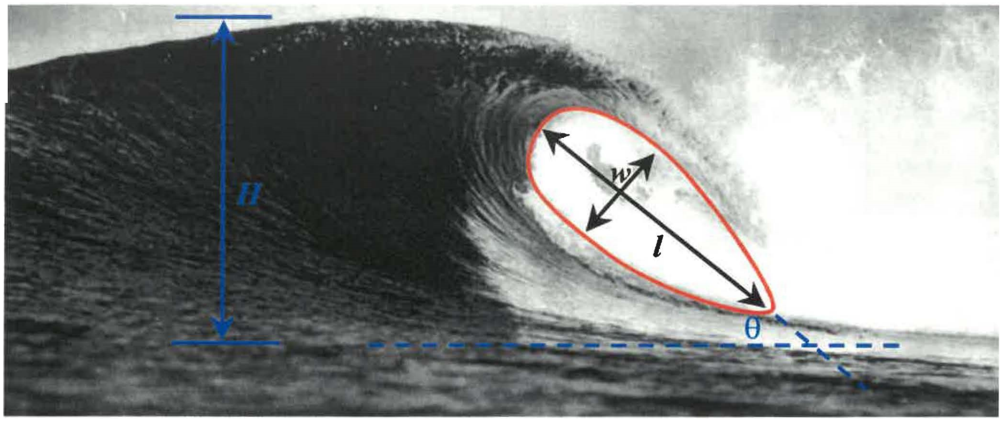


Figure 6.1. Curve fitting is applied to the forward face of a crest parallel wave image and used to calculate the vortex length (l), width (w) and angle (θ). H is the estimated wave height (after BLACK *et al.*, 1997).

For this study, a MATLAB® program named CRVFIT (GORMAN, 1996) was used to fit a cubic curve to crest parallel images of breaking waves (SAYCE, 1997; SAYCE *et al.*, 1999). A wave vortex image is loaded into MATLAB® and points around the vortex are digitised on screen. CVRFIT then applies the cubic curve equation (6.2) to the digitised points on the image by running through a fitting routine. The fitting routine manipulates the cubic curve, to a pre-selected tolerance, until a minimum squared distance (Equation. 6.4) from all the digitised points is achieved. The error function is,

$$\chi = \frac{\sum d_i^2}{\sum D_i^2} \qquad (6.4)$$

where D_i is the distance from the digitised point to the mean x and y position, and d_i is the distance from the digitised point to the fitted curve (Figure 6.3). In addition, wave height and angle are calculated from a baseline that is also digitised on screen.

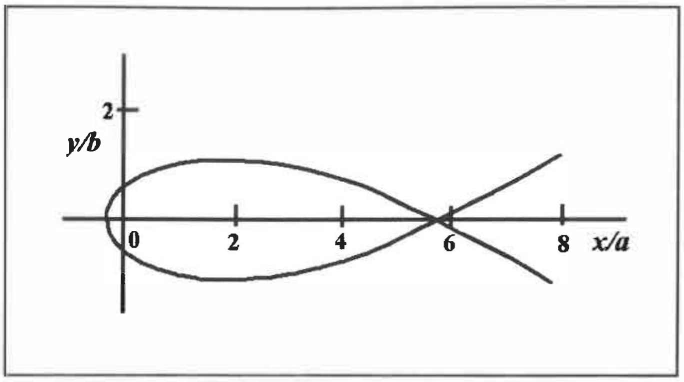


Figure 6.2. The profile of the cubic curve (LONGUET-HIGGINS, 1982).

CRVFIT outputs statistics from the fitted curve and displays the curve on the wave image (Figure 6.1). The statistics of interest for this study are vortex length (*l*), vortex width (*w*), vortex breaking angle (θ) and wave height (*H*). Although vortex area has been used previously to investigate wave breaking intensity (SAYCE, 1997; SAYCE *et al.*, 1999), many of the wave images used in this study did not have surfers present and so the estimates of dimensions could not be accurately scaled. Instead, relative measurements were made using pixels as units.

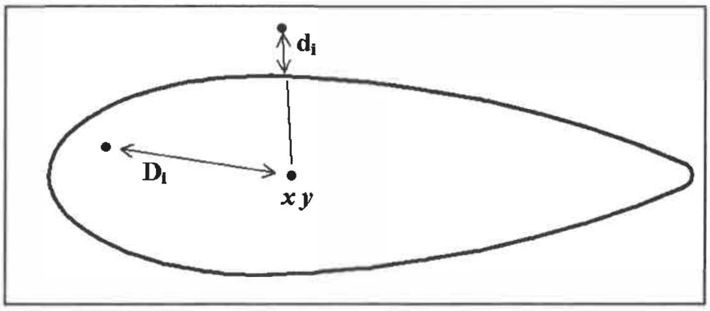


Figure 6.3. The error is derived from the mean-squared distance (Equation. 6.4) of digitised points from the fitted curve, where D_i is the distance from the mean *x* and *y* position and d_i is the distance from the fitted curve (after SAYCE 1997).

IMAGE ANALYSIS

Images of waves breaking crest parallel were collected at world-class surfing breaks around the Pacific Rim and Indonesia using two methods; *in situ* video recording and scanning of images from surfing magazines. During site visits to survey the bathymetry of world-class surfing breaks (MEAD *et al.,* 1998; MEAD and BLACK, 1999a, MEAD and BLACK, 2000a&b), there were sometimes opportunities to video waves breaking from a crest parallel position using a video camera in a water-proof housing. However, the field surveys were usually timed to coincide with seasons when the least swell was present to enable the bathymetric surveys to be undertaken. As a consequence, many surfing locations did not break during site visits and so video of the breaking waves could not be recorded. Instead, photographs from a range of national and international surfing magazines were utilised. A total of 48 images from 23 different breaks were analysed.

The wave profile video and photographs needed to be taken from the correct aspect (crest parallel) and have a clear view of the wave vortex (e.g. Figure 6.1). Video footage was searched through and a digital frame grabber and imaging software were used to save appropriate images for the curve-fitting routine. Magazine photographs had to be carefully selected because distortions through photographic enhancement or through being non-parallel to the wave crest would result in parallax errors. A scanner and imaging software were then used to convert the magazine photographs to digital images. All images (video frame grabs and scanned photographs) were saved in Tiff format (uncompressed tagged image format, *.tif).

Some modifications were carried out prior to curve-fitting analysis. Some images had to be reflected so that all images were right-hand breaking for the CRVFIT routine to operate correctly. All the Figures in this manuscript (with the exception of Plate 6.2) show right-hand breaking waves, with the wave propagating from the left to the right of the image. Right-hand wave breaking is surfing terminology that denotes the direction that surfing waves peel; viewed from the shore, right-handers peel from right to left. Several images from the video footage were also 'sharpened' in order to clearly differentiate the tube and get the best possible fit when digitising.

The digital wave images were then analysed using the MATLAB® program CRVFIT. As described above, CRVFIT outputs the cubic curve statistics of the best fit to the points digitised around the forward face of the wave. Table 6.1 is a record of the parameters calculated from the curve fitting statistics for each image analysed that were used to investigate the relationship between the wave breaking intensity and the underlying seabed gradient.

Table 6.1. *Wave vortex statistics obtained by curve-fitting to crest parallel images of waves breaking at mostly world-class surfing breaks. Wave height estimates could not be made for some images.*

Wave Location	Vortex Length on Width	Vortex Length on Wave Height	Vortex Width on Wave Height	Vortex angle (deg.)	Error in Curve Fitting
Backdoor1	2.05	0.41	0.85	48	0.0021
Backdoor2	2.19	-	-	37	0.00053
Backdoor3	2.02	-	-	50	0.0013
Backdoor4	2.21	0.40	0.89	58	0.0023
Backdoor5	2.16	-	-	44	0.0023
Bells Beach	2.64	0.26	0.69	35	0.0033
Bingin1	2.63	0.12	0.33	38	0.0013
Bingin2	2.57	-	-	44	0.0012
Bingin3	2.54	0.28	0.71	41	0.0016
Bingin4	2.62	-	-	39	0.0011
Boneyards	3.19	0.22	0.7	51	0.0032
Burleigh Heads	2.28	-	-	39	0.0031
Ipenema1	2.97	-	-	33	0.0036
Ipenema2	2.74	-	-	44	0.0034
Kirra Point	2.24	0.38	0.85	40	0.0036
Lyall Bay	3.43	-	-	53	0.0034
The Ledge	1.85	0.56	1.04	46	0.0015
Manu Bay	2.89	0.24	0.69	36	0.0024
Narrowneck Reef	1.68	0.46	0.78	35	0.0032
Off the Wall1	2.54	-	-	47	0.0027
Off the Wall2	2.34	0.31	0.72	41	0.0024
Off the Wall3	2.33	0.31	0.72	44	0.0025
Off the Wall4	2.19	0.33	0.72	51	0.0012
Off the Wall6	2.31	0.31	0.72	40	0.0048
Outsides1	2.40	0.33	0.8	33	0.0026
Outsides2	2.44	-	-	52	0.0013
Padang Padang1	2.02	-	-	29	0.0025
Padang Padang2	2.14	-	-	33	0.0018
Padang Padang3	1.97	0.4	0.78	41	0.0032
Pipeline1	1.75	0.58	1.01	40	0.0031
Pipeline2	1.75	0.55	0.96	55	0.0054
Pipeline3	1.92	0.49	0.93	35	0.0019
Pipeline4	1.82	-	-	37	0.002
Pipeline5	1.56	0.58	0.91	35	0.0022
Pipeline6	1.79	-	-	41	0.0011
Rockpiles1	2.31	0.26	0.6	50	0.0011
Rockpiles2	2.39	0.25	0.6	41	0.0028
Rocky Point1	2.90	-	-	51	0.0014
Rocky Point2	2.73	0.3	0.81	34	0.0019
Sanur	2.13	-	-	35	0.0058
Shark Is. 1	1.71	0.53	0.96	44	0.002
Shark Is. 2	1.86	0.54	1.11	41	0.0028
Shark Is. 3	1.42	-	-	29	0.0092
Summercloud1	2.27	-	-	38	0.0017
Summercloud2	2.30	-	-	45	0.001
The Wedge	1.80	-	-	-	0.0017
Whangamata1	2.95	0.18	0.53	33	0.0048
Whangamata2	2.90	-	-	43	0.0013

ANALYSIS OF SEABED GRADIENTS

Bathymetry grids, which were created from bathymetric survey information of each surfing reef in the database of world-class surfing breaks (MEAD *et al.,* 1998; MEAD and BLACK, 1999a, MEAD and BLACK, 2000a&b), were used to calculate the seabed gradient at each of the breaks. Surface mapping software (SURFER© V. 6.03, 1993-1996 Golden Software, Inc.) was used to digitise seabed profiles, which were graphed and measured to assess the local seabed gradient (Figure 6.4). This method was used to assess seabed gradients at all except three of the breaks analysed; Ipanema Beach, Lyall Bay and Narrowneck Reef. Nautical charts were used to estimate seabed gradients at Ipanema Beach and Lyall Bay, and the reef design plans were utilised for Narrowneck Reef (BLACK *et al.*, 1998).

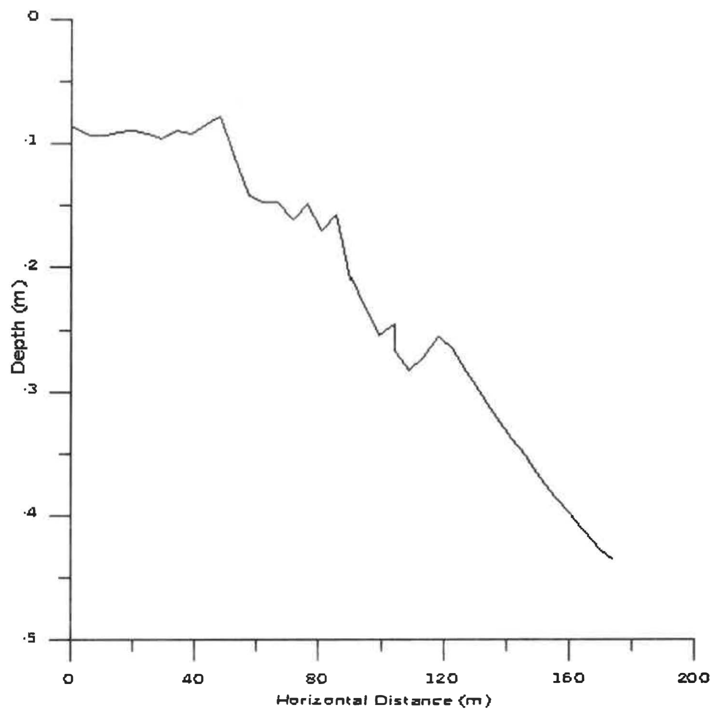


Figure 6.4. Example of seabed gradient profile created by digitising a bathymetry grid and then plotting using GRAPHER software (V. 1.3 1993-1996 Golden Software, Inc.).

Seabed gradients were measured both perpendicular to depth contours and along the path of incoming waves (orthogonal gradients). To ascertain the direction of wave propagation relative to the bathymetry grids, wave crest orientation just prior to wave breaking was measured from aerial photographs of the breaks (e.g. HUTT, 1997). In some cases, where the vortex images had been recorded using a video camera in a waterproof housing, GPS positions of the breaking waves were recorded. This allowed for a precise location of the seabed gradient that the waves were breaking on.

Seabed gradients of the magazine images were estimated by applying a wave breaking height to water depth ratio of 0.78 ($H_b/d = 0.78$). The seabed gradient 2-3 m shallower and 2-3 m deeper than the resulting breaking depth was then averaged to estimate the underlying seabed gradient. This 4-6 m range for seabed gradient estimation accounted for possible errors in wave height estimation, tidal range and increases in the height to water depth ratio due to the steep seabed gradients found at surfing breaks (U.S. ARMY COASTAL ENGINEERING RESEARCH CENTRE, 1975). In cases where the wave height was unknown, seabed gradients were averaged over a greater depth range, usually from lowest astronomical tide to a depth of 6-8 m. All estimations of seabed gradients with respect to wave breaking position took into account possible tidal ranges and local knowledge of swell directions and tidal phases that breaks would most likely produce the best quality waves, such as those photographed in surfing magazines.

RESULTS

Figures 6.5 to 6.11 were used to assess relationships between the wave vortex parameters and measured local seabed gradients.

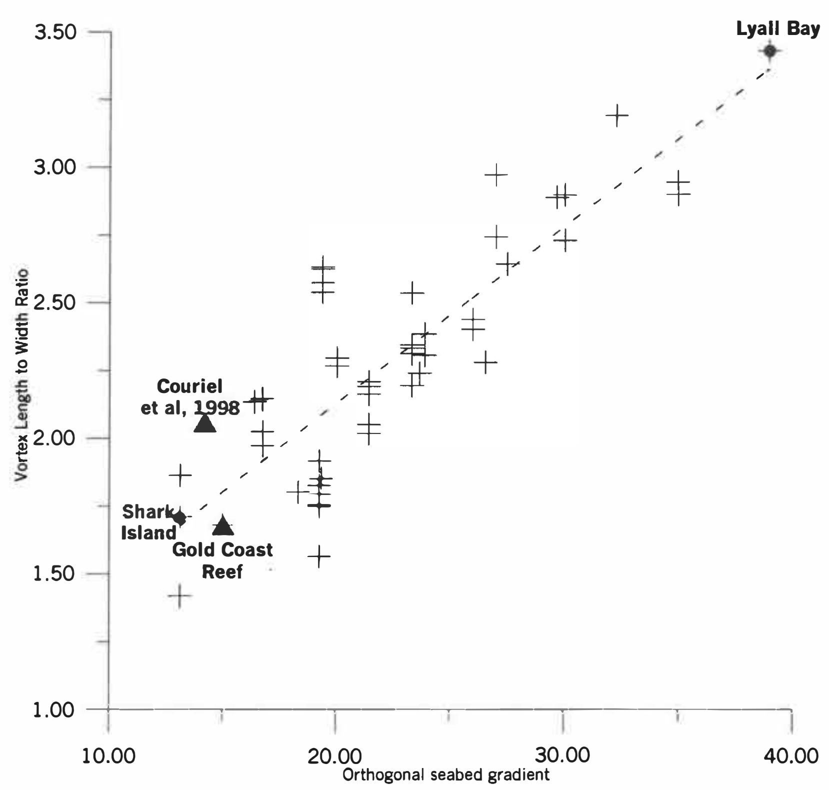


Figure 6.5. Orthogonal seabed gradient versus the ratio of vortex length to vortex width ($R^2 = 0.71$). The orthogonal seabed gradient (given as the horizontal distance to one vertical unit) is the gradient along the direction of wave propagation. Additional data points are the Gold Coast artificial reef and the mean of COURIEL *et al.*'s (1998) results.

The best relationship between vortex parameters and local seabed gradients was found between the orthogonal seabed gradient and the ratio of vortex length to vortex width ($R^2 = 0.71$) (Figure 6.5). This relationship is described by the linear equation,

$$Y = 0.065X + 0.821 \qquad (6.5)$$

where X is the orthogonal seabed gradient and Y is the vortex ratio. The ratio of vortex lenght to vortex width ranges from 1.42 to 3.43. Using this ratio as a measure of wave breaking intensity, low numerical values relate to high intensity waves and intensity decreases with increasing values of the length to width ratio. Near the line of best fit, breaking intensity ranges from Shark Island (New South Wales, Australia) as the most intense, to Lyall Bay (Wellington, New Zealand) as the least intense. Shark Island and Lyall Bay also have the steepest and gentlest seabed gradients, respectively. The artificial reef on the Gold Coast in Queensland, Australia (BLACK *et al.*, 1998), and the mean results of laboratory tests on a 1:14 seabed gradient (COURIEL *et al.*, 1998) lie close to the line of best fit and are shown to produce high intensity waves.

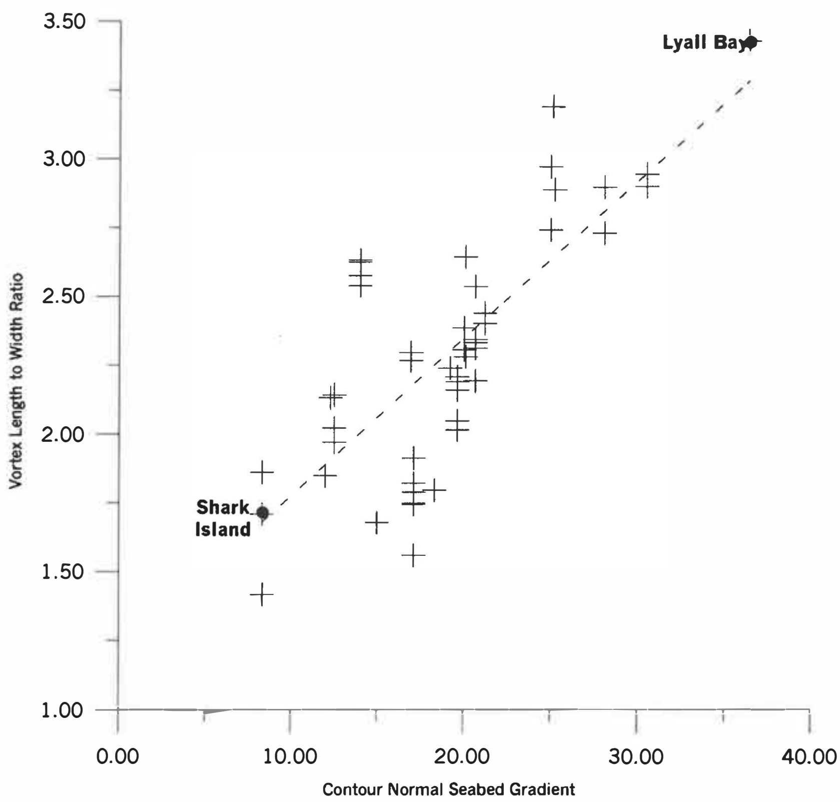


Figure 6.6. The relationship between the contour normal seabed gradient and the ratio of vortex length to vortex width ($R^2 = 0.57$). The contour normal seabed gradient (given as the horizontal distance to one vertical unit) is the steepest possible seabed gradient.

When the relationship between the contour normal seabed gradient and the ratio of vortex length to vortex width was considered (Figure 6.6), it was found that the relationship was not as good as that found when the orthogonal gradient was used (contour normal $R^2 = 0.57$ vs orthogonal gradient $R^2 = 0.71$). In this comparison, breaking intensity also ranges from Shark Island as the most intense, to Lyall Bay as the least intense near the line of best fit.

There is little to indicate the good relationships between vortex angle and other vortex parameters (Figures 6.7-6.9) that have been previously suggested (SAYCE, 1997; COURIEL *et al.*, 1998; SAYCE *et al.*, 1999). The range of wave vortex angles at these mostly world-class surfing breaks is 32° to 57°. Although the breaks with the lowest and highest seabed gradients (Lyall Bay and Shark Island, respectively) are separated by the greatest distance, when the vortex angle is compared to the ratio of vortex length to width (Figure 6.7), there is little evidence of a correlation between these parameters ($R^2 = 0.03$). A similar result is found when the relationships between vortex angle and the ratio of vortex width to wave height, and between vortex angle and the ratio of vortex length to wave height are considered ($R^2 = 0.02$ and 0.03, respectively) (Figures 6.8 and 6.9).

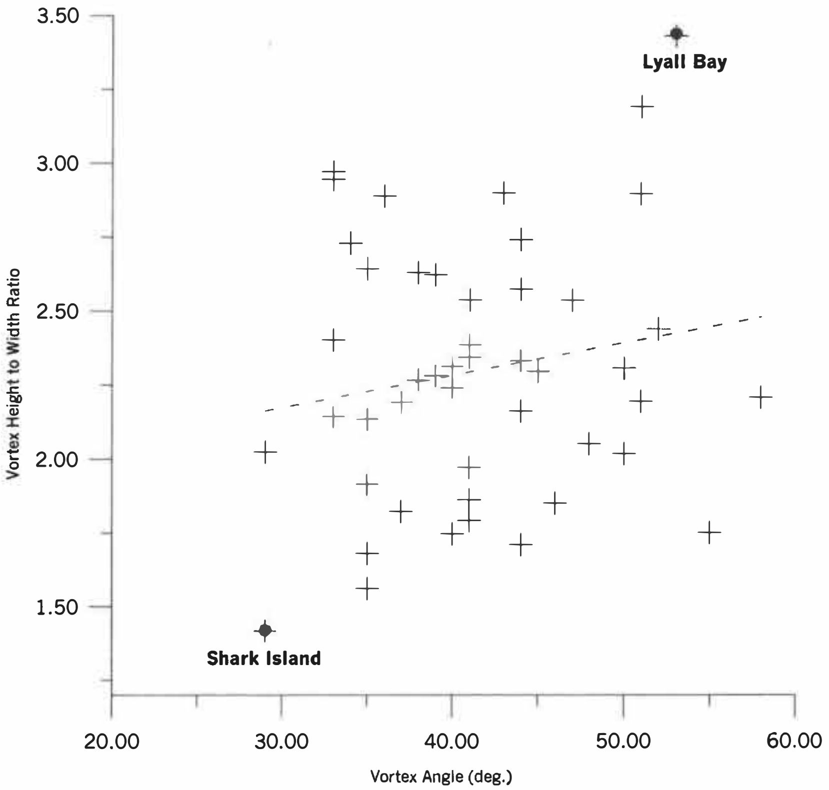


Figure 6.7. Wave vortex angle vs the ratio of vortex length to vortex width ($R^2 = 0.03$).

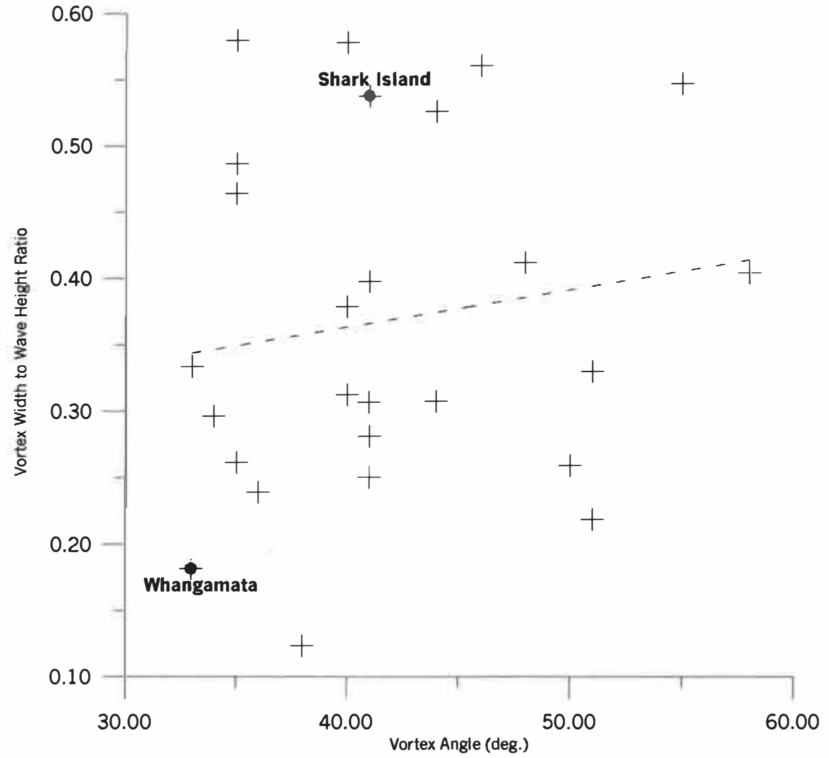


Figure 6.8. Wave vortex angle vs the ratio of vortex width to wave height ($R^2 = 0.02$). Wave height for the Lyall Bay video image could not be estimated, and so Whangamata is shown as the break with the lowest seabed gradient.

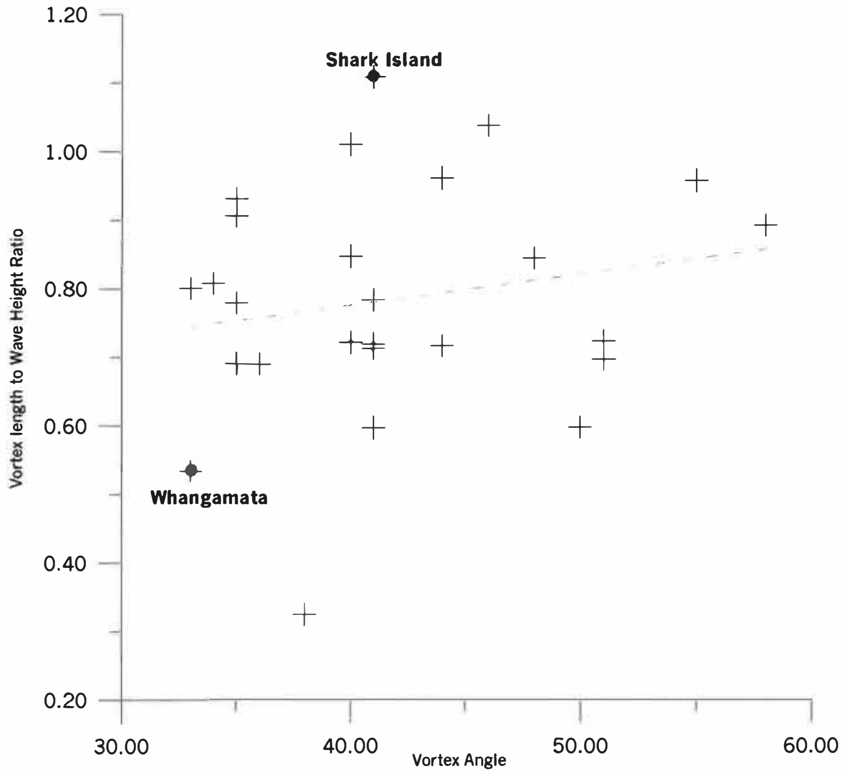


Figure 6.9. Wave vortex angle vs the ratio of vortex length to wave height ($R^2 = 0.03$). Wave height for the Lyall Bay video image could not be estimated, and so Whangamata is shown as the break with the lowest seabed gradient.

When seabed gradient is compared to vortex angle (Figure 6.10), with the contour normal seabed gradients expressed as angles, there is little evidence of a linear relationship (R^2 = 0.07). However, the breaks with the highest and lowest seabed gradients, Shark Island and Lyall Bay, respectively, are near opposite ends of the range of vortex angles in some instances, i.e. there are 3 different measured vortex angles for Shark Island (Figure 6.10). Substituting orthogonal seabed gradient (expressed in degrees) in place of contour normal gradient, made no difference in the comparison to vortex angle (R^2 = 0.07) (Figure 6.11).

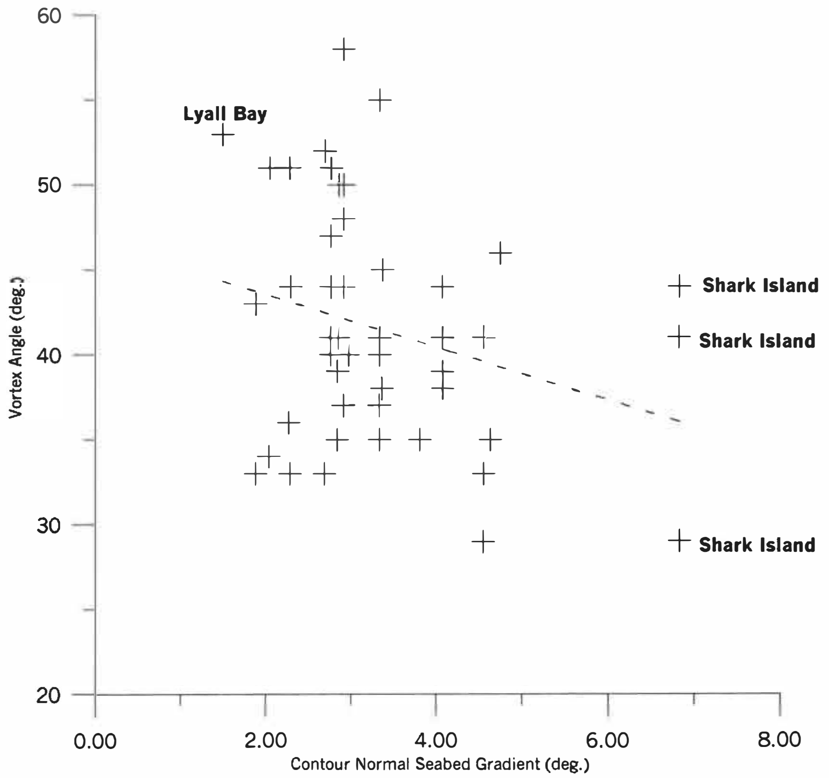


Figure 6.10. Contour normal seabed gradient (expressed as an angle (deg.)) vs the vortex angle (R^2 = 0.07).

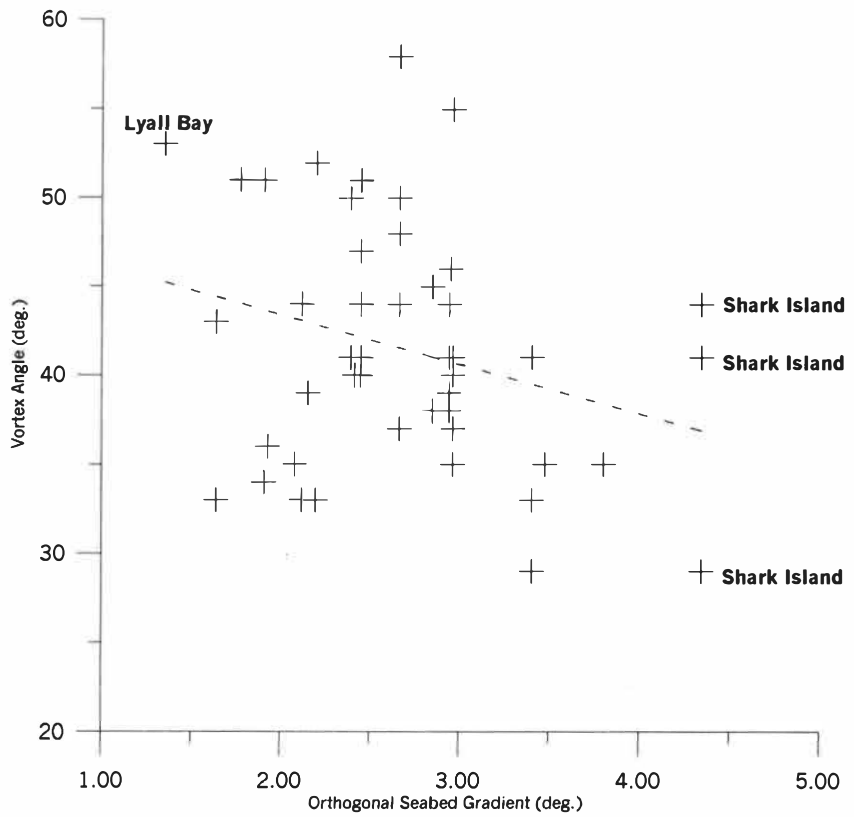


Figure 6.11. Orthogonal seabed gradient (expressed as an angle (deg.)) vs the vortex angle ($R^2 = 0.07$).

DISCUSSION

A method for predicting and describing the breaking intensity of plunging surfing waves has been developed. The ratio of vortex length to width was found to be the best parameter to use as an indicator of wave breaking intensity and this could be predicted from the orthogonal seabed gradient. The linear equation relating these variables is given by equation 6.5. This equation allows predictions of surfing tube shape, defined by a ratio that gives an immediate indication of the tube shape, and can be related to breaks of similar intensity, therefore giving a full picture of the type of plunging wave that particular reefs will produce. Quantitative descriptions of tube shape can now be incorporated into artificial surfing reef design.

Other methods of classifying breaking waves, such as the Irribarren number cannot adequately describe the variety of waves at different breaks required by surfers (BUTTON, 1991; SAYCE, 1997; SAYCE *et al.*, 1999). For waves to be considered of a high quality for surfing, they must break with a tubing profile. While the Irribarren number is useful for an estimate of breaker type (spilling, plunging, etc.), it does not define or describe the tube-shape of surfing waves. The vortex ratio describes the tube shape by giving a value of the tube length in relation to its width. This ratio is a measure of the 'roundness' of the tube and can therefore distinguish between subtle differences in the tube shape. As the ratio of vortex length to width approaches 1, the tube shape becomes more circular and less elongate. For example, a vortex ratio of 2 indicates that the tube is twice as long as it is high and so immediately gives us a feeling for its shape. Low values of the vortex ratio indicate high breaking intensity, and as the vortex ratio of the tube increases, the breaking intensity decreases. By relating calculated vortex ratios to waves at existing breaks, we can gain a very good indicator of the breaking intensity of any plunging wave.

Table 6.2. *Classification schedule of surfing wave breaking intensity.*

Intensity	Extreme	Very High	High	Medium/high	Medium
Vortex Ratio	1.6-1.9	1.91-2.2	2.21-2.5	2.51-2.8	2.81-3.1
Descriptive Terms	Square, spitting	Very hollow	Pitching, hollow.	Some tube sections	Steep faced, but rarely tubing
Example Break	Pipeline, Shark Island	Backdoor, Padang Padang	Kirra Point, Off-The-Wall	Bells Beach, Bingin	Manu Bay, Whangamata
Example Break Wave Profile					

To enable breaking intensity of high-quality surfing waves to be clearly communicated, a classification scheme has been created (Table. 6.2). Breaking wave intensity is described in five categories from extreme to medium. Waves of greater than extreme are likely to collapse (although an exact limit to vortex ratio is yet to be established) and are therefore unsurfable, and waves of less than medium fall into the categories of gentle plunging and spilling, which, while still surfable, are generally not considered high-quality by surfers. The shape of each category is described in surfing terminology and examples of surfing breaks with similar breaking intensity, as well as a picture of a wave breaking in profile at an example surfing break, is also given.

Of the two methods used to estimate seabed gradients at surfing breaks (contour normal and orthogonal), orthogonal seabed gradients proved to be the most useful for predicting the breaking intensity. This is because waves at surfing reefs do not approach normal to the seabed contours. On the contrary, waves must arrive at an angle to the seabed contours to provide a surfable peel angle, which is one of the most important factors required for high-quality surfing waves (DALLY, 1990; HUTT, 1997; MEAD and BLACK, 1999a; HUTT *et al.*, 2000).

Peel angles vary between surfing reefs (HUTT, 1997; HUTT *et al.*, 2000). Therefore the difference between the contour normal seabed gradient and the orthogonal seabed gradient varies between breaks. These variations account for the lower degree of correlation found when breaking intensity is related to contour normal gradient compared to that found when intensity is related to orthogonal seabed gradient (Figures 6.5 and 6.6). The contour normal gradient is over estimating the steepness of the actual gradient that waves encounter by varying amounts, depending on the orientation of the seabed contours to the wave orthogonals or peel angle. COURIEL *et al.* (1998) recognised this difference in contour normal seabed gradient and orthogonal seabed gradient and suggested a seabed gradient correction factor that incorporates the peel angle,

$$S' = S\cos(\alpha) \qquad (6.6)$$

where S is the contour normal seabed gradient, S′ is the orthogonal seabed gradient and α is the peel angle. However, in order to use this correction factor, the peel angle must first be known.

Comparison of aerial photographs and bathymetric surveys at each of the breaks used in this study allowed good estimates of the direction of wave propagation relative to the under-lying bathymetry, which could then be used to estimate orthogonal seabed gradients. However, there was no way of knowing the exact angle of wave propagation relative to the surfing break bathymetry during videoing or when photographs were taken of tube profiles. The discrepancies between the real and actual orthogonal gradients most likely accounts for some of the variability around the line of best fit in Figure 6.5.

The ratios of wave height to vortex length and wave height to vortex width were also assessed as possible indicators of wave breaking intensity, by relating them to vortex angle. This same analysis was undertaken by SAYCE (1997) and SAYCE *et al.* (1999). These authors had limited information on seabed gradients, and so wave vortex angle was used as an indicator for breaking intensity. Although SAYCE (1997) and SAYCE *et al.* (1999) obtained some correlation between vortex angle and vortex length parameters, there was little evidence of any relationships in the present dataset (Figures 6.8 and 6.9). One of the difficulties with using wave height ratios is the uncertainty of the flat water level or wave trough level when estimating from video footage or photographs. However, relating wave height to vortex parameters should not be discounted as a measurement of breaking intensity because, among surfers, the height of the tube in relation to the height of a wave is well known to vary (e.g. some waves may tube 'top-to-bottom', while others will only provide a small tube in the top part of the wave face). Scaled wave vortex measurements coupled with pressure sensing of wave heights at a range of different surfing sites may lead to a better understanding of wave height to vortex parameter ratios.

Wave vortex angles measured at the surfing breaks in this study range between 32° to 57°. This is a smaller range than that found by SAYCE (1997) and SAYCE *et al.* (1999) of 10° to 55°. In addition, our results show that there is little evidence to support that wave vortex angle can be used as a measure of breaking intensity, as suggested by SAYCE (1997) and SAYCE *et al.* (1999). Indeed, there are some major discrepancies between the measurements of vortex angle between those of SAYCE (1997) and the present study. For example, SAYCE (1997) measured a very low vortex angle at Shark Island of 10° while this study recorded angles from 29-44°. The vortex angle is not a stable parameter and it is much more difficult to measure than vortex length to width ratio. Part of the difficulty arises when the software positions the base of the cubic curve in relation to the impact position of the wave crest in the trough. Horizontal errors in this position, arising from photographs where the wave crest has not reached the trough, lead to errors in the estimate of vortex angle. Similar difficulties do not arise in relation to the vortex length to width ratios.

Another difficulty in using the vortex angle is the ability to accurately estimate the horizontal still water level from which to measure it from. While a crest parallel orientation may be achieved when videoing/photographing a wave profile, it is difficult to know whether or not the camera was located true to the horizontal, and so the vortex angle may be either under or overestimated. In addition, VINJE and BREVIG (1981) found that while the ratio of vortex length to width for a particular breaking wave remains similar through time, the vortex angle varied up to 10° prior to crest impact. In combination, the above problems associated with the measurement of wave vortex angle signify that it is not a useful indicator of wave breaking intensity.

Even though the seabed gradient has the greatest effect on wave breaking characteristics (PEREGRINE, 1983; BATTJES, 1988; SAYCE, 1997), wave height and period also affect the breaking intensity of waves (IRRIBARREN and NOGALS, 1947 – cited SAYCE, 1997; DALLY, 1989). Breaking intensity increases with increasing period and decreasing wave height. With respect to using equation 5 for predictions of plunging wave shape, it is important to know to what degree the changes in wave height and period effect the wave breaking intensity. The new method of predicting the tube shape of breaking waves does not incorporate wave height or period and is restricted to the category of surfing, or plunging, waves. It was therefore necessary to consider other methods to discern the degree to which wave height and period effect breaking intensity of surfing waves.

Wave periods at world-class surfing sites usually range between 9-18 s. While some locations may occasionally receive larger waves that are surfable (e.g. Hawaii's North Shore), the majority of high-quality surfing waves are surfed at heights between 1 m and 4 m. Indeed, HUTT *et al*'s (2000) classification system for surfing difficulty accounts for waves up to 4 m because waves of this height are the most regularly encountered and is the height for which artificial surfing reefs will be designed in most cases.

The best example that could be found incorporating different wave periods and heights and which also measured wave vortex ratios, was the laboratory experiment of COURIEL *et al.*, (1998). COURIEL *et al.*, (1998) used a 2D physical model to investigate the breaking intensity of four different wave periods (6, 10, 12 and 15 s) and 3 different wave heights (1, 2 and 3 m), which incorporate most of the range of wave heights and periods that are normally surfed. The seabed gradient of the physical model was 1:14, and these tests were carried out as part of the studies requested by the second author for designing the Gold Coast artificial surfing reef (BLACK *et al.*, 1998). When the vortex ratios measured during these test are considered, there is only a small amount of scatter in the results of the measured vortex ratio for all combinations of wave height and period on the 1:14 seabed gradient. The mean vortex ratio is found to be 2.14 (std dev. = 0.18, range 1.8 – 2.3, n = 22), which fits well with equation 6.5 for a 1:14 seabed gradient, giving a predicted vortex ratio of 1.8 (Figure 6.5), even though physical model scaling creates some errors (COURIEL *et al.*, 1998). A future improvement on the technique of predicting wave breaking intensity described here, would be to include the wave height and period. However, at present we can assume that the range of surfing wave heights and periods at world-class surfing breaks is not large enough to greatly affect the general results obtained by using the orthogonal seabed gradient alone to predict breaking intensity. Thus, the current technique is simple and more than adequate for the purpose of predicting the tube-shape of surfing waves.

When incorporating surfing into offshore structures (BLACK *et al.*, 1998, MEAD *et al*, 1998; MEAD and BLACK, 1999b; BLACK *et al.*, 1999; BLACK *et al.*, 2000; BLACK, 2000), it is an advantage to be able to predict the intensity of waves breaking on the designed reef. Numerical modelling in conjunction with a database of mostly world-class surfing breaks has previously been used to design surfing reefs (BLACK *et al.*, 1998, MEAD and BLACK, 1999b). An interesting test of the method of predicting breaking intensity of high-quality surfing waves is to use it on the man-made reef at Narrowneck, Surfers Paradise on the Gold Coast in Australia. When the breaking intensity of waves on the Gold Coast Reef is determined (Plate 6.4), equation 6.5 closely predicts the designed reef gradient (Figure 6.5). This equation now allows prediction and description of an important aspect of surfing, the tube-shape, during the design of offshore artificial surfing reefs.

Plate 6.4. A wave breaking with extreme intensity on the Gold Coast Reef, Queensland, Australia.

CONCLUSION

The vortex length to width ratio is a good indicator of plunging wave breaking intensity. This ratio can be calculated from the orthogonal seabed gradient (Equation. 6.5). The ratio better describes vortex, or tube, shape of plunging surfing waves than other methods used to predict wave breaking intensity such as the Irribarren number. The method of predicting breaking intensity of surfing waves is relatively simple, requiring only an orthogonal seabed gradient and a linear equation. Including wave height and period in this method could improve breaking intensity prediction, but the range of wave heights and periods at high-quality surfing breaks is not large enough to greatly affect the general results obtained by using the orthogonal seabed gradient alone. These quantitative predictions of tube shape can now be incorporated into artificial surfing reef design.

ACKNOWLEDGEMENTS

This study formed part of the larger Artificial Reefs Program, which aims to enhance amenity value along New Zealand's coastline. The program is evaluating

multiple use options for artificial reefs, with a particular emphasis on surfing and coastal protection. The Program is supported by the Coastal Marine Group at the University of Waikato and ASR Ltd (www.asrltd.co.nz).

REFERENCES

BATTJES, J. A., 1974. Surf Similarity. *Proceedings 14th Coastal Engineering Conference*, ASCE, 466-480.

BLACK, K. P.; ANDREWS, C.; GREEN, M.; GORMAN, R.; HEALY, T.; HUME, T.; HUTT, J.; MEAD, S., and SAYCE, A., 1997. Wave Dynamics and Shoreline Response On and Around Surfing Reefs. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

BLACK, K. P.; HUTT J. A., and MEAD, S. T., 1998. *Narrowneck Reef Report 2: Surfing Aspects. Technical Report prepared for the Gold Coast City Council, June, 1998. 120pp + figs & Appendices.*

BLACK, K.P.; MEAD, S.; McComb, P.; Jackson A., and Armstrong, K., 1999. *New Plymouth City Foreshore Redevelopment: Reef and Beach Feasibility Study. Prepared by the Centre of Excellence in Coastal Oceanography and Marine Geology, for the New Plymouth District Council, March 1999. 59pp + figs & Appendices.*

BLACK, K. P.; HUTT J. A.; MEAD, S. T.; JACKSON, A., and MCGRATH, J., 2000. Design of the Gold Coast Artificial Reef: Surfing aspects. Special Issue of the *Journal of Coastal Research* on Surfing. (in press).

BLACK, K.P., 2000. Artificial Surfing Reefs for Erosion Control and Amenity: Theory and Application. International Coastal Symposium (ICS2000) Rotorua, New Zealand. Special Issue of *Journal of Coastal Research* (in press).

BUTTON, M., 1991. Laboratory Study of Artificial Surfing Reefs. Unpublished Thesis, Bachelor of Engineering, Department of Civil and Environmental Engineering, University of Western Australia, 1991.

COURIEL, E. D.; HORTON P. R., and COX, D. R., 1998. *Supplementary 2-D Physical Modelling of Breaking Wave Characteristics. WRL Technical Report 98/14, March, 1998. 27pp + figs & Appendices.*

DALLY, W. R., 1989. Quantifying Beach Surfability. *Proceedings Beach Technology Conference*, Tampa, Florida, February 1989.

DALLY, W. R., 1990. Stochastic Modelling of Surfing Climate. *Proceedings The 22nd Coastal Engineering Conference*, ASCE, Vol. 1:516-529.

GALLOWAY, G. S.; COLLINS M. B., and MORAN, A. D., 1989. Onshore/Offshore Wind Influence on Breaking Waves: An Empirical Study. *Coastal Engineering*, 13, 305-323.

GALVIN, C. J., 1968. Breaker-Type Classification on Three Laboratory Beaches. *Journal of Geophysical Research*, Vol. 73, No. 12, June, 1968.

GORMAN, R., 1996. Software. National Institute of Water and Atmospheric Research, Hamilton, New Zealand.

HUTT, J. A., 1997. Bathymetry and Wave Parameters Defining the Surfing Quality of Five Adjacent Reefs. Unpublished Thesis, University of Waikato, New Zealand. Pp. 170.

HUTT, J. A.; BLACK, K. P., and MEAD, S. T., 2000. Classification of Surf Breaks in relation to Surfing Skill. Special Issue of the *Journal of Coastal Research on Surfing*. (in press).

LONGUET-HIGGINS, M. S., 1982. Parametric Solutions For Breaking Waves. *Journal of Fluid Mechanics*, 121, 403-424.

MEAD, S. T.; BLACK, K. P., & HUTT, J. A., 1998. Surfing Reef Morphological Components Combine To Create World-Class Surfing Breaks. *Proceedings 2nd Annual International Artificial Surfing Reef Symposium*. San Diego. April, 1998.

MEAD, S. T., and BLACK, K. P., 1999a. Configuration of Large-Scale Reef Components at a World-Class Surfing Break: Bingin Reef, Bali, Indonesia. *Proceedings Coasts & Ports '99*, Vol. 2, 438-443.

MEAD, S. T., and BLACK K. P., 1999b. A Multi-Purpose, Artificial Reef at Mount Maunganui Beach, New Zealand. *Coastal Management Journal* 27(4), 355-365.

MEAD, S. T., and BLACK K. P., 2000a. Field Studies Leading to the Bathymetric Classification of World-Class Surfing Breaks. Special Issue of the *Journal of Coastal Research* on Surfing. (in press).

MEAD, S. T., and BLACK K. P., 2000b. Functional Component Combinations Controlling Surfing Wave Quality at World-Class Surfing Breaks. Special Issue of the *Journal of Coastal Research* on Surfing. (in press).

MOFFAT & NICHOL, 1989. *The Patagonia Surfing Reef Feasibility Study. Report prepared for The Surfrider Foundation, Huntington Beach California, by Moffat & Nichol, Engineers, Long Beach, California. Job No. 2521, September, 1989. Pp. 54.*

PEREGRINE, D. H., 1983. Breaking Waves on Beaches. *Annual Revue Fluid Mechanics*, 15, 149-178.

SAYCE, A., 1997. Transformation of Surfing Waves Over Steep and Complex Reefs. Unpublished Thesis, University of Waikato, New Zealand.

SAYCE, A., K. P. BLACK and R. GORMAN, 1999. Breaking Wave Shape on Surfing Reefs. *Proceedings Coasts & Ports '99*, Vol. 2, 596-603

U.S. ARMY COASTAL ENGINEERING RESEARCH CENTRE, 1975. *Shore Protection Manual, Department of the Army Corps of Engineers*, US Government Press, Washington. Vol. 1, 1975. Pp 496.

VINJE, T. and P. BREVIG, 1981. *Breaking Waves on Finite Water Depths: a Numerical Study. Ship Research Institute of Norway, Report R-111.81.*

WALKER, J. R., 1974. *Recreational Surf Parameters. LOOK Laboratory TR-30, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii, 1974.*

Chapter 7

A Multi-Purpose, Artificial Reef At Mount Maunganui Beach, New Zealand

Coastal Management Journal Vol. 27(4) October-December 1999, 355-365

A Multi-Purpose, Artificial Reef at Mount Maunganui Beach, New Zealand

SHAW MEAD & KERRY BLACK
Centre of Excellence in Coastal Oceanography and Marine Geology
Department of Earth Sciences, University of Waikato
& National Institute of Water & Atmospheric Research
Private Bag 3105, Hamilton, New Zealand
E-mail s.mead@asrltd.co.nz

A multi-purpose, artificial, offshore reef has been designed for construction at Mount Maunganui Beach, New Zealand. The proposed reef will form the basis for research into coastal protection, amenity enhancement (particularly surfing, but also diving, fishing and beach recreation), biological response and social and economic impacts. In order to proceed with reef construction, a 5-year resource permit is being sought from the regulatory authority, and this application required an assessment of the likely environmental impacts of the proposed reef. The studies undertaken for the assessment included physical, biological, social and economic impacts. A comprehensive design process was undertaken to incorporate the amenity of surfing into a submerged reef shape. Programs to monitor physical and biological responses, as well as social and economic impacts, were also established. These studies support the use of multi-purpose, artificial, offshore reefs as an environmentally-friendly solution to coastal protection. The reefs also cater to the growing demand for more coastal-amenity development.

Key words and phases: multi-purpose artificial offshore reef, coastal protection, amenity enhancement, surfing, biological enhancement, environmental impacts.

In many parts of the world, coastal protection is almost at an impasse. Negative down coast impacts, compromise of aesthetic values, recent environmental laws and strong negative public reaction to rock emplacement along the coast are putting pressure on existing methods of coastal protection. This has led to uncertainty by regulators and local government authorities about how to treat shoreline erosion. Many are resorting to "managed retreat" where buildings are simply removed and the coast is left to erode (Komar, 1997). However, managed retreat can be expensive, unnecessary and sometimes impossible. While permission to damage or develop the frontal dune should never be given, coastal erosion and threats to property cannot be easily eradicated and so a solution is required.

Offshore, submerged reefs provide a shoreline protection solution with low environmental impact. Visual amenity is not impaired, the reef is constructed offshore with no disturbance to the coastal habitat and there is no requirement for rock emplacement along the shoreline. Salient growth in the lee of the reef leads to enhanced shoreline stability and protection and the natural character of the coastline is retained. An additional benefit is the incorporation of recreational and public amenity through surfing, diving/snorkelling, sheltered swimming, fishing and other water activities, as well as the enhancement of marine habitat.

Four years ago, the Artificial Reefs Program (ARP) was established to investigate alternative solutions to coastal protection that would mitigate environmental impacts as well as increase amenity values. By unifying ARP senior scientists and experienced industrial partners, the Program, operating jointly within the Department of Earth Sciences of the University of Waikato and the National Institute of Water and Atmospheric Research (NIWA), in the Centre of Excellence in Coastal Oceanography and Marine Geology, aims to:

- enhance the coastal amenity value of the shoreline by evaluating multiple use options (coastal protection, habitat for marine organisms, surfing, diving, recreational and commercial fishing, boating and swimming safety) for incorporation into coastal structures;

- focus and further develop expertise within the research community, and within industry, while providing a sound basis for senior student education (Black *et al*., 1997).

Studies within the ARP relating to the wave dynamics of surfing (Hutt, 1997; Sayce, 1997) and the response of the shoreline in the lee of offshore reefs (Andrews, 1997) has led to capabilities of reliably designing artificial offshore reefs that incorporate the amenity of surfing and provide the coast with a predictable level of protection. The next step is the development of a pilot offshore reef to focus research efforts within the ARP and the accompanying institutions.

The ARP team are proposing to construct a temporary artificial, offshore, submerged reef near Tay Street, Mount Maunganui Beach, Mount Maunganui, New Zealand (Fig. 7.1). A unique feature of the proposal is the intention that the reef be removed after the completion of the research programme (i.e. 5 years from completion of construction). The ability to remove the reef was incorporated into the project to allow for emergency removal in the event of any negative effects, and to allow the University of Waikato the option to terminate the research after 5 years. Even though the initial research has shown that negative effects will be negligible (see below), the permitting authority consider the project more feasible if the structure can be removed. The proposed reef will enable the field testing and evaluation of previous findings as well as several areas of new research. These include coastal protection, amenity enhancement (specifically surfing but also diving, fishing and beach recreation), biological response and social and economic impacts of a multi-purpose reef. The reef will provide scientific knowledge and an educational resource that will support the research community and be applicable to several areas of industry.

In order to construct a coastal structure, a coastal resource consent (permit) must be sought from the Regional Council, in this case Environment Bay of Plenty (EBoP). This requires an 'assessment of effects on the environment' (AEE) that addresses the environmental impacts of the proposal. A series of studies was carried out for the AEE and consultation was undertaken with affected parties and the general public. The studies undertaken included physical and biological processes, social and economic impacts, as well as a comprehensive design process to incorporate the amenity of surfing into the reef shape. In addition, monitoring programs for physical and biological response and socio-economic impacts were established. This paper summarizes studies that were undertaken to specify the physical and biological processes at the ARP Reef site, briefly considers reef design and discusses the predicted impacts and monitoring programs planned for the reef. The evaluations of the socio-economic impacts, consultation with effected parties and assessment of the how the proposal relates to the policy and planning documents of the region will be discussed in subsequent papers. There has been great interest in artificial reef technology in New Zealand, especially from local governments with coastal erosion concerns. The ARP Reef will act as a test case for future projects, not only for the production of a permit application, but also to demonstrate the utility of multi-purpose offshore artificial reefs.

Location and Description of the Proposed Reef

Tay Street, Mount Maunganui Beach, was selected as the preferred construction site from several alternative sites using a point scoring system that considered the following factors: access and distance from the University, sources of construction materials, logistics of construction and access, existing modifications to adjacent shoreline, perceived erosion problems and conservation significance. In addition, the existing surf culture and links between the University of Waikato and both the local port (Port of Tauranga) and tertiary education institution (Bay of Plenty Polytech) were also seen as advantageous to the project.

Mount Maunganui, arguably New Zealand's 'Surf-City', is located on the seaward side of Tauranga Harbour in north eastern New Zealand. Mount Maunganui Beach, in the south western Bay of Plenty (Fig. 7.1), is a long, open, white-sand beach (29 km), backed with sand dunes. The wave climate is smaller than the most of New Zealand, with locally-generated swells predominantly from the north to the east and generally <1 m high with 9-12 s period (Pickrill & Mitchell, 1979). Less common, but often far more energetic, are the long period swells that originate from subtropical disturbances north of New Zealand (Macky *et al.*, 1995; Bradshaw, 1991; Pickrill and Mitchell, 1979).

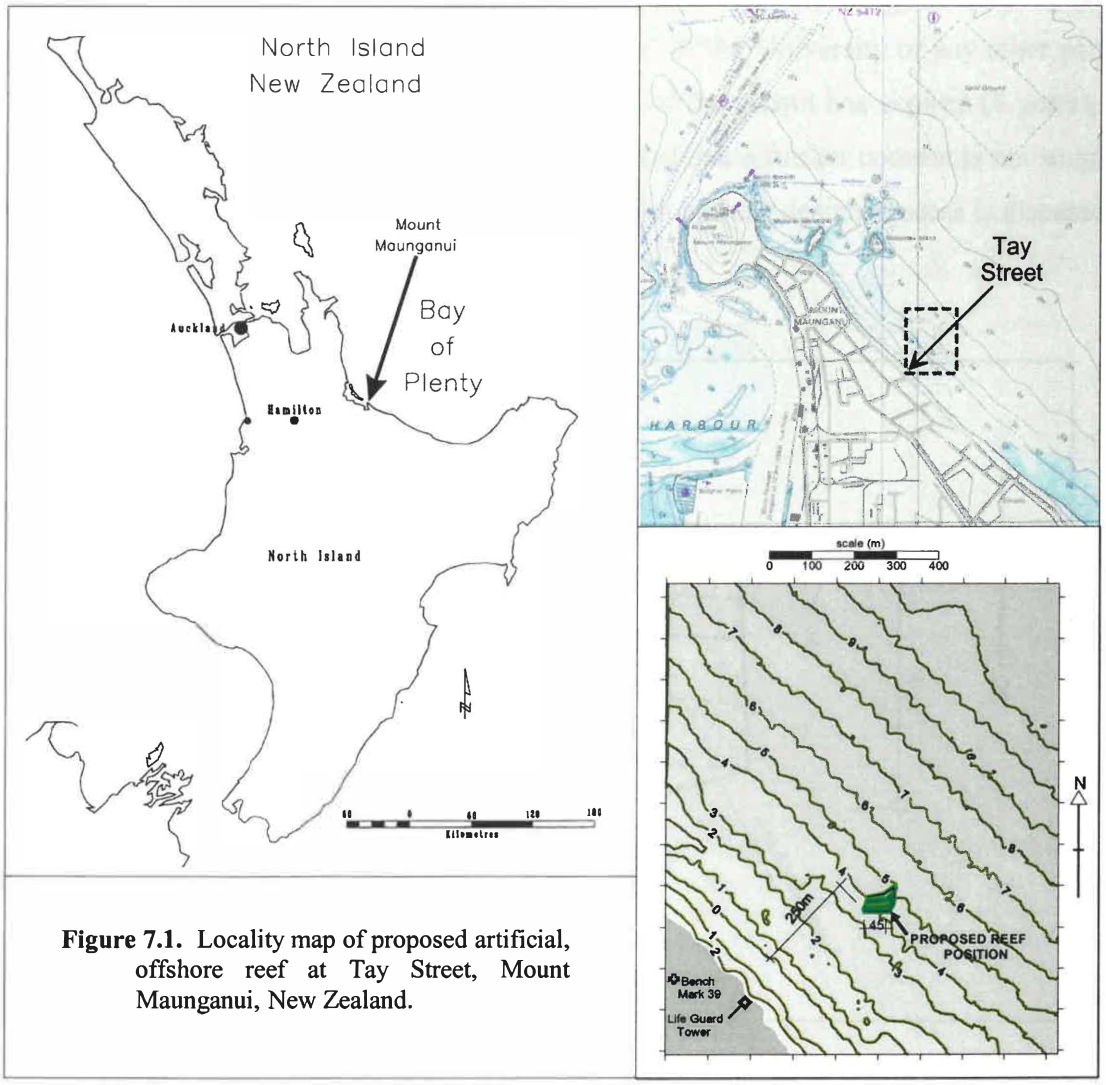


Figure 7.1. Locality map of proposed artificial, offshore reef at Tay Street, Mount Maunganui, New Zealand.

The proposed site of the ARP Reef is 250 m offshore, extending approximately 75 m from the inshore edge (~3.7 m depth) to the offshore toe (~4.6 m depth), with a cross-shore width of ~50 m (Fig. 7.2). The highest isobath of the reef is 50 m long and is 0.4 m deep at lowest astronomical tide (Fig. 7.2). Hence, the reef will always be submerged. The reef will be positioned around the centre of the highest contour (276600 m E, 712860 m N) on the 4 m isobath. It will have a surface area of approximately 2,850 m^2 and a volume of ~5,000 m^3. Construction materials include large sand-filled geotextile bags overlaying a sand-filled concrete super-structure, separated by geotextile or tyre mattresses to reduce abrasion, slumping and uneven settlement. All construction components are fixed together so that, in effect, the reef becomes a single solid unit. If the University or any other party should wish to retain the artificial reef after the term of the permit has expired (5 years), a further consent application would be made. In the event that a further consent is not sought the reef will be removed. More detail of the reef design and the design process is discussed below.

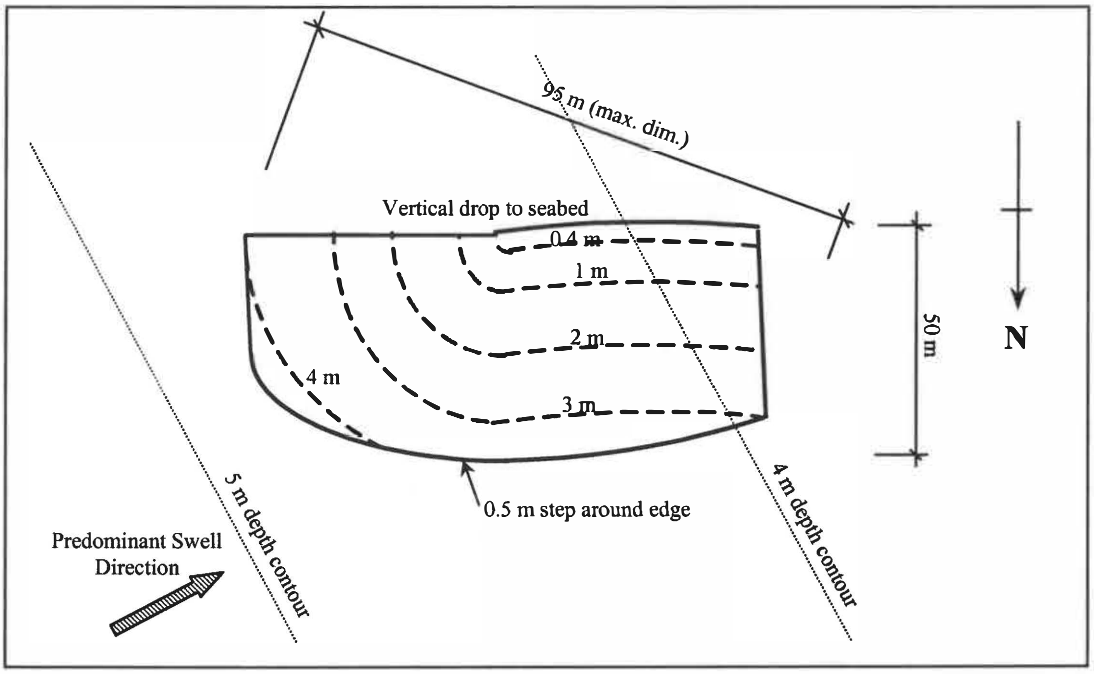


Figure 7.2. Plan view of proposed ARP reef at Tay Street, Mount Maunganui, New Zealand. (Approximate scale 1:500).

Assessment of Physical Processes and Impacts

Several inter-related studies were undertaken to assess the physical impacts of the ARP Reef proposal including sediment transport, sediment deposition in the lee of the reef, bathymetric mapping, analysis of sediment grain size, examination of the existing beach profile dynamics (erosion/accretion), recording of on-site wave data and time-lapse video. As it is beyond the scope of this paper to present all of these studies in detail, only the most significant results will be discussed.

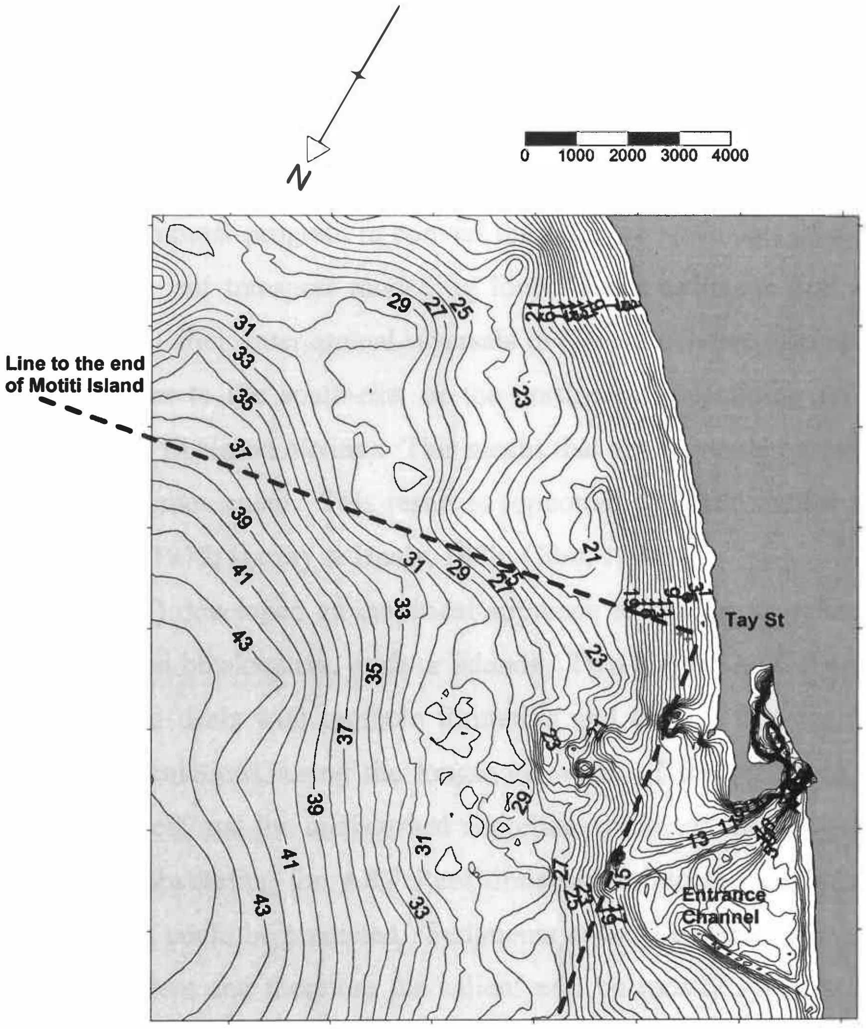


Figure 7.3. Large-scale modelling grid (100 x 100 m) of Mount Maunganui offshore area (rotated 220°). The dashed lines represent the surfable swell window.

The main physical impacts due to construction of an artificial offshore reef are associated with changes to the sediment transport systems. These changes are reflected in the deposition of sediments along the shore in the lee of the reef which ultimately leads to the formation of a salient or tombolos (Komar, 1976) that affords the coast protection. To investigate the effects of sediment transport at the ARP Reef, long-term wave data (Macky *et al*, 1995) in conjunction with two numerical models (Black & Rosenberg, 1992; Black, unpub.[1]) were utilised to examine long-shore sediment transport. Empirical equations (Andrews, 1997) were used to predict the dimensions of the consequent salient.

Two bathymetry grids were created. A large, regional grid was used to transfer the offshore wave data to the inshore Tay Street site. A second, finer model grid was then used to investigate sediment transport in the lee of the proposed reef and for design wave selection for the surfing aspects. A series of model simulations on the large-scale grid (Fig. 7.3) resulted in a suite of conversion equations that were incorporated into a custom-written FORTRAN computer program to convert the offshore wave data into inshore wave data. Subsequent sediment transport modelling found a net sediment flux of 68-77,000 m^3yr^{-1} at the Tay Street site. Inter-annual reversals in directions were also identified, with sediment moving either to the south-east or the north-west, depending on the reigning climatic influence (e.g. El Nino/La Nina). This means that net movement along the beach is small relative to gross movement. This result is supported by other studies in the Bay of Plenty region (Harray, 1977; Harray & Healy, 1978; Gibb, 1979).

Andrews (1997) developed an empirical approach to predict shoreline response to submerged and emerged breakwaters, reefs or islands. Two distinct sets of equations were developed; one set that deals with tombolo formation and one set that deals with salient formation. Initial calculations, using the longshore width of the proposed reef and the distance between the reef and the undisturbed shoreline, indicated that the ARP Reef will form a salient. By substituting the ARP Reef dimensions into the salient equation, the geometry of the salient could be predicted. Sediments at the Tay Street site are oscillating with small net movement and therefore the salient will be mostly symmetrical and have little or no impact on the adjacent coast. The predicted salient will be a maximum of 58 m cross-shore at the widest point, tapering down to zero accretion at a distance of 230 m in each direction longshore, and incorporate approximately 6670 m^3 of beach sand (Fig. 7.4).

With inter-annual reversals in sediment transport of around 68-77,000 m^3, the salient is expected to form within a year. Although it has been demonstrated that there is sediment exchange across the Tauranga Harbour mouth (Davies-Colley & Healy, 1978) and around headlands (Hume *et al.*, 1992) such as Maketu to the east, these two features have been used to define the length of Mount Maunganui Beach. This results in a beach of some 29 Km in length, which contains a minimum of 10,034,000 m^3 of sand. The salient is a very small fraction (approximately 6.6 x 10^{-4}) of the sand on this 29 Km stretch of beach, and so the impact will be negligible. However, it will form a substantial erosion buffer zone in the local Tay Street area of Mount Maunganui Beach.

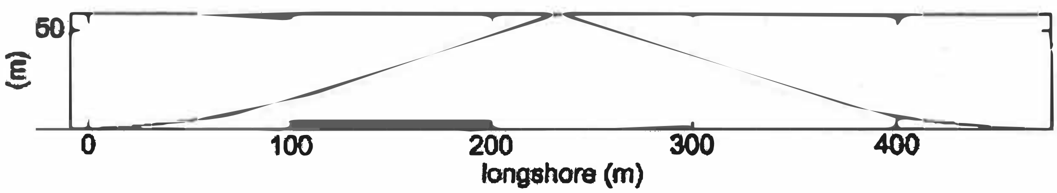


Figure 7.4. Predicted salient formation in the lee of the ARP reef. Represented at lowest astronomical tide.

While the physical impacts of reef construction are mostly related to sediment transport and salient growth, because the reef is temporary and may be removed at the end of the 5-year consent period, impacts of reef removal were addressed. While the volume of sand used to construct the ARP Reef is negligible in comparison to the volume of sand on Mount Maunganui Beach, the sediment grain size to be used in construction must be considered. Sediment of different grain size to that already present at the site may cause negative impacts both physically and ecologically if released into the existing system. Therefore, grain size analysis was undertaken to compare sediments at the Tay Street site with those from the Harbour Entrance Channel, where the construction sand is being extracted from (Fig. 7.3). Sediment grain size was found to be very similar between these areas (mean 2.38 ϕ), and so the Entrance Channel sand was deemed suitable for reef construction at Tay Street. If this sand is released from the constraints of the artificial reef it will simply be incorporated into the existing system.

Ecological Impacts

An ecological assessment of the sub-tidal habitat in the Tay Street area of Mount Maunganui Beach found that this area has similar species to other sub-tidal areas at harbour entrances and sand beaches along the north eastern New Zealand shoreline. Common species in this habitat include cake urchins, asymmetric wedge shells and other bivalves, gastropods, marine worms and hermit crabs. These organisms are indicative of protected beaches and harbour entrances, as well as of the open coast. This overlap of species is most probably due to the relatively small wave climate (compared to the rest of New Zealand) and the close proximity of Tauranga Harbour.

Constructing the proposed reef will smother and kill any organisms that inhabit the seabed upon which it is built. The proposed artificial reef will cover an area of approximately 2,850 m^2. This represents a very small fraction of Mount Maunganui Beach that would be permanently lost, even if only the seabed between 3 and 6.5 m deep is considered (2.8×10^{-4}), and so it would have a very minor, if any, negative effect on its ecology. Instead, it is probable that the proposed reef will actually enhance the ecology in its immediate vicinity by increasing topographic complexity and the availability of solid substrate.

The mobile sand substrate of Mount Maunganui Beach represents a relatively harsh environment for marine organisms to inhabit. Although Mount Maunganui Beach is exposed to only moderate swell conditions, mainly due to the relatively small swell window between the north and east (Fig. 7.3), occasional higher seas can result in large amounts of sediment movement along this coast. In addition, the topography of the area is simple and such flat sand seabeds offer limited habitat complexity. This type of shallow sub-tidal, sand substrate habitat is normally low in species diversity compared to more complex and permanent habitats, such as a rocky reef (Morton & Miller, 1968). An artificial offshore reef will increase the topographical complexity of the seabed in the Tay Street area. The reef will provide a substrate for settling organisms, and it may also subtly alter the local hydrodynamics in a way that could increase settlement in the lee of the reef(e.g. Black &

Gay, 1987). The reef and the organisms that settle on it will also provide shelter and a food source for fish and other marine life and act as a fish aggregating device (FAD) (Bohnsack & Sutherland, 1985). Although there has been much work in the area of ecological enhancement using artificial reefs in other areas of the world (e.g. Bulletin of Marine Science, 1994), there have been very few studies in New Zealand. In addition, the suitability of the geotextile substrate for marine habitation in an active wave zone remains unknown. This proposal offers the opportunity to further research these areas, with emphasis on the New Zealand ecological environment.

Surfing Aspects

Surfing has grown in popularity world-wide over the last 20-30 years and, during that time, the skills of the "average" surfer have increased significantly. Now, average surfers are performing manoeuvres on difficult waves, which would have been the domain of professionals 15-20 years ago. This has led to a continued growth in usage of world-class waves and a stronger demand for quality waves. Indeed, the sport requires high quality waves to progress.

Mount Maunganui has one inconsistent world-class break on the relatively inaccessible Matakana Island and some quality waves at times along the main and adjacent beaches. As such, Mount Maunganui has developed as a town based in part on a "surfing culture". Unfortunately, however, the surfing quality is inconsistent on the highly mobile sand banks and many of the best swells simply "close-out" (break without peeling) and cannot be satisfactorily enjoyed by the majority of surfers. While beginning surfers are still able to increase their skill levels with respect to catch waves and gaining balance, the more advanced surfers prefer to ride the face of the wave, which is impossible when waves closeout. Consequently, Mount Maunganui beaches have a surprisingly poor reputation for surfing during large swells amongst knowledgeable surfers. Moreover, because of the currents and variable sand banks, good surfing breaks at Mount Maunganui do not persist through time. Thus, while there are some exceptional days, Mount Maunganui is presently unable to provide consistent quality surfing conditions for average to world-class surfers.

In order to create new surfing reefs, an understanding of what makes a good surfing break is required. In comparison with the other factors required for multi-purpose offshore reef development, this area of science is relatively new (Walker, 1974; Buttons, 1991; Lyon, 1992). Hence, studies within the ARP have mainly concentrated on understanding the factors that are required to incorporate the amenity of surfing into artificial reefs (e.g. Black et al., 1997; Black *et al*., 1998; Hutt, 1997; Sayce, 1997). Using the knowledge gained from previous studies, supplemented by a database of 34 of the world's best surfing breaks (Mead, unpub.), computer design software (Black, unpub.[2]) provided the means to examine some 150 cases and to systematically assess the relative merits of major and subtle differences in the reef characteristics. The intricacies involved in the reef design to produce world-class surfing breaks are put into perspective if one considers the relative rarity of world-class surfing breaks along the world's thousands of kilometres of coastline that receive sufficient swell. Design of the proposed ARP Reef was strongly guided by detailed scrutiny, including numerical modelling of a range of the world-class surfing breaks, to fit a set of previously determined design criteria.

The reef had to be sufficiently large to enable an assessment of benefits to be made; and to allow its effects to be monitored (physical, biological, amenity and social), as this is the main aim of the research. In addition, it had to be small enough for relatively quick removal and to minimize costs. A reef with a maximum surfable length of 50 m was accepted. A wave that peels in only one direction down the length of the reef is more desirable than a wave peeling down both sides of the reef for only half this distance; for surfers, the longer the ride the better. Surfing waves are called left-handers or right-handers, depending on the direction that the wave breaks towards. Viewed from the beach, a right-hander peels to the observer's left. A right-hander was chosen for the ARP Reef because most swell comes from the north and a right-hander will pick this swell up with less height loss due to refraction. As consistent, high-quality surf breaks are required at Mount Maunganui and the number of surfers and surfing skills continue to rise, the reef should aim to provide quality surfing waves for competent to expert surfers (there are vast stretches of the coast available for beginners to acquire basic surfing skills). The following specific design criteria were also established:

1. with respect to surfing, the reef shall incorporate

- surfability over the widest possible range of wave heights, periods and directions in order to maximise the number of surfable days per year

- suitability for excellent surfers and average surfers aspiring to be excellent

- at least one "section" hollow enough for tube riding

- a steep wall for board speed

- a fast take-off with sufficient steepness to allow adequate board speed for entry onto the main section of the ride

2. with respect to colonization by marine organisms, the reef shall incorporate

    - removable substrate units (RSU's) containing "colonization enhancers" to maximize the potential success of marine recruitment

    - an area on the inshore side which is sheltered from the main direction of wave exposure and provides sheltered, stable habitat

3. with respect to coastal protection, the reef shall have

    - a small but measurable effect on the coast (i.e. salient formation, ecological enhancement, improved surfing conditions, socio-economic impacts)

These criteria ultimately determined the general character of the surfing reef. Specific parameters such as peel angle and seabed gradients were chosen to meet the above conditions, particularly the need to cater for competent surfers.

Monitoring

Monitoring programs to assess the impacts on the physical and biological processes around the proposed artificial reef have been established. Physical monitoring includes changes to the seabed and the artificial reef, as well as the changes to the shoreline in the lee of the reef. Biological monitoring considers the impacts on the existing communities surrounding the reef and colonization and succession processes on the reef itself. Specifically the programs include:

- Beach profile monitoring at 14 shore-normal transects (7 impact and 7 control) on a bimonthly basis for the first year and monthly thereafter. Timing of surveys will be altered to correspond to exceptional storm events.

- Bathymetric monitoring will be carried out at 3-month intervals in the first year (4 surveys) and at least one full bathymetric survey a year thereafter.

- Reef diving inspections for stability and local scour will be carried out during bathymetry surveys for the first year and 4 times per year thereafter, as well as after exceptional storm events.

- A biological survey will be undertaken once a year in October, the month when the ecological assessment was first undertaken. The ecological assessment will form the basis of these surveys which will be more concentrated in and around the reef and include the reef itself to investigate colonisation success.

- In addition, a yearly inter-tidal survey targeting the surf clam, or tua tua (*Paphies subtriangulata*), will be carried out along the shore in the lee of the reef [3].

Bathymetry surveys, biological surveys and the beach profile monitoring have already commenced and will be continued throughout the 5-year period for which the permit is being sought.

The beach profile will also be used to calculate limits that could trigger early reef removal. Although the studies performed for the AAE predict the formation of a symmetrical salient in the lee of the reef (as discussed above), as a safeguard against negative impact (i.e. erosion), existing beach profile data at Mount Maunganui Beach was analysed to understand the beach dynamics in the area. Data from two survey benchmarks, one adjacent to the proposed reef site and one 5 km east, were used for this analysis. Preliminary Lilliefors tests (Iman & Conover, 1976)) confirmed that the survey data was normally distributed and could easily be used for detailed statistical analysis. A series of calculations using the beach profile data were then set up to evaluate the extent of local erosion/accretion in the vicinity of the reef and to set limits regarding reef removal in the event of negative impacts (erosion).

Conclusion

Development of multi-purpose artificial reefs is increasingly becoming a viable and preferred option for coastal construction. These developments are being pushed forward by recent environmental laws (national and international), the growing environmental awareness and the ever increasing usage of the coastal region. The proposal for an artificial reef at Tay Street in Mount Maunganui will continue to provide new knowledge in the area of artificial reef development, and break new ground in the study of biological impacts and enhancement, coastal response to offshore structures and social and economic responses. Incorporation of multiple use options into coastal structures can meet the need for environmentally-sensitive solutions to coastal construction and to the continued growth in recreational usage of our beaches.

Notes

1. Black, K.P. (unpub.) Model Genius: a numerical model for calculation of longshore sediment transport and shoreline adjustment in the presence of offshore

obstructions. Centre of Excellence in Coastal Oceanography and Marine Geology. University of Waikato and NIWA. 1998.

2. Black, K.P. (unpub.) Maker: a MATLAB based, menu-driven program, which allows the operator to design reefs of chosen dimensions onto a defined base bathymetry. Maker converts reef designs into bathymetry grids for input into Model WBEND (Black and Rosenburg, 1992) so that surfing aspects can be assessed. Centre of Excellence in Coastal Oceanography and Marine Geology. University of Waikato and NIWA. 1998.

3. During early consultation, the local Tangata Whenua (Maori tribe with ancestral rights to the area - Ngaiterangi iwi) expressed concerns about the reefs effects on kaimoana (sea food) in the area, namely *Paphies subtriangulata*, the surf clam or tua tua. Although no tua tua were found during the ecological assessment, they are known to inhabit this stretch of coast (Park, 1995) and are often found around the low tide mark. The concern was that tua tua would be smothered or otherwise adversely effected by the construction of the artificial reef. Tua tua will not be directly effected by the construction of an offshore artificial, as they inhabit shallower waters. However, the build up to sand due to the formation of a salient behind the reef will effect the zone which they inhabit. Tua tua are very mobile bivalves that are adapted to the dynamic conditions of the exposed coast (Morton & Miller, 1968). If the highest rates of sand erosion and accretion naturally experienced along Mount Maunganui Beach are considered (e.g. ±37 m^3 per linear meter of beach in one month) and compared to the relatively slow build up of sand as the salient forms in the lee of the reef (i.e. ~35 m^3 over one year), it can be seen that tua tua will easily adapt to this change. During consultation it was mentioned by several local residents and iwi representatives that the presence of tua tua at Tay Street is very variable, sometimes there are high densities, other times there are none. It is possible that the increased sediment stability in the lee of the reef may in fact lead to a more stable population in this area. Monitoring of this species will help to gain a better understanding of the movements of this species in the Mount Maunganui area.

References

Andrews, C., 1997. Sandy Shoreline Response to Emerged and Submerged Offshore Obstacles. Unpublished MSc Thesis. Centre of Excellence in Coastal Oceanography and Marine Geology, Earth Sciences Department, University of Waikato.

Black, K. P. & S. L. Gay, 1987. Eddy Formation in Unsteady Flows. *Journal of Geophysical Research,* 92 (C9): 9514-9522.

Black, K. P., C. Andrews, M. Green, R. Gorman, T. Healy, T. Hume, J. Hutt, S. Mead and A. Sayce, 1997. Wave Dynamics and Shoreline Response On and Around Surfing Reefs. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

Black K. P., J. A. Hutt and S. T. Mead, 1998. Narrowneck Reef, Report 1: Surfing Aspects. Report to the Gold Coast City Council, March, 1998.

Black, K. P. and M. A. Rosenburg, 1992. Semi-empirical Treatment of Wave Transformation Outside and Inside the Breaker Line. *Coastal Engineering,* 16: 313-345.

Bohnsack, J. A. & D. L. Sutherland, 1985. Artificial Reef Research: a review with recommendations for future priorities. *Bulletin of Marine Science* 37: 3-10.

Bradshaw, B. E., 1991. Nearshore and Inner Shelf Sedimentation on the East Coromandel Coast. New Zealand. Unpublished MSc Thesis, University of Waikato, New Zealand.

Button, M., 1991. Laboratory Study of Artificial Surfing Reefs. Unpublished Bachelor of Engineering, Department of Civil and Environmental Engineering, University of Western Australia, 1991.

Davies-Colley, R. J. and T. R. Healy, 1978. Sediment Transport Near the Tauranga Entrance to Tauranga Harbour. *New Zealand Journal of Marine and Freshwater Research,* 12 (3): 237-43.

Gibb, J., 1979. Aspects of Beach Sediments and their transport along the New Zealand Coast. Workshop-Physical Aspects of Coastal Problems, Hamilton, 11-12 October, 1979.

Harray, K. G., 1977. Beach Erosion and Sediments at Waihi Beach. Unpublished MSc Thesis, University of Waikato, New Zealand.

Harray, K. G. & T. R. Healy, 1978. Beach Erosion at Waihi Beach. *New Zealand Journal of Marine and Freshwater Research*, 12: 99-107.

Hume, T., R. Bell, W. deLange, T. Healy, D. Hicks and R. Kirk, 1992. Coastal Oceanography and Sedimentology in New Zealand: 1967-1991. *New Zealand Journal of Marine and Freshwater Research*, 1992, 26: 1-36.

Hutt, J. A., 1997. Bathymetry and Wave Parameters Defining the Surfing Quality of Five Adjacent Reefs. Unpublished MSc Thesis. Centre of Excellence in Coastal Oceanography and Marine Geology, Earth Sciences Department, University of Waikato.

Iman, R. L. & W. J. Conover, 1976. *A Modern Approach To Statistics*. John Wiley and Sons, New York, 1976. Pp 153-155.

Komar, P. D., 1976. *Beach Processes and Sedimentation*. Prentice-Hall, Inc., Englewood Cliffs, New Jersey.

Komar, P. D., 1997. Beach Processes and the Erosion of Coastal Properties. *Proceedings of Pacific Coasts and Ports '97*, 7-11 September, 1997, Christ Church, New Zealand. Vol. 1, 1-6.

Lyons, M., 1992. Design of an Artificial Surfing Reef. Unpublished Bachelor of Engineering, Department of Civil and Environmental Engineering, University of Western Australia, 1992.

Macky, G. H., G. J. Latimer and R. K. Smith, 1995. Wave Climate of the Western Bay of Plenty, New Zealand, 1991-93. *New Zealand Journal of Marine and Freshwater Research*, 29: 311-327.

Morton, J. E. & M. C. Miller, 1968. *The New Zealand Seashore*. William Collins Sons and Co. Ltd, Glasgow, Great Britain.

Park, S., 1995. Natural Environment Regional Monitoring Network Coastal and Estuarine Ecology Program 1994/95. Environment B.O.P ISSN 11725850

Pickrill, R. A. and J. S. Mitchell, 1979. Ocean Wave Characteristics Around New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 13 (4): 501-520.

Sayce, A., 1997. Transformation of Surfing Waves On Steep and Complex Reefs. Unpublished MSc Thesis. Earth Sciences Department, University of Waikato.

Walker, J., 1974. Recreational Surf Parameters. Look Lab TR-30, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii.

Chapter 8

DISCUSSION

8.1 Introduction

The studies within the Artificial Reefs Program (ARP) have unified marine scientists from a range of disciplines, and bridged the gap between coastal science and engineering to enable the complete development of multi-purpose offshore artificial reefs that are environmentally-sensitive and enhance public amenity (Black *et al.*, 1998a; Black *et al.*, 1998b; Black *et al.*, 1999; Jackson *et al.*, 1999; Mead & Black, 1999a). By moving shoreline protection offshore and submerging it, many of the negative impacts of other coastal protection measures (Bruun, 2000) are removed and/or reduced. Visual amenity is not impaired, the reef is constructed offshore with no disturbance to the foreshore habitat and there is no requirement for rock emplacement along the shoreline. Salient growth in the lee of the reef leads to enhanced shoreline stability and protection (Andrews, 1997; Black, 1998; Black and Andrews, 2000) and the natural character of the coastline is retained. Because the structure is offshore and submerged, it opens up opportunities to incorporate additional recreational and public amenity benefits such as surfing, diving/snorkelling, sheltered swimming, fishing and other water activities, as well as the enhancement of marine habitat (Black *et al.*, 1998a; Black *et* al., 1999; Jackson *et* al., 1999; McGrath *et al.*, 1999; Mead and Black, 1999a; Walsh *et al.*, 1999; Black, 2000).

In the past, artificial reefs have been utilised for coastal protection (Toyoshima, 1972; Pilarczyk & Zeidler, 1996), ecological restoration (Pratt, 1994), fisheries enhancement (Parker *et al.*, 1974) and recently, to enhance surfing conditions (Pattiarachi, 1997). However, coastal structures with more than one purpose have not usually been considered. The concept of multi-purpose reefs is not new (Grigg, 1969; Walker & Palmer, 1971; Silvester, 1975), but only now are they being developed (Black *et al.*, 1997b; Black *et al.*, 1998a; Black *et al.*, 1998b; Black *et al.*, 1999; Jackson *et al.*, 1999; Mead & Black, 1999a; Black *et al.*, 2000).

The studies presented in this thesis have focussed on surfing, and were specifically aimed at uncovering the shape and function of the bathymetry at existing world-class surfing breaks, and to apply this knowledge to develop a multi-purpose offshore reef incorporating the amenity of surfing. Although the proposal for this thesis was bold, it was achievable because of the various supporting studies within the ARP (e.g. Andrews, 1997; Hutt, 1997; Sayce, 1997; Rennie, *et al.*, 1998; Hutt *et al.*, 1999; Makgill, 1999; Sayce, 1999; Black and Andrews, 2000). This chapter brings together the various aspects that have been learnt from the investigations of surfing breaks presented in this thesis, along with the previous work in the ARP, to describe the process that was followed to incorporate high-quality surfing breaks into multi-purpose offshore artificial reefs.

8.2 High-Quality Surfing Breaks

High-quality surfing waves constitute a relatively small fraction of the large variety of wave forms that break on the coastlines of the world. Indeed surfing breaks that consistently produce world-class surfing conditions are rare. In recent years, interest in creating artificial surfing breaks has increased in response to demands on the existing breaks due to higher participation in the sport (Walker *et al.*, 1972; Pratte, 1987; Moffat and Nichol, 1989; Button, 1991; Pitt, 1997; Pattiaratchi, 1997). Pitt (1997) estimates that there are at least 10,000,000 active surfers worldwide, and the sport is growing everyday; surfing supports a multi-dollar industry (Bartholomew, 1997). A survey conducted by the Hillary Commission in 1998 revealed that in New Zealand over 219,000 men and women over the age of 18 were regular surfers (Titcombe, 2000). In addition, the skills of surfers have increased significantly over the past few decades. Average surfers are performing manoeuvres on difficult waves that would have been the domain of professional surfers 15-20 years ago. This has added pressure to usage of world-class surfing breaks and created a stronger demand for quality waves. The sport requires high-quality waves to progress.

A specific form of wave breaking is critical for the sport of surfing. High-quality surfing waves for performance surfing must be steep-faced to produce high surfboard speed, but not so steep that the waves collapse (Button, 1991; Sayce, 1997; Couriel *et al.*, 1998; Sayce *et al.*, 1999; Mead and Black, 2000c), and they should preferably break in a plunging manner to create the sought-after 'tube-ride', where the surfer rides under the breaking crest of the wave (Plate 8.1). In addition, the waves must 'peel' as they break so that the surfer can utilise the unbroken face of the wave close to the breaking part of the wave crest as it translates laterally across the wave face (Walker, 1974a, b; Dally, 1989; Black *et* al., 1997; Hutt, 1997; Hutt *et al.*, 1998; Mead and Black, 1999b; Hutt *et al.*, 2000). The peel angle (Plate 9.2) determines surfing wave "speed" as the surfer travels laterally ahead of the breaking section on the unbroken wave face. Refraction changes the direction of wave propagation causing wave crests to align more parallel with the seabed contours (Komar, 1976). This is important for surfing because it alters the peel angle (Walker, 1974). The closer aligned the crest lines and the isobaths become, the greater velocity the surfer must attain to successfully ride the wave (Walker *et al.*, 1972).

Plate 8.1. Plunging waves are preferred for high-performance surfing, as this form of wave breaking presents the opportunity for the surfer to ride under the breaking wave crest, or in the tube, as seen here. (Photo Tony King – In: Uluwatu. Tadevan Holdings Pty Ltd. 1998).

The peel angle is defined as the angle between the trail of the broken white water and the crest of the unbroken part of the wave as it propagates shoreward (Walker, 1974) (Plate 8.2). Peel angles range between 0° and 90°, with small peel angles resulting in fast surfing waves and large angles in slow surfing waves (Walker, 1974; Hutt, 1997; Hutt *et al.*, 2000). There is a limit to how small the peel angle can get before it becomes impossible for a surfer to stay on the unbroken wave face, ahead of the breaking section; when this is no longer possible the wave is termed a 'close-out'. On the other hand, as the peel angle increases towards the maximum of 90°, peel speed is reduced until it becomes too slow to be considered good for surfing. For high-quality surfing, the waves must peel fast, which means the peel angles are low (Hutt, 1997; Hutt *et al.*, 2000).

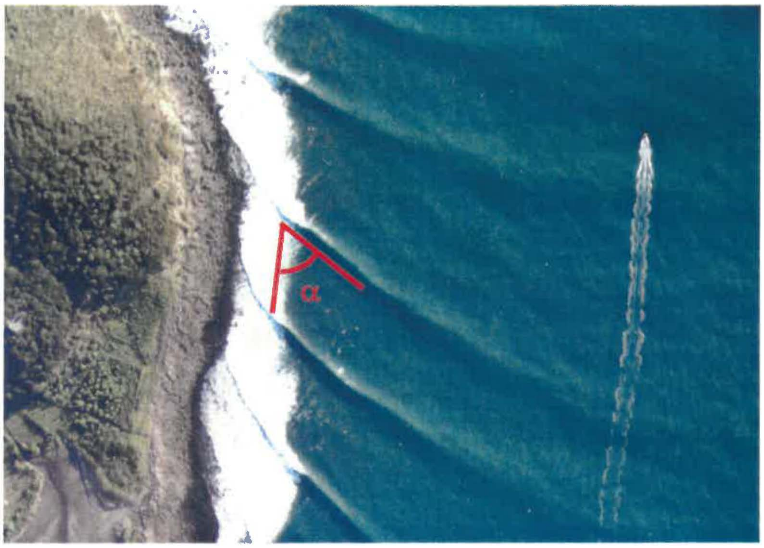


Plate 8.2. The peel angle, α, is defined as the angle between the trail of the broken white water and the crest of the unbroken part of the wave as it propagates shoreward (Aerial photo of Indicators at Raglan, New Zealand (Hutt, 1997)).

Several factors affect the peel angle and tube shape, such as wave height and period (Irribarren and Guza, 1947 – cited Sayce, 1997; Dally, 1989), and wind strength and direction (Galloway *et al.*, 1989; Moffat and Nichol, 1989; Button, 1991), but it is the underlying bathymetry that has the greatest influence on the angle at which waves peel and the shape of the breaking wave face (Peregrine, 1983; Battjes, 1988; Sayce, 1997, Sayce *et al.*, 1999; Mead and Black, 2000c). However, there has been little bathymetric investigation focusing on natural surfing breaks to elucidate how the seabed is shaped to produce waves suitable for surfing (see Walker, 1974a, b; Hutt, 1997; Sayce, 1997).

In order to gain an understanding of the optimum seabed morphologies required to produce high-quality surfing waves, it was necessary to measure the bathymetry of existing surfing breaks. World-class surfing breaks were targeted for several reasons;

1) high-quality surfing waves are in demand because of increasing usage pressure on existing world-class surfing breaks, therefore, in order to create high-quality surfing breaks we need information on existing ones;

2) the fact that there are only a relative handful of world-class surfing breaks on the thousands of kilometres of coastline which receive surfable meteorological and oceanographic (metocean) conditions suggested that there was 'something special' about the bathymetry of these breaks, and;

3) developers of multi-purpose offshore reefs would most likely prefer to incorporate high-quality surfing breaks into coastal projects; there are thousands of mediocre surfing breaks in the world.

8.3 Surfing Break Surveys

Bathymetries of 28 mostly world-class surfing breaks, located around the Pacific Rim and Indonesia, were measured using a portable surveying system that was specifically developed for the purpose (Chapter 2). This group of surfing breaks covers the whole range of geomorphic categories including coral reefs, rocky reefs, point breaks, rock ledges, river and estuarine deltas and sand beaches. To accompany the dataset, aerial photographs and wave vortex profiles were also collected for the majority of the measured breaks to gather information on the wave peel angles and tube shapes, respectively. Landmarks were also surveyed at each break using hand-held GPS receivers so that bathymetry surveys could be related back to the aerial photographs. These data represent the first ever set of measurements that include all the geomorphic categories of high-quality surfing breaks. Analysis of these surfing breaks led to the identification of form and function of bathymetric features at world-class surfing breaks and provided general design concepts for the incorporation of surfing into multi-purpose offshore reefs.

8.4 Analysis of Surfing Break Bathymetries

The bathymetric survey data were used to generate depth contour maps (Fig. 8.1) that could be used for visual analysis, as well as converted to bath-grid format for numerical modelling. The landmark surveys were overlaid on the depth contour maps to give a clearer indication of the break's location (Fig. 8.1).

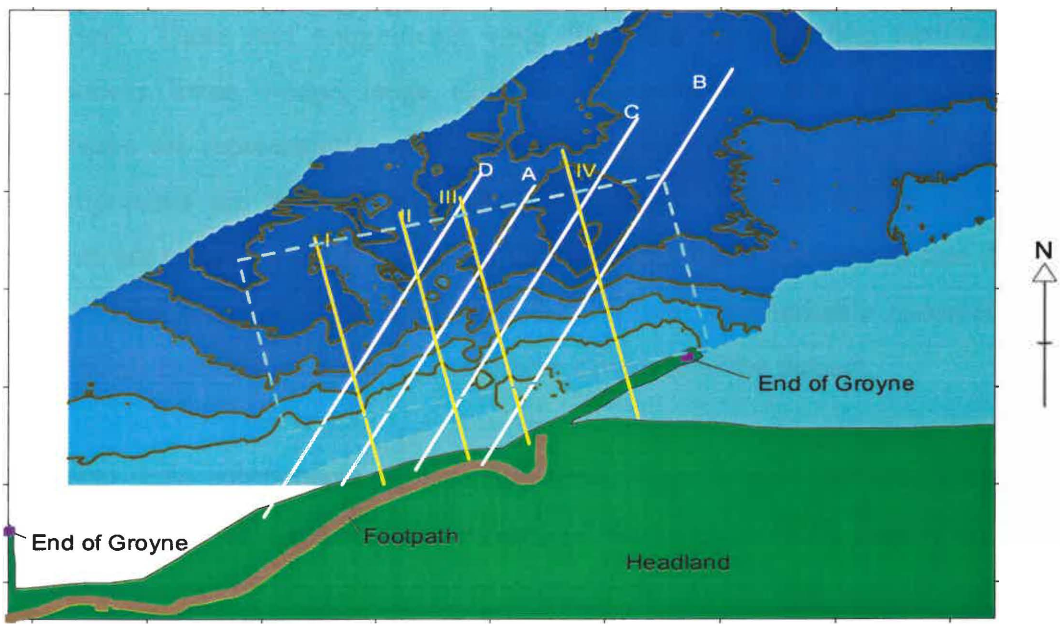


Figure 8.1. An example of a depth contour map generated from the bathymetric survey data of Kirra Point in Queensland, Australia, using Surfer© software. Landmark information has been overlaid, and the solid lines through the break indicate isobath normal seabed profiles (I-IV) and wave orthogonal seabed profiles (A-D). (Surveyed October, 1997)

Isobath normal seabed profiles, wave orthogonal seabed profiles (Fig. 8.1) and wave peel angles in relation to isobaths, were first extracted from the contour maps. These data were used for the design of artificial surfing reefs (Black *et al.*, 1998a; Mead & Black, 1999a) to incorporate seabed gradients similar to those at world-class surfing breaks, unlike previous designs, which did not utilise information of existing surfing break bathymetry (Moffat and Nichol, 1989; Pattiaratchi, 1997). The depth contour maps were then studied in more detail to discern major morphological properties. The most useful methods of analysis were visual classification of the meso-scale components that comprise surfing breaks and numerical refraction modelling (with model WBEND – Black, 1997) to discern the functions of individual components (Chapter 3), as well as common combinations of them (Chapter 4).

8.5 Meso-scale Reef Components

Several recurring meso-scale morphologies were identified from the surfing break bathymetries. These reef components were classified using surfing terminology as ramp, platform, focus, wedge, ledge, ridge and pinnacle (Fig. 8.2). Even though the surfing breaks are representative of the whole range of geomorphic categories, these seven components are common throughout the range. This is not to say that all components are present at each break, but that no break has a component that does not occur in at least three other breaks (Table 4.1), which is remarkable considering the relatively small sample size and the geomorphic diversity of the dataset.

As the meso-scale components of a surfing break control wave refraction and allow waves to peel at surfable speeds (see Walker, 1974a, b; Hutt, 1997; Hutt *et al.*, 2000), component descriptions are based on the components' shape and isobath orientation, and the component alignment relative to the 'favoured orthogonal direction' of incoming waves. The favoured orthogonal direction is defined as the wave alignment that produces the best quality surfing wave at each break. If the waves are not aligned around the favoured orthogonal direction they will either peel too fast or too slow to be useful for high-performance surfing. The brief definitions of surfing reef components are,

(1) ***Ramp*** - a seaward-dipping seabed that refracts incoming waves towards the favoured wave orthogonal direction (Fig. 8.2a).

(2) ***Platform*** - an approximately horizontal region of seabed that translates waves without refraction.

(3) ***Focus*** - a distended seabed ridge aligned so that wave orthogonals converge towards the apex of the ridge. It acts to cause height convergence and may ultimately lead to a "take-off peak" where surfers can commence their ride, or a 'section' in the wave that breaks earlier than other parts of the wave due to its increased height (Fig. 8.2b).

(4) ***Wedge*** - a sloping seabed that initiates wave breaking and which refracts incoming waves away from the favoured orthogonal direction (Fig. 8.2d).

(5) ***Ledge*** – a sharp discontinuity in depth below a platform with a gradient >1:4, which causes the waves to steepen and plunge quickly with little time for refraction to occur (Fig. 8.2e).

(6) ***Ridge*** - a seabed ridge on a wedge or ledge aligned so that the offshore isobaths are at a greater angle to the favoured orthogonal direction than the preceding isobaths of the wedge or ledge, and so that the inshore isobaths do not cause convergence along the apex of the ridge. A ridge causes a local increase in seabed gradient and leads to a "hollow" wave section with a steeper wave face and faster peel angle (Fig. 8.2f).

(7) ***Pinnacle*** - an isolated region of shallow bathymetry that causes the wave to locally rear up and steepen (e.g. a shallow rock, pinnacle or coral-head) (Fig. 8.2c).

Detailed descriptions of the form and function of each reef component are given in Chapter 3.

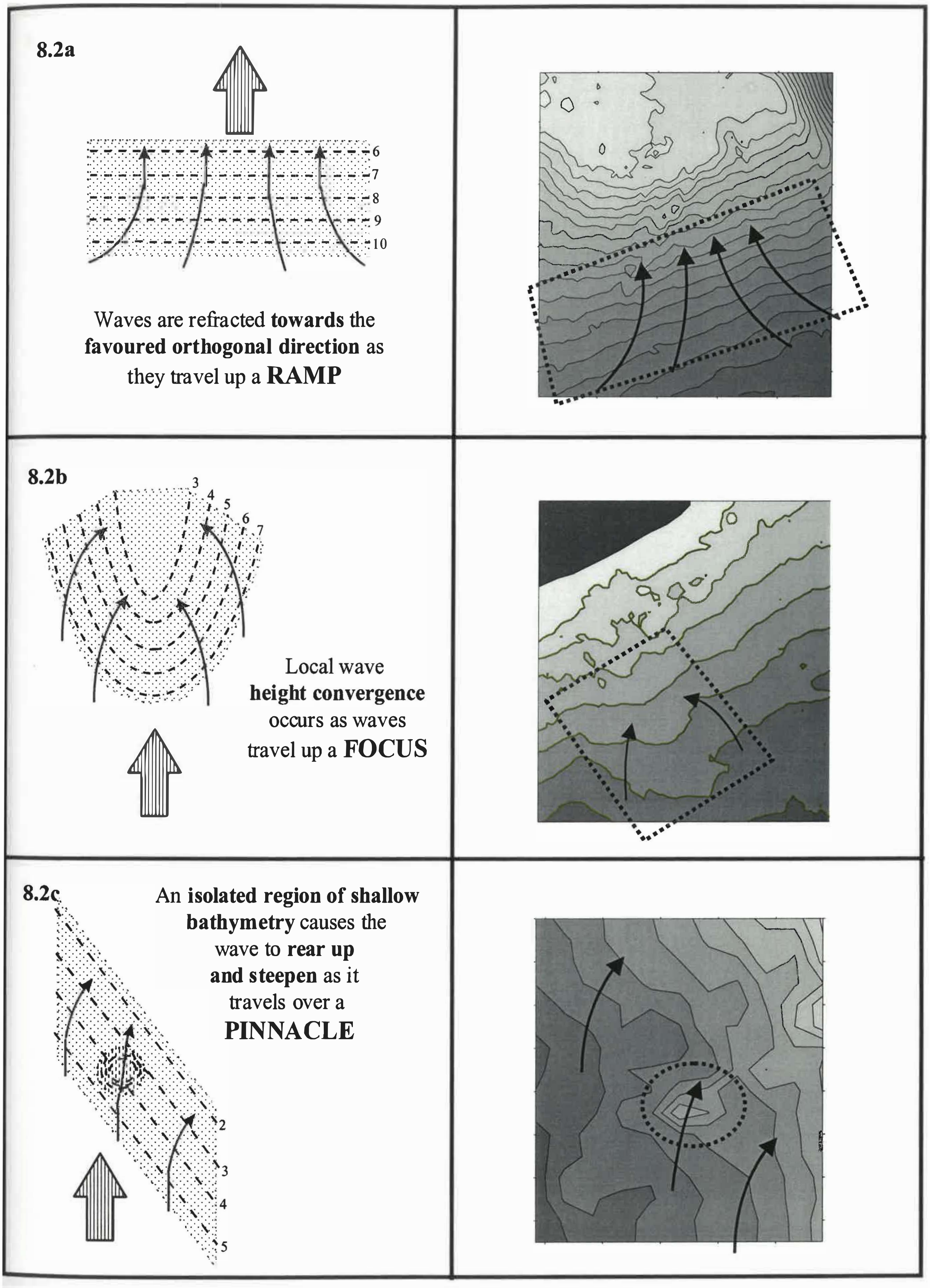


Figure 8.2. (Caption below)

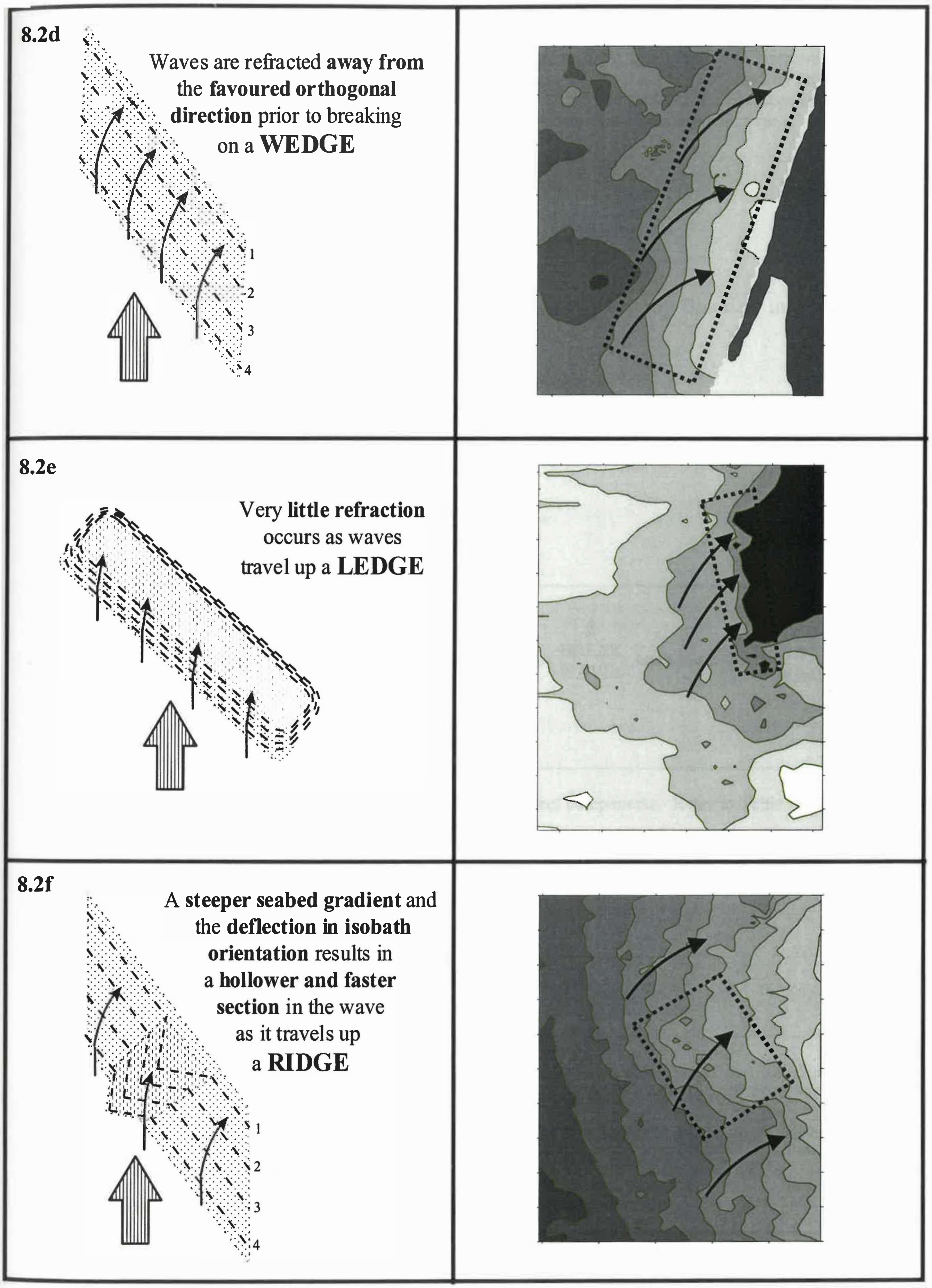


Figure 8.2. (Caption below)

Figure 8.2. Reef components that comprise the bathymetry at world-class surfing breaks. Isobaths of components become shallower in the direction of wave propagation (up the page). The large arrows represent the 'favoured orthogonal direction' and the small arrows represent transformations to the wave orthogonals. Schematic diagrams are accompanied by an example of a reef component from a measured bathymetry. Note, the platform has not been included here because it is essentially a flat component that does not refract waves that pass over it.

8.6 Reef Component Functions

The meso-scale reef components can be sub-categorised by function into two basic groups (Fig. 8.3 and Tab. 8.1),

1. components that pre-condition waves, and,
2. components that break waves.

Type 1 components align and shoal waves prior to breaking on type 2 components.

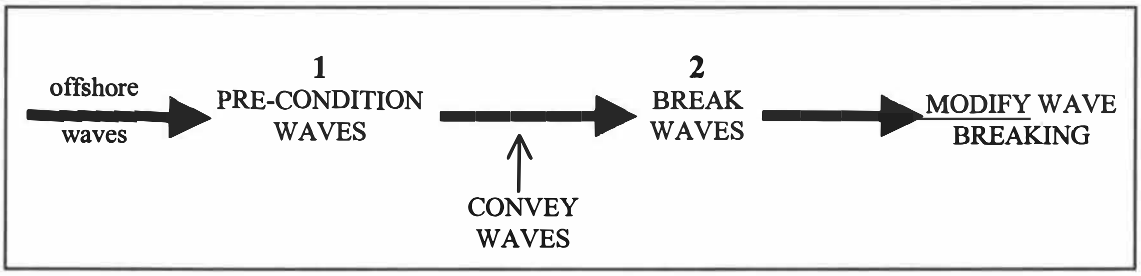


Figure 8.3. The functional order of meso-scale surfing reef components. Refer to Table 8.1 for a list of the reef components in each category.

Table 8.1. Functions of surfing reef components.

Component	Function	Details
Ramp, Focus	1. Pre-condition waves	- Pre-condition for other components
Platform		- Convey waves without change
Wedge, Ledge	2. Break waves	- Break waves for surfing
Ridge, Pinnacle		- Modify breaking waves

8.6.1 Pre-conditioning Components

The ramp, focus and platform are categorised as preconditioning components because they pre-condition waves (by aligning and shoaling) prior to breaking on one, or a combination of, the wave breaking components (most commonly a wedge). These components are located offshore of the main wave breaking region at a surfing break, and high-performance surfing waves do not break on them, except on the shallower regions of a focus (see below). While the ramp and focus steepen waves due to shoaling, and refract waves to align them closer to the favoured orthogonal direction (ramp) and to locally increase wave height (focus), the horizontal platform acts to convey waves to the wave breaking components with little change to their direction and height (Fig. 8.3 and Tab. 8.1). The platform's function is to maintain the wave orthogonals at the alignment established by a ramp or, in less common situations, a focus. The platform links components together without altering wave orientation and thus maintains a surfable wave peel angle.

8.6.2 Wave Breaking Components

Once waves have been aligned by the pre-conditioning components they break on the wave breaking components, the wedge, ledge, ridge and pinnacle. These components are generally located in shallow water depths and oriented so that waves approaching from the favourable orthogonal direction break with surfable peel angles. A wedge or ledge is always the major wave-breaking component at a surfing break. The ridge and pinnacle components are normally located on one of the other wave breaking components (a wedge or ledge) and locally modify the character of the breaking wave (Fig. 8.3 and Tab. 8.1), usually enhancing wave breaking for the performance of a single surfing manoeuvre (e.g. a tube or a floater). In surfing terminology, the part of the wave locally modified by a ridge or pinnacle, is known as a 'section'.

8.7 Component Scale

The descriptions of component functions were developed on the basis of a functional order (Fig. 8.3). This functional order of components results in a size range from larger offshore components that align, shoal and convey waves prior to breaking, to the smaller inshore components that only modify a small section of the wave. Each component has a specific function and performs this function within its own size range (Fig. 8.4). While some components may perform their function over a wide range of sizes, others are relatively restricted. For example, a ramp may orientate waves towards the favoured orthogonal direction along a whole section of coast, or it may act on a relatively smaller scale, catering to one specific break. Wave refraction begins when the water depth is equal to 0.25-0.5 the wavelength (Komar, 1976), and so a ramp can start functioning in relatively deep water with respect to a surfing break. This leads to a range in size for a ramp from as small as 100 m^2 and up to several km^2. However, a pinnacle greater than several meters across would be impossible to successfully surf; the sections would be too long to negotiate. The upper size limit of a pinnacle is set by the maximum distance that a surfer can travel to successfully negotiate the section it creates. Speed cannot be indefinitely maintained when passing below a collapsing section due to the low steepness of the wave face at the base, or when 'floating' over the white-water of the broken section. The same is true if a section created by a pinnacle breaks in a plunging form; there is a limit to how far a surfer can negotiate when the crest is breaking simultaneously along a section. If it is too long, the section becomes a close-out.

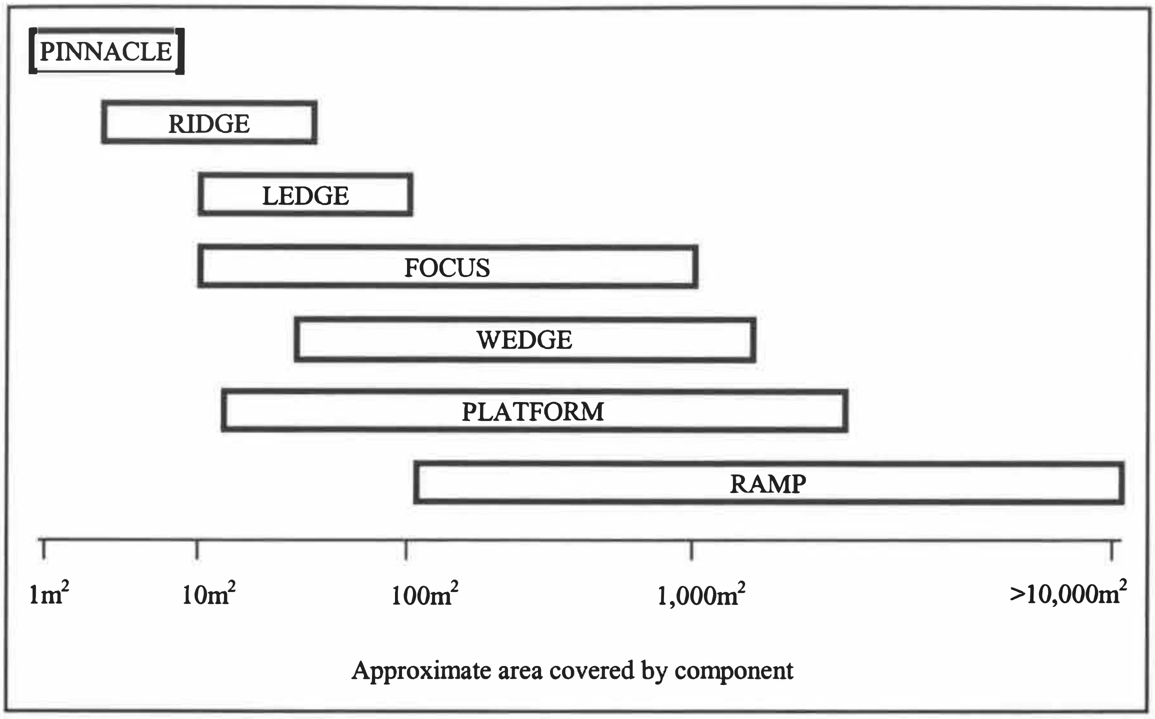


Figure 8.4. The functional scales of surfing reef components.

The classification and functional description of the meso-scale reef components (Chapter 3) led to a better understanding of seabed morphology at surfing breaks, as well as an understanding of the functional scale of components. Surf breaks are made up of a number of reef components in specific configurations, which are holistically connected through the process of refraction. Consequently, the orientation of wave orthogonals prior to breaking has a large influence on the peel angle at the breakpoint. Understanding the form and function of reef components is essential for the design of man-made surfing reefs, and points to the necessity of sophisticated configurations of reef components rather than simple one or two component configurations. In the right configurations, meso-scale reef components act to maintain surfable peel angles. However, before this new information on surfing reef morphology could be applied to reef design, a thorough understanding of how reef components are combined to produce world-class surfing breaks was required.

8.8 Combinations of Reef Components

During the classification of individual reef components, it was found that not only were there common components at many surfing breaks, but that certain combinations of these components were also recurring (Chapter 4). The most common component combinations are illustrated in Figure 8.5. Each common combination is represented by three related diagrams. The first is an example of a measured surfing break bathymetry. The second is a numerical model output of wave refraction over the same bathymetry. The third is an idealised schematic of the component combination where the more complex bathymetry of the natural reef has been simplified to the dominant components. By considering the changes to wave orthogonal direction caused by reef component combinations using the numerical model WBEND (Black, 1997), the connectivity of the various features (Fig. 8.2) and the utility of some of the common combinations (Fig. 8.5) were explored.

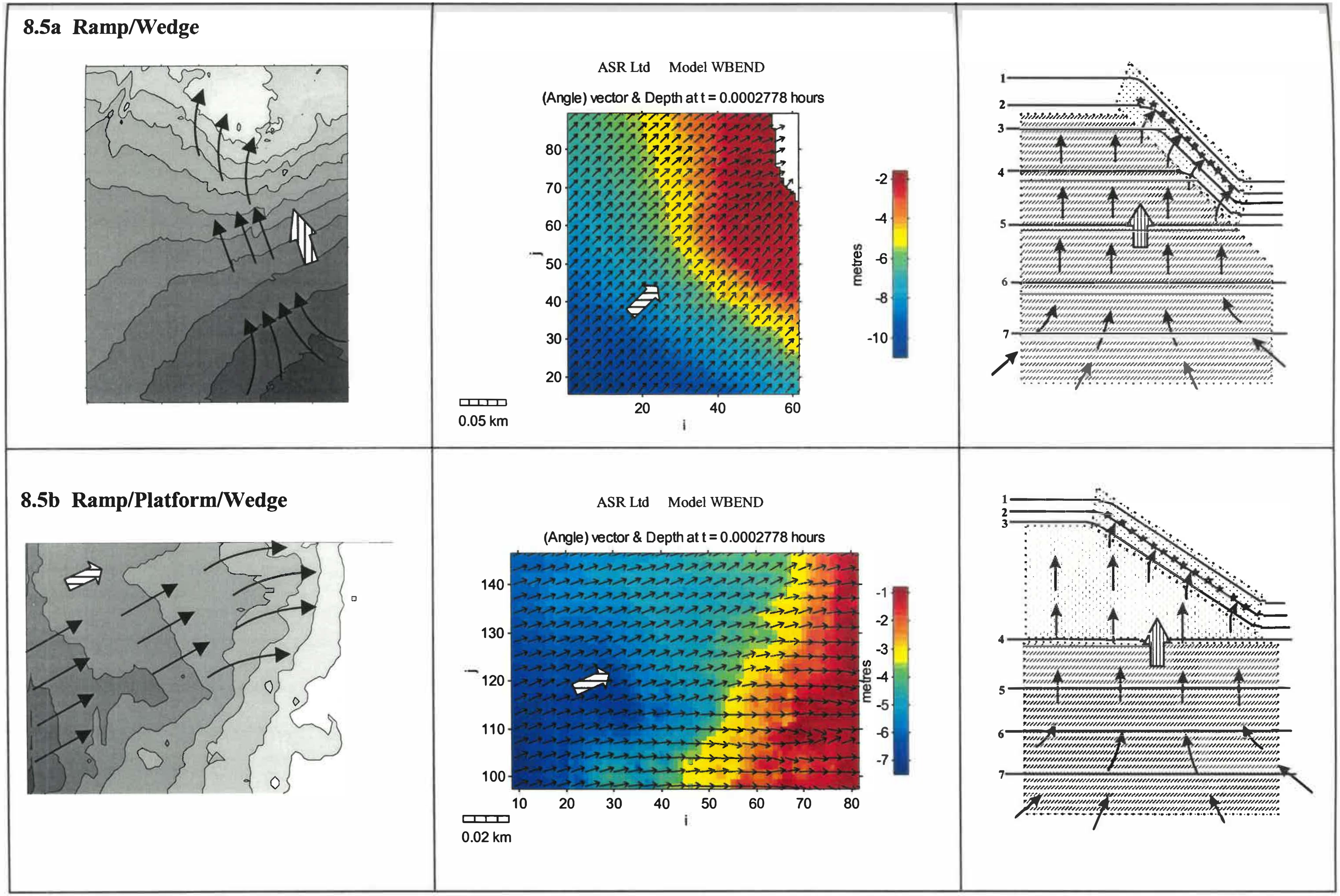


Figure 8.5. (Caption below)

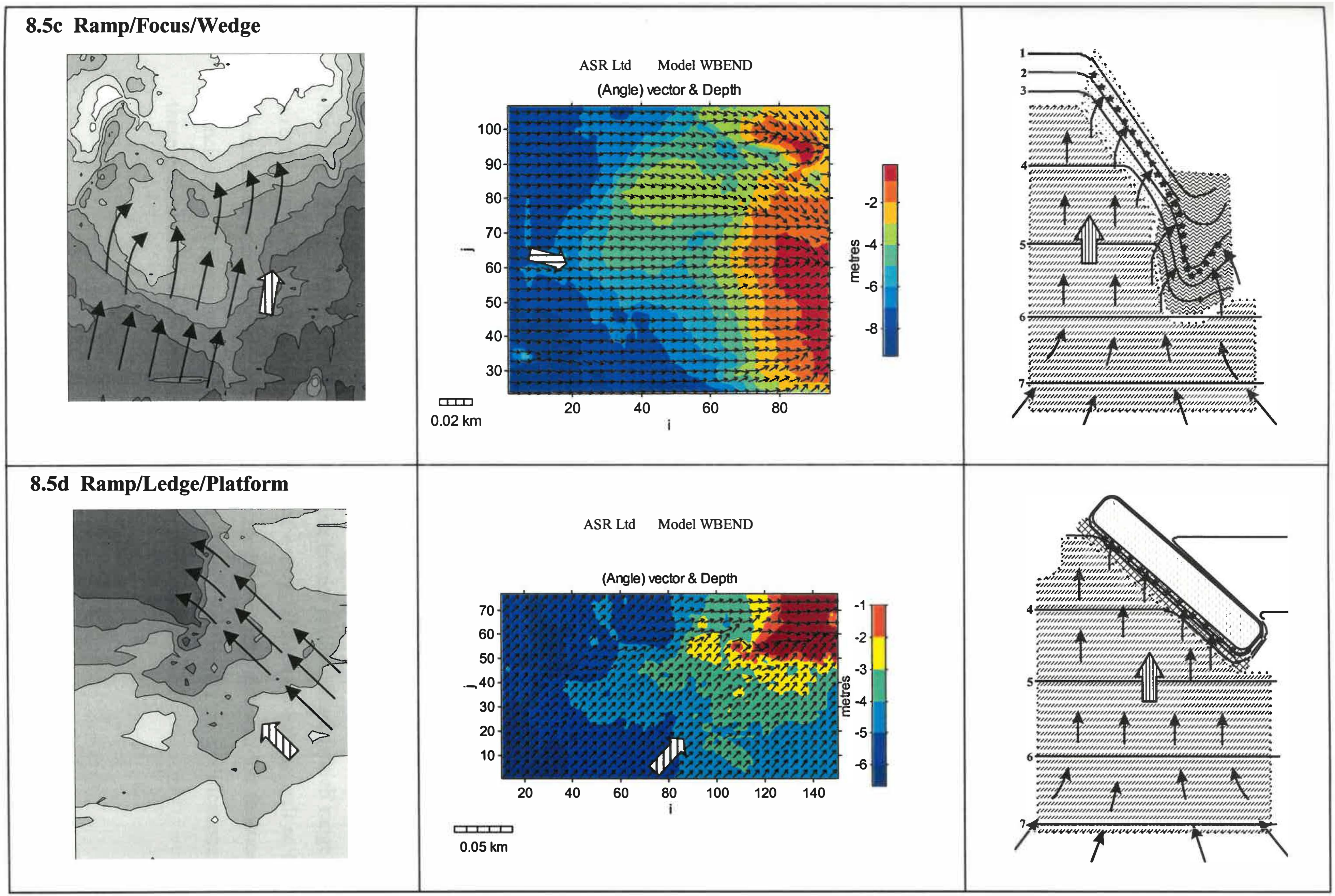


Figure 8.5. (Caption below)

Figure 8.5. Common combinations of reef components found at world-class surfing breaks. For each set of three diagrams, from left to right, the first is an example of a measured surfing break bathymetry; the second is a numerical model output of refraction of waves over the particular surfing break bathymetry; and the third is an idealised schematic of the component combination - the multi-faceted bathymetry of natural surfing reefs has been simplified to highlight the dominant components. The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. Isobaths of components become shallower in the direction of wave propagation (up the page), and break point is represented by ☆. Note, the model bathymetry has been rotated so that wave input is from the left-hand side.

The function and connectivity of the four common combinations depicted in Figure 8.4 are described in detail in Chapter 4, and then in Chapter 5, the ramp/platform/wedge configuration at Bingin Reef in Bali, Indonesia, is manipulated to gain insights as to why this configuration, with the particular scale of the components at Bingin, consistently produces high-quality surfing waves. These investigations reinforced the concept of functional order of components, where pre-conditioning components set the wave up to break on the wave breaking components with surfable peel angles. It is the specific combination of the meso-scale reef components at a surfing break that determine its overall quality and consistency. The process of refraction links components together, and so, the resulting reef component combinations have a holistic nature.

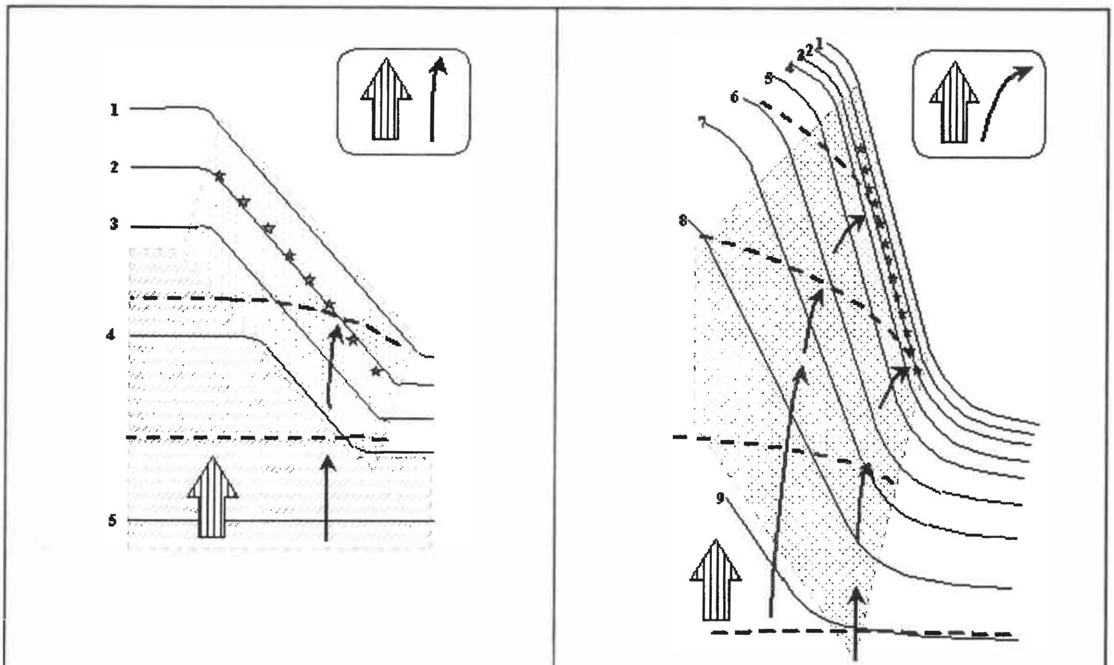
The functional descriptions of common component combinations found at world-class surfing breaks given in Chapter 4, are general in the respect that they describe the principle functions of each configuration. They demonstrate the holistic nature of each configuration by depicting the process of refraction over each consecutive reef component that consequently results in surfable peel angles when the waves break. However, the modelling of the range of surfing breaks in the dataset (which range in size from small offshore reefs to headlands of over a kilometre long), as well as the investigation presented in Chapter 5, have demonstrated that although the functional principles of common combinations hold true, there are a variety of modifications to these general descriptions that usually relate to differences in scale.

8.9 The Effect of Surfing Break Scale on Component Configurations

While individual meso-scale reef components have been isolated and classified to allow for the description of their form and function, as well as the combinations of them that comprise high-quality surfing breaks, because of the holistic nature of component configurations there are inevitably some transition zones where components mesh with each other and the strict definitions of component form and function become blurred. This is especially true when the overall scale of a surfing break is considered.

A good example of the effect of surfing break scale on reef components is the ramp/wedge configuration (Fig. 8.5a). Refraction on the ramp aligns wave orthogonals closer to the favoured orthogonal direction. Waves next encounter the wedge and are subsequently refracted away from the favoured orthogonal direction (Fig. 8.5a). The degree of refraction that occurs on the wedge prior to breaking must be such that a surfable peel angle is maintained. This is dependent on the depth of the offshore toe of the wedge, which consequently effects the wedge alignment. At a shallow depth, only a small amount of refraction can occur prior to wave breaking. Thus, orthogonal direction at the break point is only slightly different to the favoured orthogonal direction (Fig. 8.6a). As a consequence, the peel angle is not strongly influenced by refraction on the wedge, just by the incident angle determined by the ramp and the isobath orientation of the wedge.

As the size (and consequently the depth) of a wedge increases, the amount of refraction occurring on the wedge prior to breaking increases. As a result, the wedge must be rotated at a greater angle to the favoured orthogonal direction in order to maintain a surfable peel angle at breaking. Therefore difference between the orthogonal direction at break point and the favoured orthogonal direction is a greater than that for a small, or shallow, wedge (Fig 8.6b). Rotating the wedge more parallel to the favoured orthogonal direction compensates for the increased refraction that occurs on the deeper wedge prior to wave breaking. Hence, the best orientation of the wedge for quality surfing waves in relation to the favoured orthogonal direction is dependent on the depth and size of the wedge in the ramp/wedge configuration. If the angle of the wedge's isobaths to the favoured orthogonal direction does not increase with increasing depth and size, the wave will be refracted beyond a surfable peel angle at the break point and result in waves that close-out. This decrease in peel angle due to the increase in wedge size/depth is very obvious in the manipulation of the reef components at Bingin Reef described in Chapter 5, once the platform had been removed leaving a ramp/wedge configuration.



8.6a. The difference between the favoured orthogonal direction and the wave orthogonal direction at break point is small when the wedge is at a shallow water depth.

8.6. The difference between the favoured orthogonal direction and the wave orthogonal direction at break point is relatively larger when the wedge size increases.

Figure 8.6. Schematic diagrams of wedge orientation changes required to maintain a surfable peel angle at break point with increasing size/depth of the wedge. The large arrows represent the 'favoured orthogonal direction' and the small arrows represent the wave orthogonals. The dashed lines represent wave crests. Note the small difference between the favoured orthogonal direction and the direction of the wave orthogonal at break point in 8.6a (shallow water wedge), compared to the relatively large difference between these directions in 8.6b (large deep water wedge or headland).

The size of waves can also have a similar outcome on peel angle as that found by differences in the depth/size of the wedge. Large waves break earlier (in deeper water) than small waves and therefore have little time to refract away from the favoured orthogonal direction (i.e. wave crests more parallel to the isobaths) on the wedge. On the other hand, small waves break in much shallower water and so refraction can proceed to a point where the wave crests are almost parallel to the isobaths of the wedge when they break. For this reason, some breaks may produce close-out conditions when a small swell is present, but fast surfable waves once the swell reaches a critical size (e.g. Kirra Point in Queensland, Australia – Black *et al.*, 1998a). Hutt (1997) identified this process at Raglan in New Zealand and referred to the difference between the small wave height and the large wave height as refraction breaks vs headland breaks, indicating that far less refraction occurred when the wave height was large. The difference between the offshore wave direction and the wave direction at break point was shown to be 15° and 40°, for a 4 m and 1 m wave heights, respectively (Hutt, 1997). The effect of wave size on peel angle raises the question of whether or not it is an advantage to have a slower peeling wave as the wave size increases (discussed in detail in Chapter 4). At present there is not enough information to argue this point one way or another, however, it is a factor that will need to be addressed when multi-purpose reefs are designed in areas with a large range in swell heights.

Scale is also an important consideration for focus components. Some surfing breaks are essentially a large focus, for example Pipeline in Hawaii (Plate 8.3). In these cases, the deeper part of the focus aligns wave crests, which are also height reinforced into a peak as they move up the focus before breaking. Wave peeling is mainly a consequence of the height reinforcement into a peak and the consequent loss of wave height from adjacent parts of the wave. This results in a very pronounced wave height gradient from the peak formed along the apex of the focus, reducing down from the peak along the wave crest (Plate 8.3). Because wave breaking is dependent on water depth, the highest part of the wave (the peak) breaks earliest in deeper water and then along the reducing height gradient caused by the focusing as it encounters shallower water depths. While the large focus does have the advantage of greatly increasing wave height, it is susceptible to closing out in small wave conditions due to increased refraction prior to breaking (as described above) and also provides a relatively short ride due to the extraction of energy from adjacent parts of a wave.

Plate 8.3. Pipeline on Hawaii's North Shore is a good example of a large focus break. In this picture the height reduction along the wave crest due to energy extraction from the adjacent wave crest is very obvious. (Photo ASL Vol. 73, Oct. 1994)

The energy extraction caused by a focus must be considered when designing surfing breaks. It is an advantage to incorporate a focus into a surfing break, not only to define the take-off zone, but also to increase the wave height (e.g. Black *et al.*, 1998a) and lessen the difficulty required to catch a wave (by decreasing the effective seabed gradient, which results in reduced wave steepness at the break point – Chapter 3). However, as Black *et al.* (1998a) found, the focussing must be directed so as not to disrupt the rest of the surfing break by extracting too much wave energy from the adjacent wave crest and thereby divorcing itself from the rest of the wave.

8.10 Refraction Compensation on Headland and Island Breaks

The influence of increased wedge size is very pronounced when the wedge is increased to the size of a headland, point or island break. These breaks are actually very large wedges. Headland surfing breaks are most often associated with large terrestrial outcrops on otherwise straight coasts (e.g. Raglan Point in New Zealand, Fig. 8.7). Headland breaks have wedges extending to great depths and, because the wedge is in relatively deep water (> 10 m), it must therefore be orientated at a large angle to the favoured orthogonal direction (Fig. 8.6b). This is shown to be an essential characteristic of a headland break by Black *et al.* (2000a) in the design of the Gold Coast Reef. On large headlands, the waves need to approach the headland such that the orthogonal is directed essentially straight down the length of the headland (8.6b), otherwise wave refraction can cause the waves to close-out.

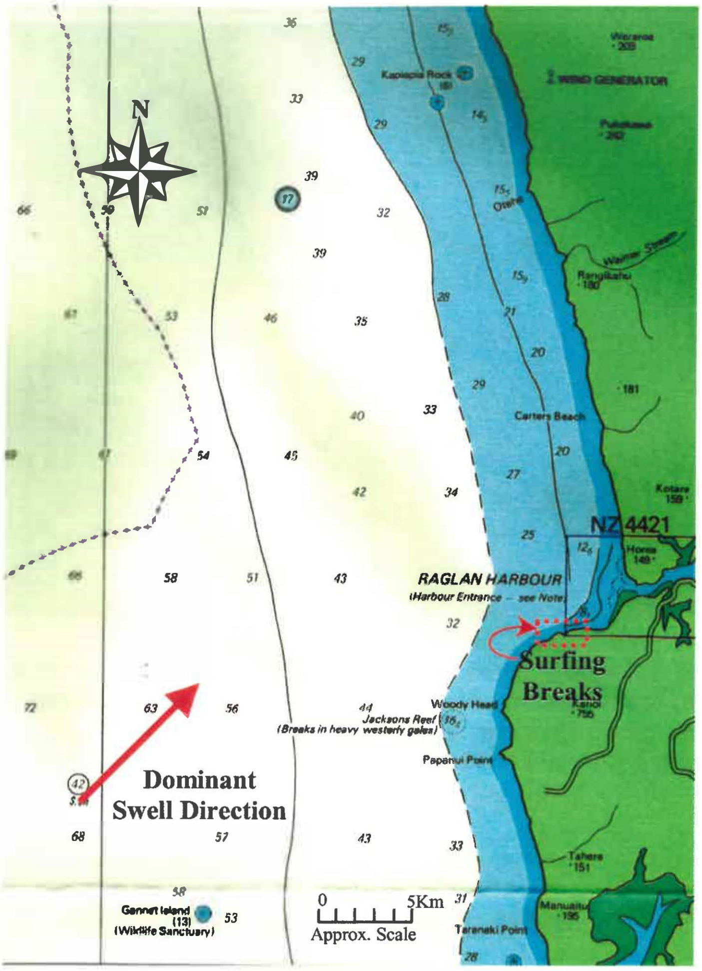


Figure 8.7. Raglan headland on the west coast of North Island, New Zealand (Nautical chart NZ43, RNZN Hydrographic Office). The dominant swell and wind directions are from the southwest. The main surfing breaks at Raglan are orientated away from the dominant swell direction, towards the north.

The 'refraction compensation' achieved by the rotation of the large wedges to a position more parallel to the wave orthogonal direction at headland breaks is sometimes found at small offshore island and reef breaks (Plate 8.4). In this case, the isobaths of the large-scale wedge continually bend away from the favoured orthogonal direction as they follow the topography of the island or reef, and so refraction is compensated and a surfable peel angle results. With the headland or island surfing break there is often a close-out section, before the peel angle is surfable, where the isobaths are initially near parallel to the wave crest (i.e. the far end of the headland or the side of an island facing the incoming swell) (Plate 8.4).

Plate 8.4. Aerial view of an island surfing break, where the wedge (reef edge) is continually bending away from the approaching waves, which compensates for refraction and produces surfable peel angles over a very long distance. Note the region at the top of the photo, where wave peel angles are very low and unsurfable where the island faces the swell direction and waves are closing out. (Photo Dick Hoole – In: Uluwatu. Tadevan Holdings Pty Ltd. 1998)

Orientation of all sizes of wedges must be properly considered during artificial reef design, as wedges are the main component on which surfing waves break. The relative orientation off the wedge components to the dominant swell directions of the artificial reefs designed for Narrowneck on the Gold Coast and Mount Maunganui demonstrate how this component must be adjusted to compensate for refraction depending on its size. The Narrowneck reef extends to a depth of almost 11 m and the length of the northern arm is ~450 m (Black *et al.*, 1998a). In comparison, the Mount Maunganui reef much smaller and shallower, with the entire length of the reef being less than 95 m and extending to approximately 4.5 m deep (Mead *et al.*, 1998b). As a consequence of size/depth of the Narrowneck reef, the wedge is rotated to ~85° to the favoured orthogonal direction to maintain surfable peel angles, while the smaller/shallower Mount Reef wedge is set 30° less, at close to 55° to the favoured orthogonal direction for the same reason (Black *et al.*, 1998a; Mead *et al.*, 1998b). Even though there are some variations in the range of wave approach angles between the two locations, this comparison is valid because the wave climates and design waves for both reefs are very similar (Black *et al.*, 1998a; Mead *et al.*, 1998b).

One of the consequences of the refraction mechanism, which may explain why surfers seek headlands (often called 'point-breaks') for surfing, is that refraction is strongly dependent on wave period. The longer period waves refract more and can therefore reach parts of the coast that are not orientated towards the dominant swell direction, i.e. the sheltered side of large headlands. As discussed above, the large wedges of headlands must be rotated away from the favoured orthogonal direction to compensate for refraction of waves beyond surfable peel angles. The orientation of a headland can produce long peeling surfing waves and also acts as a wave filter, reducing the spectral width of a swell by refracting the longer period waves into the point break, while letting other shorter period waves travel past and up the coast. This is especially significant when the dominant swell direction is similar to the dominant wind direction, as is often the case, or when the swell is being generated locally (from the dominant swell direction). On the open coast, every component of the swell (a variety of periods, wave heights and directions) can approach a break, which is unwanted for surfing; long period, straight-crested waves are preferred. In addition, the wind is directed straight onshore on the open coast, further degrading surfing wave quality. However, the orientation of a headland can mean that by the time waves have refracted into the break, the wind is nearly offshore. As a consequence, point-breaks more often have better surfing conditions than open coast breaks that are oriented towards the dominant swell direction.

For example, Raglan is a large headland on the west coast of North Island, New Zealand (Fig. 8.7), that is well-known for consistently producing high-quality surfing waves, even when the rest of the coast is unsurfable due to wind from the dominant swell direction. The dominant swell (and wind) direction on the west coast is from the southwest, but the main surfing breaks at Raglan are orientated away from the dominant swell direction, towards the north (Fig. 8.7). Indeed, swells that approach Raglan headland from the northwest are rarely good for surfing because refraction around the headland does not occur and so shorter period waves can also approach the break, 'confusing' the larger components of a swell.

The investigations of world-class surfing break bathymetries have greatly increased the understanding of the shape and function of the seabed at natural high-quality surfing breaks. Isolating and describing the large-scale reef components and how specific components combinations function to produce world-class surfing breaks represents a major advantage for incorporation of surfing into coastal construction. While some of the principles discussed above have already been applied to the design of artificial surfing reefs (e.g. Black *et al*, 1998a), these studies have expanded upon them and there are now have a wider range of options to draw upon. The numerical modelling of natural reef component configurations (Chapter 4), as well as the manipulation of reef component configurations (Chapter 5), has well demonstrated that refraction links reef components, and so a holistic approach must be taken when developing reef design.

These studies have shed light on many aspects of surfing reef bathymetry and function and made it clear that design of breaks that produce high-quality surfing waves must take many different factors into consideration. The interconnectivity of the various reef components and the effects of component size, must be taken into account to create multi-purpose facilities that optimise the characteristics of specific sites. The next objective of this thesis was to develop methods to predict the breaking intensity of surfing waves. With the dataset of world-class surfing break bathymetries and the accompanying wave vortex profiles, it was possible to advance some of the earlier work on breaking intensity that was done within the ARP (Sayce, 1997; Sayce *et al*., 1999).

8.11 Predicting the Breaking Intensity of Surfing Waves

Describing the shape of the breaking wave is imperative for describing surf quality. Therefore, a method of describing and predicting the shape of surfing waves would be a very useful tool for surfing reef design. As mentioned above (section 8.2), high-quality surfing waves for performance surfing must break in a plunging manner to provide a steep wave face, which produces high surfboard speed (Button, 1991; Sayce, 1997; Couriel *et al*., 1998; Sayce *et al*., 1999), as well as the opportunity to ride in the 'tube' (Plate 8.1). The seabed gradient has the greatest influence on the shape of breaking waves (Peregrine, 1983; Battjes, 1988; Sayce, 1997; Couriel *et al*., 1998). However, although existing methods of classifying and describing wave breaking take seabed slope into account (e.g. the surf similarity parameter - Battjes, 1974; the Irribarren number - Dally, 1989), they do not describe the actual shape of plunging/surfing wave profiles (the tube shape), and cannot adequately differentiate between the variety of waves at different breaks required by surfers (Button, 1991; Sayce, 1997; Couriel *et al.*, 1998; Sayce *et al.*, 1999). In addition, they do not well differentiate the transition between the classic breaker categories, i.e. spilling, plunging, collapsing and surging (Sayce, 1997; Couriel *et al.*, 1998; Sayce *et al.*, 1999).

Surfers are usually able to distinguish between the vortex, or tube, shape of waves at different breaks because of the subtle differences in the shape of the face of the breaking wave. As is implied by the sequence of breaker types (spilling though to surging), there is a transition between them and so it follows that within a category there is also a sequence, e.g. from gentle plunging to extreme plunging. This has previously been termed the breaking intensity (Sayce, 1997; Sayce *et al.*, 1999). There are many descriptive terms that surfers use to describe plunging waves such as 'tubing', 'hollow', 'pitching' and 'square'. However, exactly what is meant by a specific term, and how this relates to the wave's breaking intensity, is subjective and often depends on the experience of a surfer. A definitive description of wave breaking intensity is required to relate the subtleties of surfing waves in a way that can be universally understood. Thus, it is critical to have a more refined definition of the wave breaking intensity and to define the actual shape of the plunging wave profiles. A better method of wave shape definition is required for surfing waves.

Sayce (1997) and Sayce *et al.* (1999) developed methods to fit a cubic curve (Longuet-Higgins, 1982) to the face of plunging waves (Fig. 8.8). However, the previous authors had limited information about seabed gradients, and so they were only able to suggest possible relationships between the seabed gradient and the breaking intensity of plunging waves. With the bathymetric information of a wide selection of world-class surfing breaks, the possible relationships between seabed gradient and breaking intensity suggested in the earlier ARP studies (Sayce, 1997; Sayce *et* al., 1999) could be investigated and advanced. The methods used to relate the curvature of a breaking wave in comparison with the underlying bathymetry of world-class surfing breaks around the Pacific Rim and Indonesia are described in detail in Chapter 6.

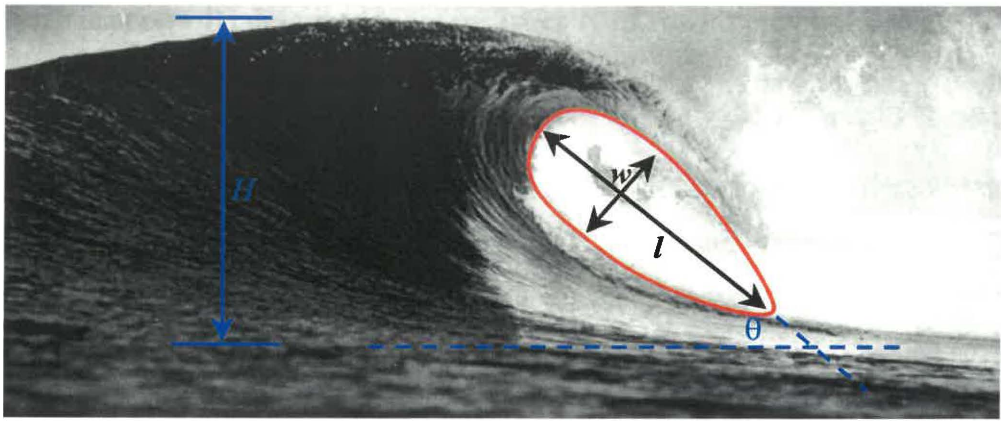


Figure 8.8. Curve fitting is applied to the forward face of a crest parallel wave image and used to calculate the vortex length (l), width (w) and angle (θ). H is the estimated wave height (after Black *et al.*, 1997).

By relating a variety of wave vortex parameters (length, width, etc.) to the seabed gradient along which they break, a new method for predicting and describing the breaking intensity of plunging surfing waves was developed. It was found that the best indicator of wave breaking intensity was the ratio of vortex length to width. This ratio can be predicted from the orthogonal seabed gradient using the linear equation,

$$Y = 0.065X + 0.821 \qquad (8.1)$$

where X is the orthogonal seabed gradient, which is the seabed gradient along the path of wave propagation, not the maximum local slope of the seabed (Fig. 8.1). Low values of the vortex ratio indicate high breaking intensity and, as the vortex ratio of the tube increases, the breaking intensity decreases. This equation allows predictions of breaking intensity, Y, defined by a ratio that gives an immediate indication of the tube shape. The vortex ratio describes the tube shape by giving a value of the tube length in relation to its width. This ratio is a measure of the 'roundness' of the tube and can therefore distinguish between subtle differences in the tube shape. As the ratio of vortex length to width approaches 1, the tube shape becomes more circular and less elongate, which is more intense. For example, a vortex ratio of 2 indicates that the tube is twice as long as it is high, and so immediately gives us a feeling for its shape. Thus, the subtle differences in the vortex shape of plunging waves on different seabed gradients can now be described more realistically than with previous indicators, such as the Irribarren number.

To enable breaking intensity of high-quality surfing waves to be clearly communicated, a classification scheme was created (Table. 8.2). Breaking wave intensity is described in five categories from extreme to medium. Waves of greater than extreme are likely to collapse (although an exact limit to the vortex ratio is yet to be established) and are therefore unsurfable, and waves of less than medium fall into the categories of gentle plunging and spilling, which, while still surfable, are generally not considered high-quality by surfers. The breaking intensity of each category is described in surfing terminology and examples of surfing breaks with similar breaking intensity, as well as a picture of a wave breaking in profile at an example surfing break, is given.

Table 8.2. Classification schedule of surfing wave breaking intensity.

Intensity	Extreme	Very High	High	Medium/high	Medium
Vortex Ratio	1.6-1.9	1.91-2.2	2.21-2.5	2.51-2.8	2.81-3.1
Descriptive Terms	Square, spitting	Very hollow	Pitching, hollow.	Some tube sections	Steep faced, but rarely tubing
Example Break	Pipeline, Shark Island	Backdoor, Padang Padang	Kirra Point, Off-The-Wall	Bells Beach, Bingin	Manu Bay, Whangamata
Example Break Wave Profile					

Incorporating other parameters that affect the shape of breaking waves, such as wave height and period, into this method could improve predictions of surfing wave breaking intensity. However, the range of wave heights and periods at high-quality surfing breaks is not large enough to greatly affect the general results obtained by using the orthogonal seabed gradient alone (discussed further in Chapter 6).

When incorporating surfing into offshore structures (Black *et al.*, 1998a, b, Mead *et al*, 1998b; Mead and Black, 1999b; Black *et al.*, 1999; Jackson *et al.*, 1999; Black *et al.*, 2000a, b; Black, 2000), it is an advantage to be able to predict the intensity of waves breaking on the designed reef. Not only to have an indication of the breaking intensity of waves that will be produced, but also to be able to communicate this clearly to others. Testing with numerical models, in conjunction with the dataset of mostly world-class surfing breaks, has previously been used to design surfing reefs (Black *et al.*, 1998a, Mead and Black, 1999b). Prediction of the tube shape of waves can now also be incorporated into the design process.

8.12 Creating a Multi-purpose Offshore Reef

8.12.1 Introduction

Multi-purpose reefs have many additional benefits in comparison to other methods of coastal protection, including the addition of amenity (Section 8.12.3 & 8.12.4), low aesthetic and environmental impact (Section 8.12.5), ecological enhancement (Section 8.12.6), and comparatively low construction costs (Black *et al.*, 1999; Jackson *et al.*, 1999; Black *et al.*, 2000b). Indeed, the benefit-cost analysis of the construction of a multi-purpose offshore reef on the Gold Coast, found that it would have a benefit-cost ratio of 60:1 (Raybould and Mules, 1998). This was mainly associated with the stabilisation and widening of the beach resulting in protection of tourism revenue and publicly owned assets (the foreshore) (Raybould and Mules, 1998). Similar high ratios of benefit-cost have also been found for the construction of multi-purpose reefs in other locations (e.g. benefit-cost ratio of 26:1 at Bournemouth in England - Black *et al.*, 2000b). Palmer (1999) concluded that offshore reefs along the Bournemouth coast would attract more people to the region (to enjoy water-sports such as surfing and wind-surfing, and to attend competitions), make the seafront as a whole look more aesthetically pleasing, create a safer swimming environment and create new habitat and a feeding ground for a wide variety of fish.

The final objective of this thesis was to bring together the knowledge gained from the research of world-class surfing breaks, and the other studies within the ARP, to produce an artificial surfing reef. The ARP aims to enhance coastal amenity value by using environmentally-sensitive coastal protection that incorporates multiple-use options. Therefore the objective was to produce, not only an artificial surfing reef, but a multi-purpose reef that would combine coastal protection, new public amenity (such as surfing, diving, fishing, increased beach area, etc.) and enhance the ecology of the area. This reef will provide a facility for continuing research of the different aspects (physical, biological and socio-economic) associated with multi-purpose offshore reefs (Mead *et al.*, 1998; Rennie *et al.*, 1998). To gain permission to construct a multi-purpose reef on a New Zealand beach, a coastal resource consent application had to be developed.

8.12.2 Mount Maunganui Reef

Tay Street, Mount Maunganui Beach (Fig 8.9), was selected as the preferred construction site from several alternative sites in the central North Island using a point scoring system that considered the following factors:

- access and distance from the University,
- sources of construction materials,
- logistics of construction and access,
- existing modifications to adjacent shoreline,
- perceived/actual erosion problems.
- existing surfing usage

The existing surf culture at Mount Maunganui and links between the University of Waikato and both the local port (Port of Tauranga) and the tertiary education institution (Bay of Plenty Polytech) were also seen as advantageous to the project. However, further considerations were needed to select a specific site in the Mount Maunganui area.

For construction purposes, in order to minimise costs, a site close to the harbour entrance was optimal. However, the coastal area around Mount Maunganui, along the Main Beach and past Motuotua Island (north west of Tay Street, Fig. 8.9) is zoned an area of conservation significance. In addition, the Main Beach is the venue of many different events (e.g. Surf lifesaving, Volleyball contests, etc.) and has the most consistent surfing breaks in the region. Therefore, the open coast to the south east of Motuotua Island was considered the most favourable area. While other sites along this stretch of coast such as Omanu and Papamoa were assessed, Tay Street was selected because its proximity to the Harbour entrance would help to minimise construction costs (while still being outside the conservation area), there are ample parking areas available, it was already a high usage location for surfing activities, there was good and existing access and public toilets and changing-rooms were present near the site.

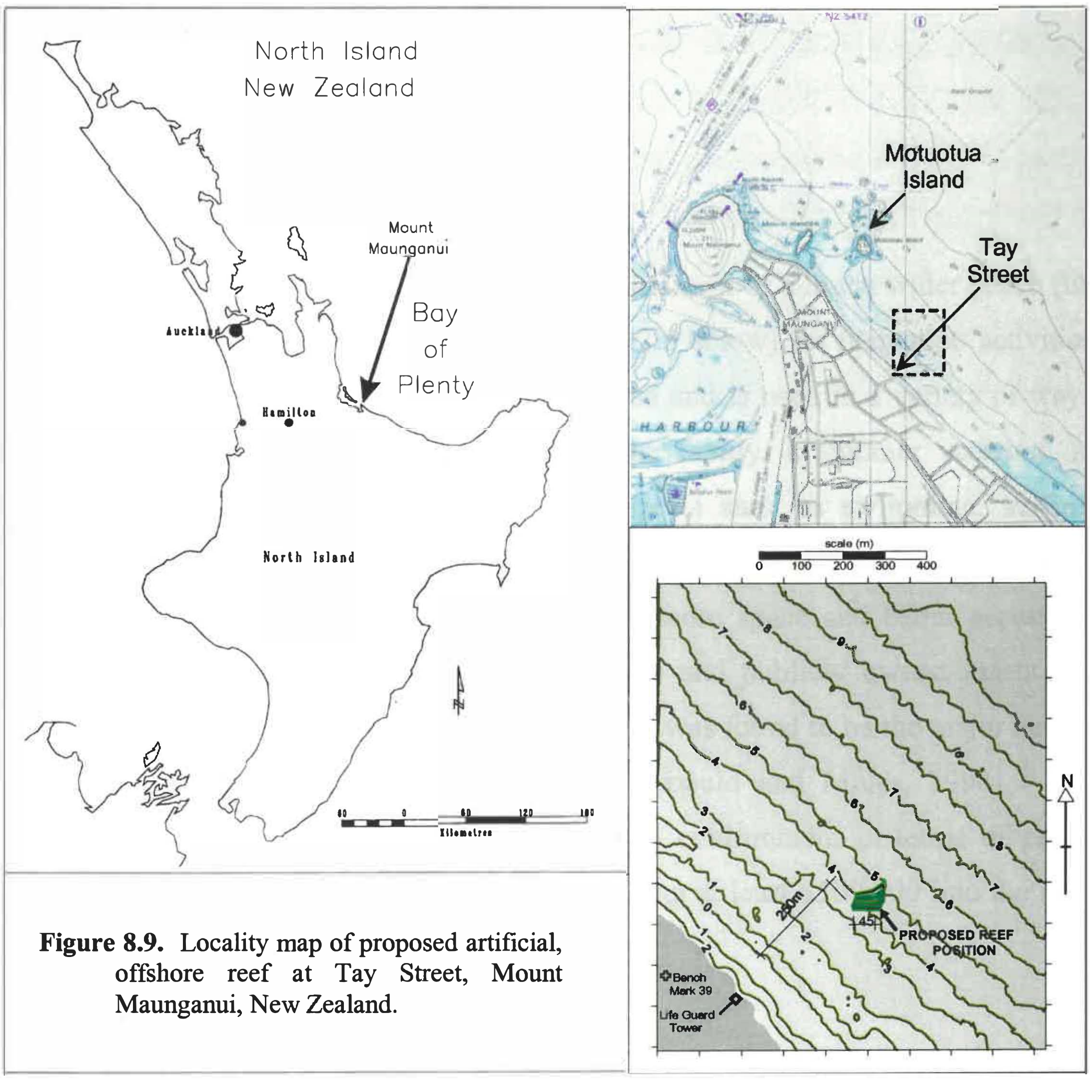


Figure 8.9. Locality map of proposed artificial, offshore reef at Tay Street, Mount Maunganui, New Zealand.

At present, the resource consent application is being processed by the Bay of Plenty Regional Council (Environment Bay of Plenty). Once consent has been granted, the final stage of detailed reef design and construction will proceed. The final stage of the Mount Maunganui reef project is subject to a commercial contract.

Chapter 7 summarises the reef design process and the physical and biological processes that were considered as part of the Assessment of Environmental Effects undertaken to develop the coastal resource consent application for a multi-purpose reef at Mount Maunganui. Here, these studies are referred to as examples for producing a design and consent application for a coastal resource consent to construct a multi-purpose offshore reef. While this discussion is based around the environmental investigations that must be undertaken for coastal resource consent in New Zealand, similar procedures must be followed in many other parts of the world.

8.12.3 Amenity Enhancement

The most obvious amenity enhancement comes in the form of a much wider beach (the salient in the lee of the offshore reef – Section 8.12.5 below) for recreation activities. The beach provides a very valuable recreation venue and is used in a variety of ways. Types of beach usage include a day out with the family, a summer vacation, an invigorating stroll, for the enjoyment of water sports such as swimming, surfing, snorkelling, diving, boating, etc., or any one of a number of organised events from Iron-man to beach-volleyball. A wider beach provides more space and better access for these activities. The protection of tourism revenue and publicly owned assets (the foreshore) by stabilisation and widening of the beach, was found to be the major benefit of the multi-purpose reef on the Gold Coast (Raybould and Mules, 1998). This demonstrates the high economic value of the beach environment in terms of public amenity. Indeed, the Mount Maunganui reef will bring at least $500,000 into the local economy each year (Gough, 1999).

In addition, because the structure is offshore and submerged, it opens up opportunities to incorporate additional recreational and public amenity benefits such as surfing, diving/snorkelling, sheltered swimming, fishing and other water activities (Black *et al.*, 1998a; Black *et* al., 1999; Jackson *et* al., 1999; McGrath *et al.*, 1999; Mead and Black, 1999a; Black, 2000). The reduction of wave height in the lee of the reef creates an area for sheltered swimming and other water activities. The biological enhancement (Section 8.12.6 below) provides the basis for diving/snorkelling and fishing. Specific shaping of the reef creates high-quality surfing waves.

Surfing is arguably the most difficult amenity to incorporate into multi-purpose reef design. Several surfing studies were undertaken prior to the initiation of the ARP (Walker and Palmer, 1971; Walker, *et al.*, 1972; Walker, 1974a, b; Silvester, 1975; Pratte, 1987; Dally, 1989; Moffat & Nichol, 1989; Dally, 1990; Button, 1991; Lyons, 1992). However, much of this information could not be directly applied to the design of surfing reefs that would produce high-quality surfing waves. For example, video website observations at Cables Stations artificial reef in Western Australia (Button, 1991; Lyons, 1992; Pattiaratchi, 1997), constructed in early 1999, have shown that it rarely breaks with good surfing form (www.coastaldata.transport.wa.gov.au /coastcam/con_cables.html). Local surfers have been disappointed with its performance, citing that it is too deep and usually only provides a short-ride when it does break (A. Meager, pers. comm.). A major design flaw is the depth of the reef. The wave climate at the location is mostly below 1 m and rarely above 2 m, but the reef is 1 m deep at low tide (Pattiaratchi, 1997). As a result it rarely breaks. While occasional good days have been reported (at low tide with large swell (Flaulkner, 1999)), on smaller days the waves are slow and sluggish and only twenty metres long (Flaulkner, 1999). Indeed, the plan of the reef shows that its shallowest depth contour is far shorter than the deeper contours (Pattiaratchi, 1997). In the small wave climate at Cable Stations, the majority of waves will break on the shallowest contour, and so this contour should be of the maximum possible size. This design flaw, in addition to it being too deep, means that the reef does not optimise the number of surfable days. Further problems associated with wedge orientation have also been identified from the design plans that would also restrict the number of surfable days. Numerical modelling of a reef shaped and orientated similar to the Cable Stations design has shown that the peel angle tends to be very fast and near the limit of surfability (Black, pers. comm.), which means that surfable waves would occur only over a limited range of swell conditions.

In order to optimise the number of surfable days at a particular site and produce high-quality surfing waves, new information was required. Consequently, a large percentage of studies within the ARP have been directed towards surfing related issues such as the peel angle and degree of surfing difficulty (Hutt, 1997; Hutt *et al.*, 2000), predicting the breaking intensity of surfing waves (Sayce, 1997; Sayce *et al.*, 1999; Chapter 6), and the geomorphology and function of natural surfing reefs (Chapters 3-5). During the process of reef design, the findings of these studies are applied to create reefs that will break waves to a specific design criteria.

8.12.4 Surfing Reef Design

The first step in surfing reef design is to establish the design criteria. For Mount Maunganui reef, the final stage of detailed reef design is subject to a commercial contract. However, the initial design had to represent the fundamental shape of the final reef to be able to consider its impacts for resource consent application (discussed below), and so, a detailed set of criteria had to be established. After considering the present surfability of the local breaks, the aspirations of the surfer in the area and the research aspects of the project, the following general criteria for the reef design were adopted (Mead *et al.*, 1998b):

1. The reef should be sufficiently large to enable an assessment of benefits to be made. This would include monitoring of coastal protection, ecological enhancement, recreational value, visual impact, amenity value, socio-economic impacts and reef longevity. However, the reef must also be kept to less than 100 m in its longest dimension to ensure that it was within planning restrictions (Rennie, 1998) and to keep construction costs to a minimum (at the time of planning, no funding body had been identified for this research-based project).

2. As consistent, high-quality surf breaks are required at Mt. Maunganui and surfing skills are continuing to rise, the reef should aim to provide quality surfing waves for competent surfers.

3. All types of surf users (surfboard, ski, boogie board, body board etc.) should be considered.

Next, specific design criteria were also established for the type of break the reef would provide with respect to surfing (Mead *et al.*, 1998b). These included,

- surfability over the widest possible range of wave heights, periods and directions in order to maximise the number of surfable days per year,
- surfability across the full range of design wave heights,
- suitability for excellent surfers and average surfers aspiring to be excellent,
- at least one "section" hollow enough for tube-riding,
- a steep wave-face for board speed, and,
- a fast take-off with sufficient steepness to allow adequate board speed for entry onto the main section of the ride.

Specific parameters such as peel angle and tube shape, which relate directly to reef shape, were selected to meet these design criteria.

The thesis has shown that investigations of the physical impacts of a multi-purpose reef must be closely coupled with its design. The size, shape and position of the reef will influence the magnitude of the impacts on the physical processes (Andrews, 1997; Black and Andrews, 2000). At the same time, physical factors, such as the wave climate and existing bathymetry, will affect the design of the reef (Chapters 3, 4 and 5). Offshore wave data were transformed to inshore wave data (described below in Section 8.12.5) to obtain the 'design wave' for the surfing aspects of the reef.

At the Tay Street site, the design wave parameters included wave heights of 1-3 m, periods of 5-13 s and a wave approach angle of 50° ± 10° True (with 50° being almost exactly shore normal (Fig. 8.9)). This could be further reduced to the 'design wave', which is the most common condition at the site, of a wave height of 1 m, 11 s period and wave approach of 50°. Even though it is expected that waves of less than 1 m would be surfed, it is expected that conditions would most likely be of a low quality. Design conditions are meant to provide stringent wave parameter limits for reef testing and reef optimisation, rather than specifying the full range of surfable conditions. As such, waves less than 1 m were neglected because they are considered marginal for surfing, but it should be recognised that the reef is still expected to provide surfable waves outside the design range.

Different designs for different sites

Once the design wave parameters have been identified and the existing seabed is known, it is possible to begin the design process. Each site varies in terms of existing bathymetry, wave climate, etc. The primary purpose and size of the reef will also differ from project to project. Therefore, each case requires a different design. The studies presented in this thesis have indicated that there exists a relatively small set of reef components and component combinations. However, these studies have also shown that the variety of site-specific conditions (wave height, wave direction, etc.) has a large effect on component scale and orientation, and combining components to produce waves of a pre-determined quality is an extremely complex task that must addressed holistically. Sophisticated computer models (e.g. WBEND – Black, 1997) have made it possible to design surfing breaks that produce waves to fit specified criteria.

Mount Maunganui Reef Design

A number of different reef design programs have been utilised for the investigation of reef design characteristics (Black *et al.*, 1998a; Mead *et al.*, 1998b), the latest program in this suite, MAKER (Black, pers. comm.), was used for the preliminary design of the Mount Maunganui Reef. Because the reef was to be relatively small, due to budget restrictions and planning requirements (Rennie, 1998), it was important to first consider how the design could maximise the length of the surfing ride while minimising reef volume. This was accomplished by essentially making the Mount reef entirely a wedge (Fig. 8.12). This was possible by the,

- relatively small range of surfable wave approach angles (Fig. 8.10), and,
- small wave climate (wave heights are rarely above 2 m (Mead *et al.,* 1998b).

This meant that the already limited range of wave approach angles (Fig. 8.10) could be further reduced by positioning the reef in shallow water and allowing the straight depth contours of the existing seabed to act as a ramp component. Without the need to construct pre-conditioning components, all the volume of the reef could be concentrated on a wave-breaking component, a wedge. The volume of the reef could have been reduced further by increasing the steepness of the reef face. However, the design criteria was for waves to suit excellent surfers and average surfers aspiring to be excellent, increasing the seabed gradient results in increased the wave breaking intensity (Chapter 6) and would restrict the break to only the very best surfers.

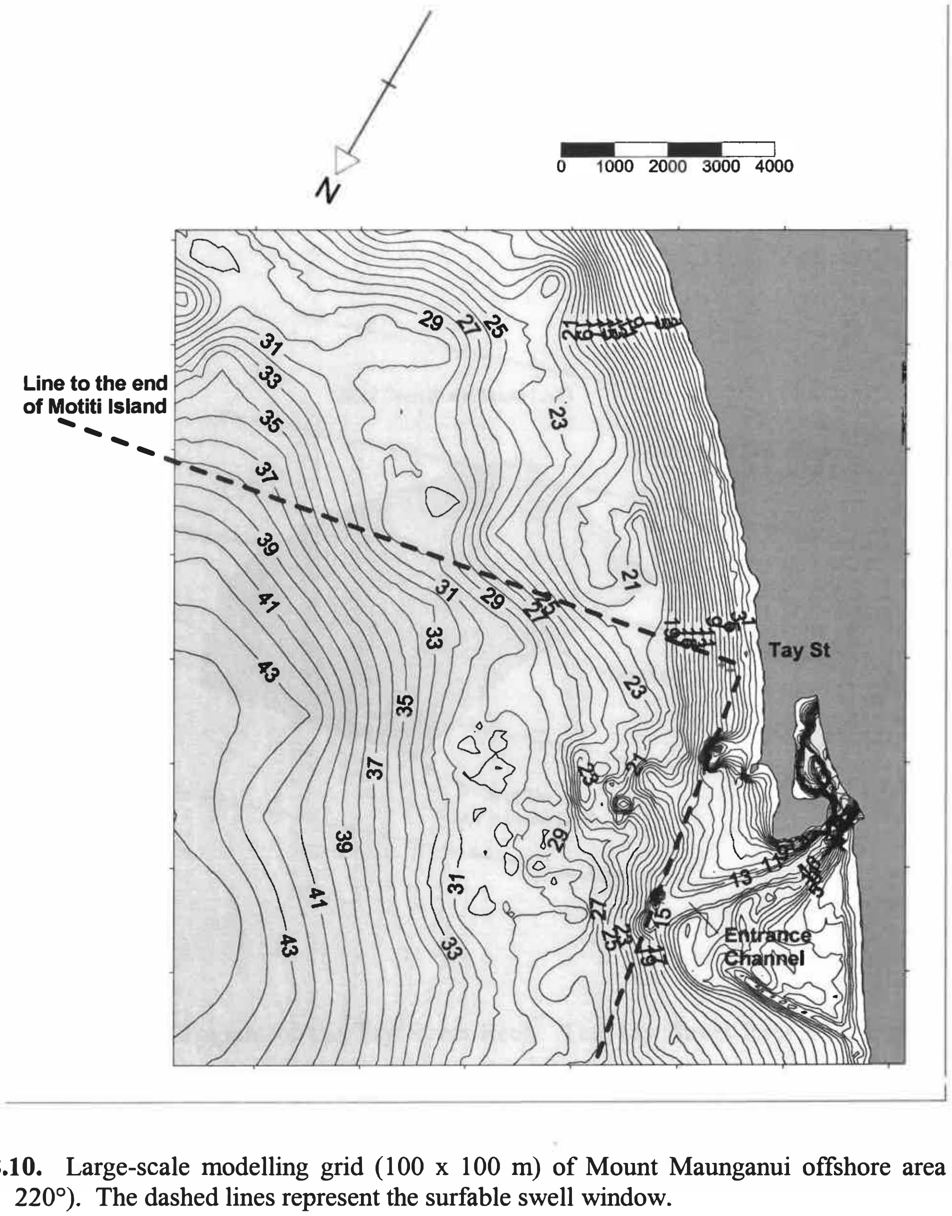


Figure 8.10. Large-scale modelling grid (100 x 100 m) of Mount Maunganui offshore area (rotated 220°). The dashed lines represent the surfable swell window.

Over 50 reef designs were tested with model WBEND to select the initial design that could broadly fit the design criteria and specifications. Designs were first tested using the design wave (1 m, 11 sec and 50° True) over a range of tidal heights. If the design looked promising, further tests were carried out over a range of wave heights, periods and directions at different phases of the tide. This resulted in some 150 model runs to produce the initial reef design and the idealised features relevant to the thesis are shown in Figure 8.11. The reef is positioned 250 m offshore (Fig. 8.10), extending approximately 75 m from the inshore edge (~3.7 m depth) to the offshore toe (~4.5 m depth), with a cross-shore width of 50 m. The highest contour of the reef is 50 m long (extending offshore west-east) and 0.4 m deep at lowest astronomical tide. The reef has a surface area of approximately 2,850m^2 and a volume of ~5,020m^3.

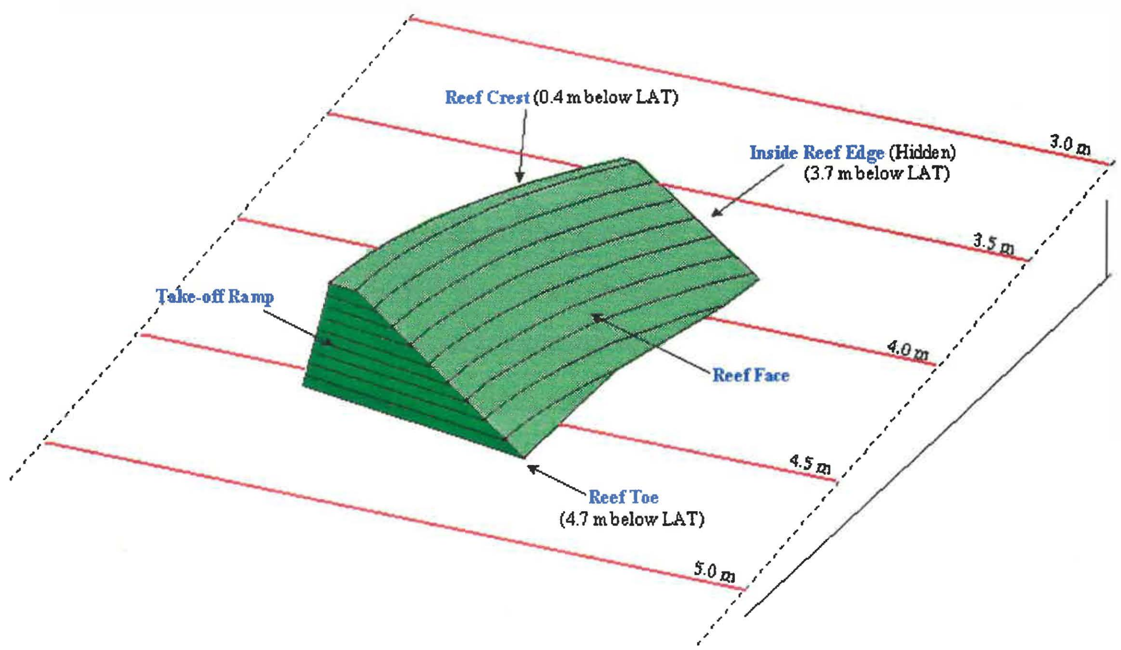


Figure 8.11. Schematic diagram of the Tay Street Reef. The Tay Street Reef is orientated with the longest axis running east-west across shore at an angle to the natural sea bed gradient.

Dominant characteristics of the initial reef design are peel angles, which are rarely less than 40° and a seabed gradient of 1:12 on the main reef segment and 1:6 on the take-off ramp. In combination, the wave is fast (rating of 6-7) (Hutt *et al.*, 2000) and hollow, which fits well with the design criteria. The wave will be faster on high tide than on low tide, as more refraction can occur before breaking (as discussed above). Depending on the range of the tide, waves will only break close to low tide when the swell is small. On larger swells (>1.8 m) waves will break on all tides. The tidal influence also varies the position of the take-off zone. At high tide the break point moves shoreward as the water depth increases.

The initial reef design is simple in appearance, even though it required over 150 model runs to produce. However, it incorporates some of the key morphological features identified and discussed within this thesis. The existing bathymetry functions as a ramp component, aligning waves to the favoured orthogonal direction. The wedge is curved (Fig. 8.12) and orientated so as to maintain a wave peel angle of ~40° over all wave heights and directions and the full tidal range. The gradient of the reef is such that the waves will have a high breaking intensity (Table 8.2).

The final reef design will be more sophisticated that the design presented above and be in line with local surfer's aspirations. Fine-tuning of the existing design will be undertaken during the detailed design phase of the project, when components like the ridge and focus may be added to create a section and define the take-off zone, respectively. At this stage sediment transport and circulation around the reef will also be investigated in more detail. The final stage of reef design is subject to a commercial contract, and so further details cannot be included here. However, the initial design was adequate to assess the impacts on coastal processes and the ecological impact of the proposal.

8.12.5 Coastal Processes and Protection

The most important aspects of a consent application to construct a multi-purpose offshore reef are the effects it will have on the coastal processes. These aspects of environmental assessment are closely coupled to the amount of coastal protection the structure will achieve, which must be addressed since this is normally the primary purpose of multi-purpose reefs (e.g. Black *et al.*, 1997b; Black *et al.*, 1998a,b; Black *et al.*, 1999; Jackson *et al.*, 1999; Black *et al.*, 2000b).

The main physical impacts caused by the construction of an offshore reef are associated with changes to the sediment transport systems. These changes are reflected in the deposition of sediments along the shore in the lee of the reef, which ultimately leads to the formation of a salient or tombolo (Komar, 1976) that affords the coast protection. In simple terms, coastal erosion occurs because of waves and currents. The waves suspend the sand off the seabed into the water column, but it is the currents that carry the sand away and cause erosion (U.S. Army Coastal Engineering Research Centre, 1975). In addition, the currents are often wave-induced. By reducing the wave energy that reaches the shore with an offshore obstacle, sediment suspension and wave-driven currents are reduced, resulting in the widening of the shore in the form of a salient or tombolo (Andrews, 1997; Black and Andrews, 2000). The salient is preferred because some sand is still able to bypass between the reef and the beach, unlike the tombolo, which can act as a groyne, obstructing sediment movement along the shore and causing erosion downstream (Andrews, 1997; Black and Andrews, 2000). The salient acts as a buffer zone during storm events giving additional protection to the coast and enhances the amenity value by increasing the space available for beach recreation.

Numerical models (e.g. WBEND - Black, 1997) and empirical equations developed through studies within the ARP (Andrews, 1997; Black and Andrews, 2000) have been used to assess the impacts of multi-purpose reefs on sediment transport and the response of the shoreline, respectively (Black, 1998; Mead *et al.*, 1998b). Several inter-related studies were undertaken to assess the physical impacts of the proposed reef at Mount Maunganui including sediment movement, sediment deposition in the lee of the reef, bathymetric mapping, analysis of sediment grain size, examination of the existing beach profile dynamics (erosion/accretion), recording of on-site wave data and time-lapse video (Mead *et al.*, 1998b). Further detailed sediment modelling studies are required for final reef design and to assess the local movement of sand that may interfere with the surf break. However, the investigations already made led to a good understanding of the coastal processes operating at the Tay Street site and allowed the general impacts of the reef to be assessed.

To investigate the physical impacts of the Mount Maunganui Reef, long-term wave data (Macky *et al*, 1995) in conjunction with two numerical models, WBEND (Black & Rosenberg, 1992; Black, 1997) and GENUIS[2] (Black, unpub.), were utilised to examine long-shore sediment transport. The transformation of offshore wave data to inshore wave data was not only imperative for sediment transport, but also to elucidate the 'design wave' for the surfing aspects of the reef (Section 8.12.4 above). Two bathymetry grids had to be created for this purpose. A large, regional grid (100 x 100 m cells) was used to transfer the offshore wave data to the inshore Tay Street site (Fig. 8.10). Nautical charts of the region were digitised and combined with existing bathymetric data from around the harbour entrance. The bathymetry from 10 m deep to the low tide mark and beach profiles from the low tide mark to the top of the dunes was measured to create a second, finer model grid (5 x 5 m cells). A series of model simulations on the large-scale grid resulted in a suite of conversion equations that were incorporated into a Fortran program (CONVERT – Mead, unpub.) to convert the offshore wave data into inshore wave data. These data could then be used in sediment transport modelling using the fine bathymetry grid. The method of nesting model grids to transform wave data from offshore locations to proposed reef sites has been used in other multi-purpose reef projects (Black *et al*., 1998a, b; Jackson *et al*., 1999; Black *et al*., 2000b).

At the Tay Street site, annual sediment movement was predicted to be 211,000m^3 to the north west and 143,000m^3 to the south east (from the available long-term data – Macky *et al*., 1995). The net sediment flux was found to be 68-77,000 m^3/yr (the range from combining both model results). Inter-annual reversals in directions were also identified, with sediment moving either to the south-east or the north-west, depending on the reigning climatic influence (e.g. El Nino/La Nina). This result is supported by other studies in the Bay of Plenty region (Harray, 1977; Harray & Healy, 1978; Gibb, 1979) and implies that net movement along the beach is small relative to gross movement and that the resulting salient formation would be symmetrical.

---

[2]Model GENIUS: a numerical model for calculation of longshore sediment transport and shoreline adjustment in the presence of offshore obstructions.

Empirical equations can be used to predict the dimensions of the salient that will result from the construction of a multi-purpose reef (Andrews, 1997; Black and Andrews, 2000). At Mount Maunganui, initial calculations (Eqn. 8.2), using the longshore width of the proposed reef (*B*) and the distance between the reef and the undisturbed shoreline (*S*), indicated that the reef would form a salient.

Salients form when $\frac{B}{S} < 2.00$ (8.2)

Next, by substituting the reef dimensions into the salient equations (Eqns. 8.3 and 8.4) of Andrews (1997) and Black and Andrews (2000), the geometry of the salient can be predicted. The average salient amplitude for offshore reefs is given by,

$$\frac{X}{B} = 0.498\left(\frac{B}{S}\right)^{-1.268} \qquad (8.3)$$

where X is equal to S - Y_{off}, which is the distance between the undisturbed shoreline and the reef (S), minus the length of the shore normal between the undisturbed shoreline and offshore extremity of the salient (Y_{off}). Salient basal width is given by,

$$\frac{Y_{off}}{D_{tot}} = 0.125 \qquad (\pm\, 0.020) \qquad (8.4)$$

where, D_{tot} is the total length of shoreline affected.

From these equations, the predicted salient at Mount Maunganui was a maximum of 58 m cross-shore at the widest point, tapering down to zero accretion at a distance of 232m in each direction longshore, and incorporate approximately 6670 m^3 of beach sand (Fig. 8.11). With inter-annual reversals in long-shore sediment transport of around 68-77,000 m^3, the salient is expected to be mostly symmetrical (Fig. .8.11), and form within a year. Because a salient will form and not a tombolo, and due to the inter-annual reversal of long-shore sediment transport at the site, the reef will not cause downstream impacts such as erosion. The salient is a very small fraction of the sand on this 29 km stretch of beach, and so the impact on the total sediment supply will be negligible. However, it will form a substantial erosion buffer zone in the local Tay Street area of Mount Maunganui Beach.

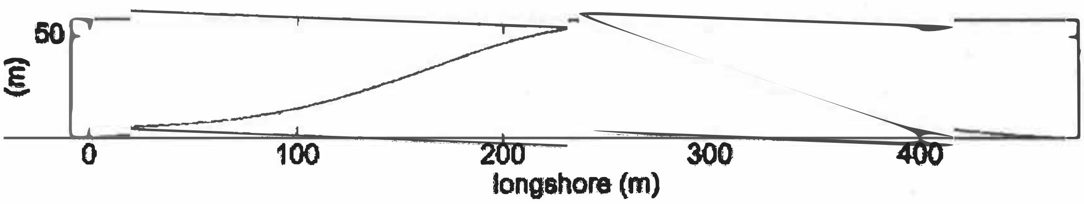


Figure 8.12. Predicted salient formation in the lee of the ARP reef at Mount Maunganui. Represented at lowest astronomical tide.

8.12.6 Biological Enhancement

Artificial reefs provide substrate for a variety of marine organisms (Pratt, 1994). Constructing a structure on the seabed will smother and kill almost everything that is residing there at the time. However, a new structure may in fact provide a better habitat and consequently a community with higher species abundance and diversity than previously existed at the site. There has been a large amount of work on ecological enhancement using artificial reefs throughout the world (e.g. Bulletin of Marine Science, 1994). From these studies it is evident that, as a general rule, species abundance and diversity are greater when the habitat is more stable (in comparison to mobile substrates), the topography more complex (a higher number of different niches are available) and when the reef is larger (Pratt, 1994). Construction of artificial reefs also provides the opportunity to create specific habitat and 'seed' specific species that may be of commercial or cultural value (e.g. Saito, 1992). Therefore, the biological enhancement due to the construction of a multi-purpose reef may include, increased environmental value (increases in bio-diversity and abundance), increased amenity in the form of a diving and snorkelling venue and enhanced fisheries by the incorporation of specific habitat.

An ecological assessment of the sub-tidal habitat in the Tay Street area of Mount Maunganui Beach found that this area has similar species to other sub-tidal areas at harbour entrances and sand beaches along the north eastern New Zealand shoreline[3]. While the area was found to be ecologically healthy in terms of a fine to coarse sand habitat, it has low biodiversity (15 species from 5 phyla, mainly marine worms and bivalves – Mead *et al.*, 1998b) in comparison to the rocky reefs in the area (Park, 1995). This is typical of shallow sub-tidal, sand habitat (Morton & Miller, 1968), such as would be found at the majority of sites where coastal protection is required (soft shores are more likely to be at risk of erosion than hard shores), and is due to the mobile and abrasive nature of sand. Construction of a multi-purpose reef provides a more complex and stable habitat and will therefore increase the biodiversity. The reef itself provides a substrate for larval organisms in the water column to settle on and become established. Indeed, after only two weeks in place, the geotextile containers used to construct the multi-purpose reef on the Gold Coast were already well covered by juvenile seaweeds (Fig. 1.2). Once primary producers become established, these organisms, and the reef itself, provide shelter and a food source for fish and other marine life and act as a fish aggregating device (FAD) (Bohnsack & Sutherland, 1985). In addition, a reef may also subtly alter the local hydrodynamics in a way that could increase settlement in the lee of the reef (e.g. Black & Gay, 1987). Although there has been much work in the area of ecological enhancement using artificial reefs in other areas of the world (e.g. Bulletin of Marine Science, 1994), there have been no such studies in New Zealand. This proposal offers the opportunity for research in this area within New Zealand.

Another valid factor in an ecological assessment is to consider the fraction of habitat that will be lost in comparison to the total area of similar habitat in the region. For example, at Mount Maunganui, the proposed reef will cover an area of approximately 2,850m^2. If the whole 29 Km stretch of beach is taken to have similar biology as the area surveyed and only an area between the 3 m and 6.5 m deep is considered (the depths covered by the on-site samples – Mead *et al.*, 1998b), the seabed covered by the artificial reef would be approximately 2.8 x 10^{-4} of this area. This is a very conservative

[3]Since I undertook this first site assessment in 1997, two more biological assessments have been undertaken by students at the Tauranga Polytech as part of the Marine Studies course (Murphy, 1998 &

estimate of total area, as it suggests that there are no links between the rest of the coast or inshore and offshore of these depths, which is untrue. Even so, this small fraction of seabed that would be permanently lost is an insignificant proportion of Mount Maunganui Beach, and so the effect on the ecology of the area would be very minor, if any.

Multi-purpose offshore reefs move the protection out to sea and below the water, preserving the aesthetic value and enhancing the amenity and environmental values of the coast. The investigation of coastal processes at Mount Maunganui has demonstrated how coastal protection can be achieved with low environmental impact. This is an immense improvement on existing methods of coastal protection such as groynes, breakwaters and seawalls, that not only often have detrimental impacts on the adjacent coast (Bruun, 2000), but also negatively impact on the amenity and aesthetic value of the coast. Offshore reefs are a natural solution to coastal protection (Andrews, 1997; Black, 2000; Black and Andrews, 2000). Coastal science can be used to apply superior of coastal protection methods that are synonymous with 'nature's way'.

The studies presented here have advanced the understanding of natural surfing breaks and the ability to incorporate high-quality surfing breaks into multi-purpose reefs. However, there are still many areas of future research that should to be addressed to optimise surfing wave quality of artificial reef designs. For instance, whether or not the peel angle should decrease with increasing wave height has still not been determined (Chapter 4), and the effects of offshore bathymetry on surfing breaks, or possibly for creating surfing breaks, has not yet been addressed. Although we now have an large amount of information on the parameters that produce high-quality surfing breaks (tube shape, peel angles, seabed gradients, etc. (Hutt 1997; Sayce, 1999; Sayce *et al.,* 1999; Hutt *et al.,* 2000; this thesis)), there has been very little research into how surfers actually perform on specific waves. What is the maximum speed that can be attained on a wave? What is the length of the maximum section of a breaking wave that can be successfully ridden? Research into how surfers utilise different types of waves, and

---

1999). These studies have found similar species and abundances as those found in the original assessment.

specific parts of waves, will be very valuable for the development of high-quality surfing reef designs.

8.13 Summary

This chapter has brought together various topics that contribute to the development of multi-purpose offshore reefs, with an emphasis on the incorporation of high-quality surfing breaks, and has demonstrated how this thesis has achieved all of the objectives identified in Chapter 1. By identifying the morphology and function of surfing reef components and the common combinations of them that are found at natural world-class surfing breaks, and creating a method of predicting and communicating surfing wave breaking intensity, high-quality surfing breaks can be confidently incorporated into multi-purpose offshore reef designs, such as that proposed for Mount Maunganui.

The Mount Maunganui reef is subject to further development following the granting of resource consent. The new knowledge gained from the research presented here has already been applied to its design and will be utilised in the detailed design phase. The Mount Maunganui reef will provide the basis for future research in the ARP and will also be a benefit to the district, providing consistent high-quality surfing waves and a wider beach that will be a focus for surfing and other beach activities, as well as make a significant contribution to the local economy. Continued research into multi-purpose offshore reefs will lead to a better understanding of how they can be applied to protect the coast and enhance the environmental and amenity values of developed coastal areas all over the world.

Chapter 9

SUMMARY AND CONCLUSIONS

9.1 Introduction

This research formed part of the Artificial Reefs Program, which aims to enhance the coastal amenity value of the New Zealand shoreline by evaluating multiple use options for incorporation into coastal constructions. The main aim of this study was to investigate the bathymetry of world-class surfing breaks in order to incorporate high-quality surfing breaks into multi-purpose offshore reefs. This chapter summarises the key findings and conclusions.

9.2 Surfing Break Surveys

A compact and portable, self-contained marine surveying system, nicknamed Horatio, was developed and 28 mostly world-class surfing breaks were surveyed. These breaks are located in New Zealand, Australia, Indonesia, Hawaii, California and Brazil, and include the geomorphic categories of coral reefs, rocky reefs, headlands, rock ledges, river and estuarine deltas and sand beaches.

These were used to identify the form and function of the bathymetric features that comprise world-class surfing breaks. Together with aerial photographs and wave vortex information, these data represent the first ever set of world-class surfing break surveys that cover a full range of geomorphic categories.

9.3 Surfing Reef Geomorphic Components

Natural surfing reefs are comprised of several meso-scale reef components. Geomorphic components were classified as ramp, platform, wedge, ledge, focus, ridge and pinnacle. These account for the high wave quality at world-class surfing reefs.

Numerical modelling was utilised to investigate component function in relation to wave refraction and wave breaking. It was found that sophisticated configurations of reef components are essential to produce a reliable quality surfing wave, rather than simple one or two-component configurations.

Several common configurations of large-scale reef components were identified. The reef component combinations have a holistic character such that the relative sizes and placement of the components determines the overall quality and length of the surfing break. Refraction and wave attenuation across these multiple components, when found in the right configurations, leads to reliable and surfable wave peel angles. Designs of artificial surfing reefs must apply these holistic principles in order to produce high-quality surfing facilities that optimise the characteristics of specific sites.

For example, not only for its speed and hollow waves, but also because of the stability of the wave peel angle over a variety of wave heights and offshore directions, Bingin Reef proved to be a world-class surfing break. Although there are many other factors such as wave steepness, speed of ride, length of ride, height of wave, prevailing winds, etc., that add to a surfing break's reputation, consistency of a break is a very important factor.

Bingin Reef's reputation as a break that consistently produces world-class surfing waves stems from the ramp-platform-wedge configuration of the large-scale reef components that constitute the break's bathymetry. Omission or reorientation of components invariably downgraded its surfing characteristics. After removing the platform, surfable peel angles could only be achieved by moving the wedge component offshore and rotating it at a greater angle to the ramp. However, peel angles of the modified configuration were mostly greater than those that normally occur at Bingin and were too high (slow) for the break to remain world-class. Moreover, a high variation in peel angles occurred with changes in wave height, which resulted in quality waves over a narrower range of conditions. The bathymetry of the natural world-class surfing reef at Bingin is much more sophisticated than a simple (one or two component) configuration.

9.4 Surfing Wave Breaking Intensity

A method for predicting and describing the breaking intensity of plunging surfing waves was developed. This method uses the orthogonal seabed gradient to predict the wave vortex height to width ratio, which was found to be the best indicator of wave breaking intensity. This ratio can be calculated from the orthogonal seabed gradient, using the simple linear equation,

$$Y = 0.065X + 0.821 \tag{9.1}$$

where X is the orthogonal seabed gradient. The subtle differences in the vortex shape of plunging waves on different seabed gradients can now be described far better than with simplistic indicators, such as the Irribarren number. Including wave height and period in this method could improve breaking intensity predictions, but the range of wave heights and periods at high-quality surfing breaks is not large enough to greatly affect the general results obtained by using the orthogonal seabed gradient alone. These quantitative predictions of tube shape will be incorporated into artificial surfing reef design.

9.5 Mount Maunganui Reef

A series of inter-related investigations were undertaken to produce a coastal resource consent application for a multi-purpose offshore reef at Mount Maunganui, on New Zealand's north-eastern coast. Although not yet constructed, the investigations have demonstrated how coastal protection can be achieved with low environmental impact, and how amenity and environmental values of the coast can be enhanced. This is an immense improvement over existing methods of coastal protection such as groynes, breakwaters and seawalls, that not only often have detrimental impacts on the adjacent coast, but also negatively impact on the amenity and aesthetic value of the coast. The proposal for an artificial reef at Tay Street in Mount Maunganui will continue to provide new knowledge in the area of artificial reef development. It will break new ground in the study of biological impacts and enhancement in New Zealand, the incorporation of surfing breaks into offshore multi-purpose reefs, the coastal response to offshore structures and the social and economic impacts.

Incorporation of multiple use options into coastal structures can meet the need for environmentally-sensitive solutions to coastal construction and to the continued growth in recreational usage of our beaches. Consequently, development of multi-purpose artificial reefs is increasingly becoming a viable and preferred option for coastal construction and the world's first reefs, especially the large Gold Coast Reef for coastal protection and surfing, have been developed during the period of this thesis. Hopefully, the incorporation of multiple use options into coastal structures may be better achieved with the knowledge gained on the surfing aspects during this study.

References

Andrews, C., 1997. *Sandy Shoreline Response to Emerged and Submerged Offshore Obstacles*. Unpublished MSc Thesis. Centre of Excellence in Coastal Oceanography and Marine Geology, Earth Sciences Department, University of Waikato.

Bartholomew, W., 1997. Quality of Surfing Lifestyle. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

Battjes, J. A., 1974. Surf Similarity. *Proc. 14th Coastal Engineering Conference*, ASCE, 466-480

Beamsley, B., 1996. Shoreface Wave Height Reinforcement and Frictional Dissipation Off Waihi Beach, with Emphasis on Seabed Characteristics and Numerical Modelling. Unpublished MSc Thesis, Earth Sciences Department, University of Waikato.

Bilderback, 1994. *Mr Lucky Does Australia*. Australian Surfing Life, Ed. Tim Baker, Volume 73, October 1994.

Black, K. P., 1997. *Wave refraction model WBEND*. Occasional Report, Centre of Excellence in Coastal Oceanography and Marine Geology, Department of Earth Sciences, University of Waikato, New Zealand.

Black, K. P, 1998. *Narrowneck Reef Report 3: Sediment Transport*. Technical Report prepared for the Gold Coast City Council, July, 1998.

Black, K. P., 2000. Artificial Surfing Reefs for Erosion Control and Amenity: Theory and Application. International Coastal Symposium (ICS2000) Rotorua, New Zealand. Special Issue of *Journal of Coastal Research* (in press).

Black, K. P. & S. L. Gay, 1987. Eddy Formation in Unsteady Flows. *Journal of Geophysical Research,* 92 (C9): 9514-9522.

Black, K. P. and M. A. Rosenburg, 1992. Semi-empirical Treatment of Wave Transformation Outside and Inside the Breaker Line. *Coastal Engineering,* 16: 313-345.

Black, K. P., C. Andrews, M. Green, R. Gorman, T. Healy, T. Hume, J. Hutt, S. Mead and A. Sayce, 1997a. Wave Dynamics and Shoreline Response On and Around Surfing Reefs. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

Black, K. P., R. M. Gorman, S. Stephens, B. J. Beamsley, T. R. Healy, R. G. Bell and J. W. Oldman, 1997b. *Port Gisborne Dredging Development AEE.* Prepare for Port Gisborne Ltd., by Centre of Excellence in Coastal Oceanography and Marine Geology, Department of Earth Sciences, University of Waikato and National Institute of Water and Atmospheric Research.

Black, K. P., J. A. Hutt & S. T. Mead, 1998a. *Narrowneck Reef Report 2: Surfing Aspects*. Technical Report prepared for the Gold Coast City Council, June, 1998.

Black, K. P., J. A. Hutt & S. T. Mead, 1998b. *Takapuna Boat Ramp: Surfing Impact Assessment and Reef Feasibility Study.* Report for North Shore City Council, October, 1998.

Black, K.P., Mead, S., McComb, P., Jackson, A. and Armstrong, K., 1999. *New Plymouth City Foreshore Redevelopment: Reef and Beach Feasibility Study*. Prepared by the Centre of Excellence in Coastal Oceanography and Marine Geology, for the New Plymouth District Council, March 1999.

Black, K. P., J. A. Hutt, S. Mead, A. Jackson, J. McGrath, 2000a. Design of the Gold Coast Artificial Reef: Surfing aspects. Special Issue of the *Journal of Coastal Research* on Surfing. (in press).

Black, K. P., S. Mead and A. Jackson, 2000b. *Beach Amenity Options and Coastal Protection at Bournemouth*. Technical Report Prepared for Leisure and Tourism Services, Bournemouth Borough Council, May, 2000.

Black, K. P., and C. Andrews, 2000. Sandy Shoreline Response to Submerged and Emerged Breakwaters, Reefs or Islands. Special Issue of the *Journal of Coastal Research* on Surfing. (in press).

Bohnsack, J. A. & D. L. Sutherland, 1985. Artificial Reef Research: a review with recommendations for future priorities. *Bulletin of Marine Science* 37: 3-10.

Bradshaw, B. E., 1991. *Nearshore and Inner Shelf Sedimentation on the East Coromandel Coast. New Zealand*. Unpublished MSc Thesis, University of Waikato, New Zealand.

Brunn, P., 2000. Coastal Protection Structures. *Proceedings Coastal Structures '99*, Losada (ed.), Balkema, Rotterdam. Pp. 737-746.

Bush, D. M., O. H. Pilkey Jr., and W. J. Neal, 1996. *Living by the Rules of the Sea*. Duke University Press, Durham and London, 1996. Pp. 179.

Button, M., 1991. *Laboratory Study of Artificial Surfing Reefs*. Bachelor of Engineering, Department of Civil and Environmental Engineering, University of Western Australia, 1991. Pp 85 + appendices

Couriel, E. D., P. R. Horton and D. R. Cox, 1998. *Supplementary 2-D Physical Modelling of Breaking Wave Characteristics*. WRL Technical Report 98/14, March, 1998.

Dally, W. R., 1989. Quantifying Beach 'Surfability'. *Proceedings, Beach Technology Conference*, Tamp, Florida, February 2000.

Dally, W. R., 1990. Stochastic Modelling of Surfing Climate. *Proceedings, Coastal Engineering Conference*, ASCE, Vol. 1, 516-529.

Davies-Colley, R. J. and T. R. Healy, 1978. Sediment Transport Near the Tauranga Entrance to Tauranga Harbour. *New Zealand Journal of Marine and Freshwater Research,* 12 (3): 237-43.

Dell, P. M., T. R. Healy and C. S. Nelson, 1985. A Prelminary Investigation of Sediments on the East Coast Coromandel Inner Shelf and Implications for Cross-shelf Sediment Transport. *Proceedings 7^th^ Australasian Conference on Coastal and Ocean Engineering*, Christchurch, New Zealand.

Faulkner, K., 1999. *Hardware: Cable Station Artificial Reef.* Deep Vol. 5, No. 2, Summer, 1999.

Galloway, G. S., M. B. Collins and A. D. Moran, 1989. Onshore/Offshore Wind Influence on Breaking Waves: An Empirical Study. *Coastal Engineering*, 13: 305-323.

Galvin, C. J., 1968. Breaker-Type Classification on Three Laboratory Beaches. *Journal of Geophysical Research*, Vol. 73, No. 12, June, 1968.

Gibb, J., 1979. *Aspects of Beach Sediments and their transport along the New Zealand Coast*. Workshop-Physical Aspects of Coastal Problems, Hamilton, 11-12 October, 1979.

Gorman, R., 1996. *Software*. National Institute of Water and Atmospheric Research, Hamilton, New Zealand.

Gough, V.J., 1999. *Assessing the Economic Effects of Recreation Facility Development: Proposed Artificial Surfing Reef, Mount Maunganui, New*

Zealand. Unpublished 0516.590 Directed Research Project, Department of Geography, University of Waikato, New Zealand. Pp. 58 + appendices.

Gourlay, M. R., 1981. Beach Processes in the Vicinity of Offshore Breakwaters. *Proceedings of the Fifth Australasian Conference on Coastal and Ocean Engineering*, Perth.

Grigg, R., 1969. *Artificial Reefs: A Plan For Multiple Use*. Surfer Magazine, January, 1969.

Harray, K. G., 1977. *Beach Erosion and Sediments at Waihi Beach*. Unpublished MSc Thesis, University of Waikato, New Zealand.

Harray, K. G. & T. R. Healy, 1978. Beach Erosion at Waihi Beach. *New Zealand Journal of Marine and Freshwater Research*, 12: 99-107.

Hume, T., R. Bell, W. deLange, T. Healy, D. Hicks and R. Kirk, 1992. Coastal Oceanography and Sedimentology in New Zealand: 1967-1991. *New Zealand Journal of Marine and Freshwater Research*, 1992, 26: 1-36.

Hurn, J., 1993. *Differential GPS Explained*. Trimble Navigation Ltd. Pp. 47.

Hsu, J. R. C., and R. Silvester, 1990. Accretion Behind Single Offshore Breakwaters. *Journal of Waterway, Port, Coastal and Ocean Engine*ering 116(3); 362-381.

Hutt, J. A., 1997. *Bathymetry and Wave Parameters Defining the Surfing Quality of Five Adjacent Reefs*. Unpublished Thesis, University of Waikato, New Zealand.

Hutt, J. A, K. P. Black, A. Jackson and J. McGrath, 1999. Designing the Shape of the Gold Coast Reef: Field Investigations. *Proc. Coasts & Ports '99*, Vol. 2: 299-304.

Hutt, J. A, K. P. Black and S. T. Mead, 2000. Classification of Surf Breaks in relation to Surfing Skill. Special Issue of the *Journal of Coastal Research* on Surfing. (in press).

Iman, R. L. & W. J. Conover, 1976. *A Modern Approach To Statistics*. John Wiley and Sons, New York, 1976. Pp 153-155.

Jackson, A., K. P. Black, R. Tomlinson, S. T. Mead, J. Mathew, J. A. Hutt & D. Skelly, 1999. *Recommendations for Noosa Main Beach Restoration and Protection*. Report for Noosa Council, August, 1999.

Komar, P. D., 1976. *Beach Processes and Sedimentation*. Prentice-Hall Inc., New Jersey.

Komar, P. D., 1997. Beach Processes and the Erosion of Coastal Properties. *Proceedings of Pacific Coasts and Ports '97*, 7-11 September, 1997, Christ Church, New Zealand. Vol. 1, 1-6.

Longuet-Higgins, M. S., 1982. Parametric Solutions For Breaking Waves. *J. Fluid Mech.*, 121:403-424.

Lyons, M., 1992. *Design of an Artificial Surfing Reef.* Bachelor of Engineering, Department of Civil and Environmental Engineering, University of Western Australia, 1992.

Makgill, R., 1998. *Artificial Reef Development and the Resource Management Act 1991: A Case Study of an Application for a Coastal Permit to Construct an Artificial Reef in the Coastal Marine Area.* Unpublished Dissertation, University of Waikato, New Zealand.

Macky, G. H., G. J. Latimer and R. K. Smith, 1995. Wave Climate of the Western Bay of Plenty, New Zealand, 1991-93. *New Zealand Journal of Marine and Freshwater Research*, 29: 311-327.

McComb, P.J., Black, K.P., Atkinson, P.N., Healy, T.R. and Bell, R.G., 1997. High-resolution wave transformation on a coast with complex bathymetry. *Pacific Coasts and Ports '97,* Christchurch, 7-11 September 1997.

McGrath, J., E. Boak and A. Jackson, 1999. Infrastructure to Enhance the Natural Capacity of the Environment to Support a Tourist Economy – A Coastal Case Study: The Northern Gold Coast Beach Protection Strategy. *Proc. Coasts & Ports '99*, Vol. 1: 64-69.

Mead, S. T., K. P. Black & J. A. Hutt, 1998a. Surfing Reef Morphological Components Combine To Create World-Class Surfing Breaks. *2nd Annual International Artificial Surfing Reef Symposium.* San Diego. April, 1998.

Mead, S. T., K. P. Black & J. A. Hutt, 1998b. An Artificial Offshore Reef at Tay Street – Mount Maunganui Beach. *Annex IIIC: Reef Design and Physical and Biological Processes.* Report submitted to Environment Bay of Plenty, July, 1998.

Mead, S. T. & K. P. Black, 1999a. A Multi-Purpose, Artificial Reef at Mount Maunganui Beach, New Zealand. *Coastal Management Journal* 27(4).

Mead, S. T. & K. P. Black, 1999b. Configuration of Large-Scale Reef Components at a World-Class Surfing Break: Bingin Reef, Bali, Indonesia. *Proc. Coasts & Ports '99*, Vol. 2:438-443.

Mead, S. T. & K. P. Black, 2000a. Field Studies Leading to the Bathymetric Classification of World-Class Surfing Breaks. Special Issue of the *Journal of Coastal Research* on Surfing. (in press).

Mead, S. T. & K. P. Black, 2000b. Functional Component Combinations Controlling Surfing Wave Quality at World-Class Surfing Breaks. Special Issue of the *Journal of Coastal Research* on Surfing. (in press).

Mead, S. T. & K. P. Black, 2000c. Predicting the Breaking Intensity of Surfing Waves. International Coastal Symposium (ICS2000) Rotorua, New Zealand. Special Issue of *Journal of Coastal Research* (in press).

Moffat & Nichol, 1989. *The Patagonia Surfing Reef Feasibility Study*. Report prepared for The Surfrider Foundation, Huntington Beach California, by Moffat & Nichol, Engineers, Long Beach, California. Job No. 2521, September, 1989.

Morton, J. E. & M. C. Miller, 1968. *The New Zealand Seashore*. William Collins Sons and Co. Ltd, Glasgow, Great Britain.

Palmer, L., 1999. *The proposed artificial reef for Southbourne could provide recreational benefit to the Dorset region*. Unpublished 3rd year project, Maritime Leisure Management, Southampton Institute.

Park, S., 1995. *Natural Environment Regional Monitoring Network Coastal and Estuarine Ecology Program 1994/95*. Environment B.O.P ISSN 11725850

Parker, Jr., R. O., R. B. Stone, C. C. Buchanan & F. W. Steimle, Jr., 1974. Fishery Facts-10: *How to Build Marine Artificial Reefs*. NOAA. US Government Printing Office, Washington D.C. 47p.

Pattiaratchi, C. 1997. Design Studies for an Artificial Surfing Reef at Cable Station, Western Australia. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

Peregrine, D. H., 1983. Breaking Waves on Beaches. *Ann. Rev. Fluid Mech.*, 15:149-178.

Pickrill, R. A. and J. S. Mitchell, 1979. Ocean Wave Characteristics Around New Zealand. *New Zealand Journal of Marine and Freshwater Research*, 13 (4): 501-520.

Pilarczyk, K. W. & R. B. Zeidler, 1996. *Offshore Breakwaters and Shore Evolution Control*. A. A. Balkema, Rotterdam. 560p.

Pilkey, O. H., and K. L. Dixon, 1996. *The Corps and the Shore*. Island Press, Washington, D. C. / Covelo, California. Pp. 272.

Pitt, B. A. 1997. Surfing into the 21st Century - Harbord Reef. *Proceedings of the 1st International Surfing Reef Symposium*, Sydney, Australia. March, 1997.

Pratt, J. R., 1994. Artificial habitat technology and ecosystem restoration: managing for the future. *Bulletin of Marine Science* 55(2-3):268-275.

Pratte, T. P., 1987. Ocean Wave Recreation. *Proceedings of Coastal Zone '87*, ASCE, Seattle, Washington, 1987.

Raichle, A. W., 1998. Numerical Predictions of Surfing Conditions at Mavericks, California. *Shore & Beach*, April, 1998, 26-30.

Raybould, M. and T. Mules, 1998. *Northern Gold Coast Beach Protection Strategy: A Benefit-Cost Analysis*. Report prepared for the Gold Coast City Council, February 1998.

Readers Digest, 1986. *Readers Digest Guide to the Coast of New South Wales*. Editor, R. Rullens.

Rennie, H. G., 1998. An Artificial Offshore Reef at Tay Street – Mount Maunganui Beach. *Annex IIIB: Assessment of Relevant Policy and Planning Documents*. Report submitted to Environment Bay of Plenty, July, 1998.

Rennie, H. G., D. Makgill, and C. A. Makgill, 1998. An Artificial Offshore Reef at Tay Street – Mount Maunganui Beach. *Annex IIID: Consultation and Social Impact Report*. Report submitted to Environment Bay of Plenty, October, 1998.

Saito, K., 1992. Japan's Sea Urchin Enhancement Experience. *Proceedings, Sea Urchin, Kelp and Abalone Conference, Sea Grant Extension Programme*. University of California, Bodega Bay Marine Laboratory, Bodega Bay, California, March 18-21 1992.

Sayce, A., 1997. *Transformation of Surfing Waves Over Steep and Complex Reefs*. Unpublished Thesis, University of Waikato, New Zealand.

Sayce, A., K. P. Black and R. Gorman, 1999. Breaking Wave Shape on Surfing Reefs. *Proc. Coasts & Ports '99*, Vol. 2:596-603.

Silvester, R., 1975. *Synthetic Surfing Sites*. University of Western Australia, Nedlands, Western Australia.

Titcombe, R., 2000. *Surfing in the Wellington Region*. In: Lyall Bay Surfing Reef Feasibility Study, a proposal submitted to the Lyall Bay Reef Charitable Trust by ASR Ltd, May 2000.

Toyshima, O., 1972. *Detached Breakwaters*. In: Coastal engineering for practising engineers, K. W. Pilarczyk ed. Chapter 8, 118p.

U.S. Army Coastal Engineering Research Centre, 1975. *Shore Protection Manual*, Department of the Army Corps of Engineers, Vol. 1, 1975.

Vinje, T. and P. Brevig, 1981. Breaking Waves on Finite Water Depths: a Numerical Study. *Ship Res. Inst. of Norway*, Rep. R-111.81

Walker, J. R. & R. Q. Palmer, 1971. *A General Surf Site Concept*. LOOK Laboratory TR-18, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii, 1971.

Walker, J. R., R. Q. Palmer & J. K. Kukea, 1972. Recreational Surfing on Hawaiian Reefs. *Proc. 13th Coastal Engineering Conference*, 1972.

Walker, J. R., 1974a. *Recreational Surf Parameters*. LOOK Laboratory TR-30, University of Hawaii, Department of Ocean Engineering, Honolulu, Hawaii, 1974.

Walker, J. R., 1974b. *Wave Transformations Over a Sloping Bottom and Over a Three-Dimensional Shoal*. PhD. Dissertation, University of Hawaii, 1974.

Walsh, A., R. Tomlinson, J. McGrath, E. Boak and A. Jackson. Environmental Monitoring of the Northern Gold Coast Beach Protection Strategy. *Proc. Coasts & Ports '99*, Vol. 2:708-713.

Appendix 1

List of Publicity associated with the Artificial Reefs Program.

Adams, D., 1998. Forget The Beach - Life's a Wave. *The Riversider Magazine*, issue 16, p. 3.

Anderson, I. 1997. Surf Theories Wiped Out. *New Scientist*, 6 September, 1997.

Ansle, G., 1999. Good vibes for surfing business: waves that break at the right angle and height are no longer a dream on the Gold Coast. *Weekend Herald* (Weekend Business), 10 April 1999.

Barilotti, S., 1998. Our Mother Ocean - future Shack. *Surfer Magazine*, Annual Collector's Issue, August, 1998.

Bennett, M., 1997. In The Pipeline. *Mount & Papamoa Times*, October 23, 1997.

Black, K. P., 1997. Surfing Reef Programme. *North & South*, December 1997.

Black, K. P., 1997. Taped Interview with BBC World (London) for the technology radio programme. October, 1997.

Black, K. P., 1997. Interviews with 2 Gold Coast Radio Stations on the Narrowneck surfing reef, October, 1997.

Black, K. P., 1997. Radio interview on the National Current Affairs Radio Programme PM in Australia, December, 1997.

Black, K. P., 1997. The Narrowneck Surfing Reef. Interviews with 3 Queensland radio stations, October, 1997.

Black, K., S Mead & J.Hutt, 1999. Narrowneck , world first sand reef. *Core*, August 1999, p.19.

Black, K., 1999. Artificial surf reefs. *The Fondle*, no.4. 9-11.

Black, K., 2000. Hanging five for year 2000. Article about Mt Maunganui project. *Sunday Star times*, 23 May 1999.

Bollinger, T., 1998. Scientist Surfies Spearhead Reef Research. *Tearaway Magazine*, August, 1998.

Costella, P,. 2000. Artificial Reef. Documentary on Queenland's Gold Coast solution to summer cyclones, Quantum, 9 March 2000.

Daily News, 2000. Central beach and surf reefs are an exciting concept. New Plymouth reefs, *Daily News*, 25 March 2000.

Deiley, R., 1997. The Perfect Wave. *Gold Coast Bulletin*, November 21, 1997.

Ekizian. F., 1998. Nosso Cientista Favorito *Fluir E' Tricampea* (Brazilian Surfing Magazine), November, 1998.

Economist, 1997. On The Beach. *The Economist*, December 20, 1998.

Ferguson, A., 1997. Surf's Up Thanks to Hamilton's Scientific Wave Makers. *New Zealand Herald*, 10 July 1997.

Fitzhenry, M., 1999. Stockton surfing nirvana in the pipeline. *The Newcastle Herald*, Friday 15 January 1999.

Garner, T. 1997. Mount Surfing Reef on Drawing Board. *New Zealand Herald*, 28 August, 1997.

Gerritsen, J., 1998. Breaking the Rules of the Waves. *New Zealand Education Review* August 12, 1998.

Glaskin, M., 2000. Brournemouth's making waves – literally. 31 March 2000.

Gough, V. Student work may decide fate of reef. *Bay of Plenty Times*, 28 May 1999, p3.

Gundry, S., 1998. Surfers Paradise: Kerry Black is making waves to save coastlines. *North & South*, February 1998.

Hamilton, P., 2000. Surfers plan perfect wave for Lyall Bay. *Evening Post*, 14 July 2000.

Hamilton Press, 2000. Demand for fake reefs. *Hamilton Press*, 19 July 2000.

Hannam, J., 1997. First, Design Your Wave! *Off Campus*, University Alumni, Autumn 1997.

Hodgetts, L., 1997. Reef Work to Swell Surfing Reputation. *Weekend Bulletin*, November 8-9, 1997.

Holdom, N., 1998. Designer keen to develop artificial surf reef. *Daily News*, 1 December 1998.

Hunter, K., 1999. Surfers' paradise at Boscombe?.

Hutt, J.A., T.Hume, K,Black and S.Mead (1997). ARP, Artificial Reefs Program. *New Zealand Surfing Magazine*, May/June 1997.

Kerr, P., 1999. Reef could net $500,000 a year. About the proposed artificial surf reef at the Mount. *Bay of Plenty Times*, 20 November 1999.

Kerr, P., 1999. Progressive group backs reef proposal. Article regarding the proposed Mt Maunganui project. *Bay of Plenty Times*, 23 August 1999.

Kirkpatrick, D., 1997. Surf Reef May Be Up In A Year. *Bay of Plenty Times*, December 2, 1997.

Kirkpatrick, D., 1998. 'Beach in a Bag' Reef '98 Start Likely. *Bay of Plenty Times*, March 13, 1998.

Klaassen, E., 1999. Opunake Reef. *Opunake & Coastal News*, Vol.10:4, 17 February 1999.

Macbrayne, R,. 1999. Reef backers on the crest of a wave. *Weekend Herald*, June 5-6, 1999

Mead, S., and K. P. Black, (1995). Artificial Surfing Reefs: Fact, Fiction of Just Around the Next Headland? *Groundswell Surfing Magazine*, December 1995.

Mead, S., and K. P. Black, (1996). Dropping Into The Ledge. *Groundswell Surfing Magazine*, July 1996.

Mead, S. and K. P. Black (1997). Onshore Offshore - A Column About Surfing and Our Coast. Bi-monthly column, *New Zealand Surfing Magazine*, Jan/Feb 1997.

Mead, S. and K. P. Black (1997). Onshore Offshore. Bi-monthly column, *New Zealand Surfing Magazine*, May/June 1997.

Mead, S. and K. P. Black (1997). Onshore Offshore - Banks, Waves and grains of sand. Bi-monthly column, *New Zealand Surfing Magazine*, July/August 1997.

Mead, S., K. P. Black and J. A. Hutt (1997). Onshore Offshore - Surfing Theory of Relativity. Bi-monthly column, *New Zealand Surfing Magazine*, September/October 1997.

Mead, S., K. P. Black and J. A. Hutt (1997). Onshore Offshore - Horatio Does It Again. Bi-monthly column, *New Zealand Surfing Magazine*, November/December 1997.

Mead, S., K. P. Black and J. A. Hutt (1998). Onshore Offshore - Reef Construction - Bags, Boulders or Building Rubble. Bi-monthly column, *New Zealand Surfing Magazine*, January/February 1998.

Mead, S., K. P. Black and J. A. Hutt (1998). Onshore Offshore - *Waves, Energy and Bottles of Coke*. Bi-monthly column, *New Zealand Surfing Magazine*, March/April 1998.

Mead, S., K. P. Black and J. A. Hutt (1998). Onshore Offshore - The Virtual Reality of Computer Modelling. Bi-monthly column, *New Zealand Surfing Magazine*, May/June 1998.

Mead, S., K. P. Black and J. A. Hutt (1998). Onshore Offshore - Wave Bending and the Search For the Perfect Point Break. Bi-monthly column, *New Zealand Surfing Magazine*, July/August 1998.

Mead, S., K. P. Black and J. A. Hutt (1998). Onshore Offshore - Getting Really Ripped. Bi-monthly column, *New Zealand Surfing Magazine*, July/August 1998.

Mead, S. T., K. P. Black & J. A. Hutt, 1998. An Artificial Offshore Reef at Tay Street - Mount Maunganui Beach, Report 1: Reef Design and Physical and Biological Processes. Application for a coastal resource consent to Environment Bay of Plenty, June, 1998.

Mead, S. T., 1998. Finding the Ultimate Wave. Foundation, No. 32 September, 1998, Foundation for Research, Science and Technology.

Mole, C., 1999. *Westshore residents call for artificial reef.* Hawkes Bay Today, 31 August 1999

Morrison, D., 1998. Takapuna Reef Stands Trail. Green Room, *New Zealand Surfing Magazine*, July/August 1998.

Napier Radio Interview, 1999. Westshore reef possibility, 6 December, (Shaw Mead)

NZ Fishing, 1999. Artificial reef plans underway. Article about Mount Maunganui Reef, in *New Zealand Fishing*, February 1999, p.12.

Paltridge, A., 1999. Sea wall may go to create city beach. *Daily News*, New Plymouth, 3 February 1999.

Paltridge, A., 1999. Exciting beach plan opens up city to sea. New Plymouth *Daily News*, 10 April 1999

Perry, N., 1998. Surfer's Boon in Beach Plan. New Zealand Herald, September 4, 1998.

Prime TV News, 1999. Mount Reef update 7 December (featured interview with Shaw Mead).

Robinson, S., 1998. Making Waves - The Creation of Artificial Surfing Reefs May Offer Frustrated Board Riders New Breaks. *Time*, June 1, 1998. pp. 50-51.

Robson, B., 1997. Artificial Reef Talks Begin To Sort Out Risks. *Bay of Plenty Times*, August 20, 1997.

Rodley, A., 1999. Signs look good for artificial surf reef. *The Daily News*, July 6, 1999.

Rogers, T., 1998. They're Building Perfect Waves at Aussie Hot Spot. *San Diego Union*, April 28, 1998.

Rooney, E., 1998. Surfers Hopeful of Solution. *North Shore Times Advertiser*, August 6, 1998.

Smith, P. (1995). Coast Protection, Better Waves. *Bay News*, June 14, 1995.

Smith, P. (1997). Reef Boost For Mount Surfing. *Bay News*, August 13, 1997.

Smith, P. (1997). Delight Over Mount Surf Reef Project. *Bay News*, August 20, 1997.

Smith, P. (1997). Reef Project May Happen Next Year. *Bay News*, December 10, 1997.

Smith, P., 1997. Artificial surfing reef planned. *Mount & Papamoa Times*; 23 October 1997.

Stolz, G., 1997. Artificial Reef For Surfers. *Weekend Bulletin*, October 18-19, 1997.

Southerden, L., 1997. The Low-Down on Artificial Surfing Reefs: Making Waves. Deep, issue 11, Summer 1997-1998.

Tearaway, 1998. Scientist surfies spearhead reef research. The study of environmentally sensitive ways of treating coastal erosion. *Tearaway Magazine*, August 1998.

TV Globo (1997). (Shaw Mead) Television interview on Brazilian National Television. Hotel Othon Palace, Rio de Janeiro, Brazil, 9 June 1997.

TV One News (1997). (Shaw Mead) Television interview on New Zealand National Television. Raglan Point, New Zealand, 25 July 1997.

Waikato Times, 1999. Perfect wave eyed. Note in "Briefly" section of *Waikato Times*, 4 February 1999.

Withiel, C., 1998. Breakwater Worries Surfers. *North Shore Times Advertiser*, 24 August, 1998.

Appendix 2

Examples of the various file formats used during the operation of Horatio and the post-processing of the bathymetric survey data.

A) Example of Base Station data file format.

1st line represents positional information (GMT, Lat, Lon, elevation)

2nd line represents speed-over-ground (not used)

```
#GXGXP,185104,3822.21807,S,14416.83973,E,-0065,M
#GXSOG,185104,003.07,k,100,Tn
#GXGXP,185106,3822.21827,S,14416.83931,E,-0066,M
#GXSOG,185106,003.04,k,100,Tn
#GXGXP,185107,3822.21849,S,14416.83889,E,-0067,M
#GXSOG,185107,003.03,k,236,Tn
#GXGXP,185108,3822.21880,S,14416.83835,E,-0068,M
#GXSOG,185108,002.94,k,236,Tn
#GXGXP,185110,3822.21902,S,14416.83791,E,-0069,M
#GXSOG,185110,002.96,k,238,Tn
#GXGXP,185111,3822.21925,S,14416.83747,E,-0070,M
#GXSOG,185111,002.95,k,237,Tn
#GXGXP,185112,3822.21948,S,14416.83701,E,-0071,M
#GXSOG,185112,002.92,k,237,Tn
#GXGXP,185114,3822.21981,S,14416.83633,E,-0072,M
#GXSOG,185114,002.88,k,238,Tn
#GXGXP,185115,3822.22004,S,14416.83586,E,-0073,M
#GXSOG,185115,002.84,k,238,Tn
#GXGXP,185116,3822.22028,S,14416.83540,E,-0074,M
#GXSOG,185116,002.83,k,238,Tn
```

B) Example of Tattletale logger data file format.

GMT, lat, lon, depth.

```
,185554,3822.29607,S,14416.88415,E, 4.050
,185555,3822.29632,S,14416.88483,E, 3.265
,185556,3822.29632,S,14416.88483,E, 3.195
,185557,3822.31324,S,14416.89655,E, 3.739
,185558,3822.31266,S,14416.89646,E, 3.902
,185600,3822.31193,S,14416.89611,E, 3.638
,185601,3822.31137,S,14416.89599,E, 3.366
,185602,3822.31137,S,14416.89599,E, 3.498
,185603,3822.31069,S,14416.89616,E, 3.661
,185605,3822.31035,S,14416.89633,E, 3.483
,185605,3822.31035,S,14416.89633,E, 3.576
,185606,3822.31000,S,14416.89655,E, 3.312
,185608,3822.29467,S,14416.88750,E, 3.630
,185609,3822.29412,S,14416.88745,E, 4.104
,185610,3822.29405,S,14416.88769,E, 4.058
,185612,3822.29375,S,14416.88778,E, 3.692
,185613,3822.29375,S,14416.88778,E, 3.692
,185614,3822.30683,S,14416.89631,E, 3.506
,185616,3822.30654,S,14416.89655,E, 3.980
```

C) Introductory text displayed on TxTools© when Horatio is powered up.

```
     ++++++++++++++++++++++++++++++++++++++++"

         BATHOMETRIC SURVEY LOGGING SYSTEM"
                VERSION 5b"

                John Radford"
             University of Waikato"
              September 1996"
               update 4/5/97"
       LOGGER............TATTLETALE MODEL 5F, 480K"
       DEPTH SOUNDER.....SIMRAD 0-30 M "
       SOUNDER OFFSET:
       SOUNDER MULTIPLIER:
       Depth = volts * multiplier + offset"
       GPS...............GEO-EXPLORER"
     ++++++++++++++++++++++++++++++++++++++++"

TO CHANGE THE CALIBRATION COEFICIENTS, HIT 2, OTHERWISE HIT 1
```

D) Horatio set up schedule.

```
"ENTER SOUNDER MULTIPLIER "

"ENTER SOUNDER OFFSET "

TO PRINT ECHO SOUNDER VOLTS HIT 2, OTHERWISE HIT 1

HIT 1 FOR CONTINUOUS (CTRL-C TO EXIT) ,2 FOR 10 READINGS ECHOTEST

IF YOU ARE IN THE NORTHERN HEMISPHERE HIT 1, SOUTH HIT 2, TEST HIT 3

ENTER THE TIME IN SECONDS BETWEEN LOGGING GPS POSITION AND SOUNDINGS "

TO ACCEPT YOUR CHOICE TYPE 1, TO RESET, TYPE 2;"

"THE SYSTEM WILL START IN 10 SECONDS, DISCONECT THE PC COMMS CABLE"

//++++++++++++++++++++++++++++++++++++++++++++++++++++++++++++

"MEMORY LOCATIONS USED   "

" OUT OF A TOTAL OF "

" TO DOWNLOAD HIT ALT-O (RUNNING TXTOOLS SOFTWARE) "
```

E) Example of a log-file format after differential correction with MAINSHAW.

```
Position adjusted to base station true lat/lon:   -38.36228056
144.28182444
time in seconds from  0 :  0    0
  time            lat               lon                 depth
  68154.0000    -38.36337172    144.28299128      4.05000
  68155.0000    -38.36337664    144.28299986      3.26500
  68156.0000    -38.36337739    144.28299711      3.19500
  68157.0000    -38.36366139    144.28318694      3.73900
  68158.0000    -38.36365339    144.28318011      3.90200
  68160.0000    -38.36364439    144.28316494      3.63800
  68161.0000    -38.36363672    144.28315844      3.36600
  68162.0000    -38.36363839    144.28315394      3.49800
  68163.0000    -38.36362956    144.28314994      3.66100
  68165.0000    -38.36362589    144.28314761      3.48300
  68165.0000    -38.36362589    144.28314761      3.57600
  68166.0000    -38.36362239    144.28314611      3.31200
  68168.0000    -38.36337189    144.28298444      3.63000
  68169.0000    -38.36336522    144.28297894      4.10400
  68170.0000    -38.36336539    144.28298069      4.05800
  68172.0000    -38.36336506    144.28297461      3.69200
  68173.0000    -38.36336731    144.28297153      3.69200
  68174.0000    -38.36358756    144.28311061      3.50600
  68176.0000    -38.36358839    144.28310611      3.98000
  68177.0000    -38.36358764    144.28310686      3.70800
```

F) Example of AMG output data file.

Decimal time, northing (relative to base), easting (relative to base), distance from base, northing, easting, depth.

```
OUTPUT FILE: AMG.OUT, FROM AMG PROGRAM
 EASTING  NORTHING  ZONE  LATITUDE  LONGITUDE
    0.00         0.00         -0.23          0.23   253067.67 -7047120.23
0.00
71162.00        -9.71       -164.69        164.98   253057.96 -7047284.69
4.05000
71163.00        -9.71       -164.69        164.98   253057.96 -7047284.69
3.63800
71165.00        -9.77       -164.80        165.09   253057.90 -7047284.80
4.10400
71166.00        -9.77       -164.98        165.27   253057.90 -7047284.98
4.10400
71167.00        -9.76       -165.02        165.31   253057.91 -7047285.02
3.90200
71169.00        -9.85       -165.06        165.36   253057.82 -7047285.06
3.48300
71170.00        -9.91       -164.95        165.25   253057.76 -7047284.95
3.63800
71171.00       -10.01       -165.02        165.32   253057.66 -7047285.02
3.70800
71172.00       -10.05       -165.05        165.35   253057.62 -7047285.05
4.10400
```

```
71174.00        -10.06      -165.03       165.33    253057.61 -7047285.03
3.70800
71175.00        -10.08      -165.08       165.39    253057.59 -7047285.08
3.48300
71176.00        -10.14      -165.04       165.35    253057.54 -7047285.04
3.63800
71177.00        -10.26      -165.12       165.44    253057.41 -7047285.12
3.70800
71180.00        -10.31      -165.24       165.56    253057.36 -7047285.24
3.98000
71181.00        -10.32      -165.33       165.65    253057.35 -7047285.33
3.90200
71183.00        -10.06      -165.19       165.50    253057.61 -7047285.19
4.10400
```

G) Example of tidal data file format created from Dobie pressure data or COSTIDE4.

ID line, decimal time, tide elevation

padang

29700 1.0

30600 1.05

31500 1.1

32400 1.15

33300 1.2

34200 1.25

35100 1.3

H) Example of data file format from TIDE – final data file (differentially corrected and path deviations removed, converted to metric grid and tidally corrected)

```
TIME        EAST        NORTH       DSEP  DTOT  DEPTH SMOOTH D
      GRADIENT
29855       8.08        -76.33      0     0     0.34  0.43
      40.91
29857       6.22        -77.49      2.19  2.19  0.5   0.44
      49.57
29858       5.28        -78.5       1.38  3.57  0.59  0.44
      60.57
29860       3.89        -78.86      1.44  5.01  0.47  0.44
      70.51
29861       2.5         -79.5       1.53  6.54  0.47  0.43
      80.87
```

29862	0.79	-80.5	1.98	8.52	0.27	0.43	87.81
29863	-0.4	-81.79	1.76	10.27	0.4	0.42	97.37
29864	-1.75	-82	1.37	11.64	0.43	0.42	106.26
29866	-4.39	-82.76	2.75	14.39	0.5	0.42	100.8
29869	-7.23	-83.72	3	17.39	0.5	0.41	102.74
29870	-8.8	-84.36	1.7	19.08	0.39	0.39	119.06
29871	-10.84	-85.11	2.17	21.25	0.39	0.38	124.64
29872	-12.25	-85.23	1.42	22.67	0.35	0.36	123.47
29874	-13.79	-85.41	1.55	24.22	0.4	0.36	117.4
29875	-15.48	-85.88	1.75	25.97	0.38	0.35	104.45
29876	-17.26	-86.09	1.79	27.77	0.29	0.33	102.44

Appendix 3

Protocol for Operating Horatio,

- depth sounder calibration,
- the base station, and,
- the survey.

A3.1 Depth Sounder Calibration

Prior to surveying the depth sounder should be calibrated. This is achieved via an inbuilt calibration function in Horatio (which is set up to log directly to the laptop PC[1]) and requires a tape measure and a drop off into water of less than 7 m deep (e.g. a jetty). The steps required for calibration of the depth sounder are as follows.

1. Connect the depth sounder to the waterproof case via the external plug and the 7 m cable.
2. Open TxTools© on the laptop PC and configure the communications set up as follows,

Port	1
Baud rate	19200
Data bits	8
Stop bits	1
Handshake	none
Parity	none

3. With the communication cord plugged into com port 1 of the laptop PC and TxTools© the current application, plug the communication cord into the datalogger/control unit and switch the power to Horatio to the ‘on’ position. This will result in the introductory text of Horatio (Appendix 3) being displayed in TxTools© on the laptop PC screen.
4. Select 1 at the first prompt and 2 ‘Print echo sounder volts’ at the second prompt.
5. Two options are available, ‘continuous’ or ‘10 readings’. ‘10 readings’ can be selected to check that the depth sounder is functioning properly. For calibration select ‘continuous’. The voltage signal (0 to 0.4999 V) from the depth sounder is output at 1 second intervals to the screen.
6. With the tape measure taped to the depth sounder cable, lower the sounder to the bottom.

---

[1] A Toshiba Satellite™ T2130CS laptop PC with a 486 processor was used during all fieldwork. Tattletale communication problems may arise using a laptop PC of faster processing speed.

7. Lift the sounder 1 m off the bottom and record several voltages at this depth (total depth minus 1 m). Continue this process in 0.5 m increments to the surface. The first step of 1 m allows for the 0.61 m depth below which the depth sounder does not properly work.
8. Graph the depth versus the voltage and calculate the gradient (multiplier) and the y-intercept (offset).
9. Restart Horatio as described in 2 above.
10. Select 'To change the calibration coefficients' at the first prompt and input the calculated values.
11. The depth sounder is now calibrated.

Water temperature, salinity and air pressure can all effect depth sounder measurements, therefore, it is important to calibrate the depth sounder prior to surveying.

A3.2 The Base Station

The base station must be set up with an unobstructed view of the sky from an elevation of 10° above the horizon in order to be able to receive all available satellites. A main supply or car battery power source is preferred to maximise survey time and minimise the chance of power loss. The steps required to set up the base station are as follows.

1. Open Procomm Plus® on the laptop PC and configure the communications set up as follows,
   - Port Com 1
   - Baud rate 9600
   - Data bits 8
   - Stop bits 1
   - Parity none

   Alt-P allows the communications set up to be changed.
2. Connect the GeoExplorer® GPS receiver via the communications cable to communication port 1 on the laptop PC and turn on.
3. Select 'Configuration' on the main menu of the GeoExplorer® GPS receiver and go to 'Communication'.

4. Select 'Port A' and configure as follows,
   - Baud rate 9600
   - Data bits 8
   - Stop bits 1
   - Parity none
   - Precision 5

   Precision is the number of decimal places in the longitude and latitude recorded in the data file. This must be set at the maximum of 5 to obtain sub-meter precision.
5. Return to the main menu on the GeoExplorer® GPS receiver and select 'Position'. This displays the current position 'GPS position' or the previous position 'Old Position'. Once the current position is being calculated ('GPS position' is displayed), the base station file can start to be recorded.
6. As the current position is being calculated, the position information (GXGXP) and speed-over-ground readings (GXSOG) will scroll down the laptop PC screen. Press Alt-F1 to begin recording a file to the hard-drive.
7. Carry out the bathymetry survey.
8. Once the survey is complete, press Alt-F1 to stop logging the base station file.

It is important to disable the screen-saver on the laptop PC, otherwise logging will be terminated when it engages. The logging status (logging, not logging) and communications set up are indicated in the status bar at the bottom of the Procomm Plus® screen.

A3.3 The Survey

Horatio is set up using a laptop PC and TxTools© software. Once set up, the system can be attached to any type of vessel to carry out the bathymetry survey. The steps required to set up and operate Horatio are as follows.

1. Open TxTools© on the laptop PC and configure the communications settings as follows,
   - Port 1

- Baud rate 19200
- Data bits 8
- Stop bits 1
- Handshake none
- Parity none

2. With the communication cord plugged into the communication port 1 of the laptop PC and TxTools© the current application, plug the communication cord into the datalogger/control unit. Connect the GeoExplorer® GPS receiver and the depth sounder to the their respective communication ports on Horatio.
3. Switch the Horatio power switch to the 'on' position. This will result in the introductory text of Horatio (Appendix 3) being displayed in TxTools© on the laptop PC screen.
4. Check the communication configuration of the GeoExplorer® GPS receiver is set correctly. Select 'Configuration' from the main menu. Select Port A and configure as follows,
   - Baud rate 2400
   - Data bits 8
   - Stop bits 1
   - Parity none
   - Precision 5

   Note, this is a different baud rate than the base station receiver is set at.
5. Listen for the 'clicks' issuing from the depth sounder that indicate it is working.
6. On the laptop PC, select '1' at the first two prompts and then either 1 or 2 for northern or southern hemisphere, respectively, depending on the location of the survey. Option 3 can be used to test it the system is operating; real-time data is written to the laptop PC screen.
7. At the next prompt input the frequency of data points to be recorded. This can be at 1, 2, 3 or 4 second intervals.
8. At the last prompt select '1' to 'accept the settings' or '2' to 'reset' and input a different group of settings.
9. The message 'The system will start in 10 seconds, disconnect the PC comms cable', will be displayed. Disconnect the communication cable from the data logger/control unit and seal the waterproof case.

10. After 10 seconds the LED will begin to flash to indicate that the unit is set, but not logging.
11. Attach the system to the survey vessel with an appropriate method, making sure that the top of the waterproof case, where the GeoExplorer® GPS receiver is located, has a clear view of the sky from an elevation of 15° above the horizon in order to be able to receive all available satellites.
12. When ready to begin the survey, switch the logging switch to on and begin. The LED will remain steady (or flicker slightly) when the system is logging positional data. If the LED begins to flash during a survey, there are not enough satellites in the appropriate positions to calculate accurate fixes. Stop surveying until positions can again be calculated. This is usually not more than a few minutes. Satellite availability can be checked prior to surveys using Trimble's QuickPlan© software.
13. When the survey is complete or the logger is nearing its capacity (4.5 hrs of continuous logging), switch the logging switch to the off position. DO NOT TURN OFF THE POWER. The depth sounder and GeoExplorer® GPS receiver can now be unplugged to conserve power. The LED should now be flashing.
14. Open TxTools© on the laptop PC, ensure that the communication settings are configured the same as listed in 1 above, and plug the communications cable into communication port 1. The message 'to download hit ctrl-C' should start to scroll down the screen.
15. Press ctrl-C and the message 'memory locations used = ####, To download Hit alt-O (running TxTools© software)' will print to the screen.
16. Press alt-O and a TxTools© dialogue box asking for the start and end address will appear on screen. The start address is always zero. Type the number of 'memory locations used' as the end address and select 'OK'.
17. Give the rover file an appropriate file name (*.dat) and select 'OK' to start downloading Horatio.

The depth sounder and GeoExplorer® GPS receiver must be plugged in prior to powering up the system and remain plugged in until the survey is complete. If the system is to be run for extended times out of the water, the depth sounder must be kept in water to prevent damage. Precision must be set the same (i.e. 5 decimal places) for the base station and roving GeoExplorer® GPS receivers.

Appendix 4

Wave Refraction Model WBEND.

A4.1 List of notation

x,y,z	orthogonal space dimensions
F	wave power (Wm^{-1})
θ	wave angle (radians)
F_D	combination of bed friction (F_f) and wave breaking (F_b) dissipation terms
F_f	bed friction coefficient
E	wave energy (Jm^{-2})
Cg	wave group speed (ms^{-1})
ρ	fluid density (kgm^{-3})
g	gravitational constant (9.81 m^2s^{-1})
H	wave height (m)
k	wave number (m^{-1}) = $2\pi/L$, L = wavelength (m)
ω	wave radian frequency (Hz)
Ψ	smoothing function for wave height or wave angle
ε	eddy viscosity coefficient (m^2s^{-1})
φ	wave height (m) or wave angle (°)
C_f	friction coefficient
H_L	friction term expressed as wave height loss per unit path length s
s	unit path length (m)
f	frequency (Hz)
H_f	wave height associated with spectrum band of frequency f (m)
H_{rms}	root-mean-square wave height (m)
Δf	spectral bandwidth (Hz)
$S(f)$	spectral density ($m^2.s$)
N_f	number of frequencies in the spectrum
ω_{av}	average radian frequency (Hz)
k_{av}	average wave number (m^{-1})
γ	breaking ratio

A4.2 General description

Model WBEND (Black and Rosenberg, 1992a, Black, 1997) is a 2-dimensional numerical wave refraction model for monochromatic waves or a wave spectrum over variable topography. The model applies a fast, iterative, finite-difference solution of the wave action equations to solve for wave height, wave period, breakpoint location and longshore sediment transport. WBEND provides for:

- variable bathymetry;
- time-varying boundary conditions;
- the wave spectrum;
- options to "enhance" the wave shoaling to overcome the limitations of linear theory;
- a range of friction formulae for different physical conditions;
- third-order differential approximations to eliminate grid scale "wiggles";

- a "diffusion" scheme to parameterize diffraction;
- longshore sediment transport on beaches;
- continuity of style throughout the suite of linked models and support software;
- software tools for data input, model output manipulation and graphical presentation;
- graphical output using the Matlab routine Plot3DD[1].

A4.3 Model equations

WBEND is a two-dimensional wave propagation model that uses, as a basis for refraction, the wave action equation for the conservation of wave power in two dimensions given by,

$$\frac{\partial}{\partial x}(F\cos\theta)+\frac{\partial}{\partial y}(F\sin\theta)=-F_D \qquad \text{(A4.1)}$$

where x and y are orthogonal co-ordinates, θ is the wave angle and F_D $(=F_f+F_b)$ is a combination of the bed friction (F_f) and wave breaking (F_b) dissipation terms. F is the wave power which, for Airy waves, is

$$F = EC_g = \frac{1}{8}\rho g H^2 C_g \qquad \text{(A4.2)}$$

where E is the wave energy, C_g is the group speed, ρ is the fluid density, g is gravitational acceleration and H is the wave height.

The wave angle is obtained from the equation for conservation of wave number

$$\frac{\partial}{\partial x}(|k|\sin\theta)-\frac{\partial}{\partial x}(|k|\cos\theta)=0 \qquad \text{(A4.3)}$$

The model solves equations A4.1 and A4.3 for wave power and wave angle respectively using a shoreward marching iterative scheme (Black and Rosenberg, 1992b). Height and angle are directly obtained on a regular finite difference grid, which eliminates the need for interpolation, as required when a ray tracking procedure is used.

To obtain the wave number k, the dispersion relation for linear waves,

$$\omega^2 = gk\tanh(kh) \qquad \text{(A4.4)}$$

is solved using an iterative *Newton-Raphson* technique, given the radian frequency ω and depth h.

[1] Plot3DD, Gorman, R.M. (1995)

A formulation based on the horizontal eddy viscosity in the hydrodynamic model 3DD (Black, 1995) is used to smooth the height and angle solutions. This has the effect of spreading energy along the wave crests, similar to the process of diffraction. While solving the wave action and conservation of wave number equations, heights and angles are smoothed by the function ψ given by,

$$\psi = \varepsilon(\frac{\partial^2 \varphi}{\partial y^2}) \tag{A4.5}$$

where ε is the eddy viscosity coefficient and φ is either wave height or angle. The dominant wave direction is along the model's x-axis, and so the term acts primarily along the wave crests. The eddy viscosity coefficient is set by calibration. Simulations of several different environments (e.g. Black and Rosenberg, 1992b; Hutt, 1997; McComb et al., 1997) have indicated that appropriate values are in the range $0.02 < \varepsilon < 0.06$.

For monochromatic cases, the wave-energy frictional dissipation term is given by,

$$F_f = \frac{\rho C_f}{6\pi}\left(\frac{H\omega}{\sinh(kh)}\right)^3 \tag{A4.6}$$

where C_f is the friction coefficient.

For a wave spectrum, mean bed orbital velocity is obtained from the variance in the spectrum, using the linear theory transform function to relate sea surface wave height and period to bed orbital motion. The transform function is applied to each spectral estimate and then the spectrum is re-constituted to obtain total bed orbital variance. The friction term adopted in the model, expressed as a height loss H_L per unit path length s, becomes,

$$\frac{\partial H_L}{\partial s} = \frac{2.83 C_f H_f H_{rms} \omega_f^2 \omega_{av}}{3\pi g C_g \sinh^2(k_f h)\sinh(k_{av} h)} \tag{A4.7}$$

where H_f is the height of the wave associated with the spectral band of frequency f, radian frequency ω_f and wave number k_f given by,

$$H_f = 2.83(S_f \Delta f)^{1/2} \tag{A4.8}$$

where S_f is the spectral energy density of the band with frequency f, and Δf is the bandwidth.

H_{rms} is the root-mean-square wave height calculated from the total variance in the spectrum as,

$$\langle \eta^2 \rangle = \sigma^2 = \int_0^{\infty} S(f)df = \sum_0^{f_n} S_f \Delta f$$

$$H_{rms} = 2.83\sigma \qquad \text{(A4.9)}$$

$$H_s = 4\sigma$$

while the average radian frequency ω_{av} is given by,

$$f_{av} = \frac{\Sigma H_f f}{\Sigma H_f} \quad \text{and} \quad w_{av} = 2\pi f_{av} \qquad \text{(A4.10)}$$

The summations are across all N_f frequencies in the spectrum. The corresponding wave number k_{av} is defined by the dispersion relation as,

$$\omega_{av}^2 = gk_{av} \tanh(k_{av} h) \qquad \text{(A4.11)}$$

The group speed C_g is the speed coinciding with the frequency ω_{av} and wave number k_{av}.

When solving in the model, the wave path length is assumed to consist of a series of straight line segments across each cell of width Δx for a wave travelling at angle θ. Thus the path length is

$$\Delta s = \Delta x / \cos\theta \qquad \text{(A4.12)}$$

The total height loss is summed across the model grid, row-by-row, after initially solving eqn A4.1, assuming $F_D = 0$.

Wave breaking is assessed by checking if height exceeds a depth limitation, that is if,

$$H > \gamma h \qquad \text{(A4.13)}$$

where γ is user selected and is typically of order 0.6-0.8.

A4.3.1 Model Grids and files

The model adopts a rectangular grid for bathymetry. The x-direction is positive to the east and corresponds with increasing 'I', while the y-direction is positive northwards and corresponds with increasing 'J'. The cell (1,1) is located at the bottom left corner of the grid and the maximum coordinate cell (I_{max} , J_{max}) is at the top right corner. The model assumes the shoreline is at the eastern side of the grid (maximum *I*). Wave angle is defined relative to the left ("east") of the grid and is positive anti-clockwise (Cartesian axes).

Model WBEND requires three input files which are:

1. Information file
2. Wave height, period and angle file, or spectrum file
3. Bathymetry file

One information file controls the model by providing the input data and output file names. More information on the options used in the information file can be found in the WBEND user's manual (Black, 1997).

WBEND has three types of boundary condition that can be used: the probability file listing wave events and their probability of occurrence; the spectrum file containing spectral densities and frequencies for a sea surface spectrum; and the sediment transport contour file for calculation of surf zone littoral drift. WBEND produces several output files, outlined in detail in the user's manual. The binary file, *filename.out*, was the main file used for the present study. This contains depths, wave heights, wave periods, and bottom orbital motion over the full grid for each simulated event.

A4.4 Previous applications of the model and selected references

Model WBEND has been used for a range of applications since its original development in 1991. The broad categories of study include:

- investigations for proposed marina developments;
- beach, bay and shelf sediment dynamics studies;
- artificial surfing reef investigations;
- surf zone wave transformations.

A selection of publications which have arisen from these applications are summarised below:

Black, K.P.; Rosenberg, M.A. (1992a). Natural stability of beaches around a large bay. *Journal of Coastal Research*. 8(2): 385-397.

Black, K.P.; Rosenberg, M.A. (1992b). Semi-empirical treatment of wave transformation outside and inside the breaker line. *Coastal Engineering*. 16: 313-345.

Black, K.; Rosenberg, M.; Symonds, G.; Simons, R.; Pattiaratchi, C.; Nielsen, P. (1995) *Measurements of wave, current and sea level dynamics of an exposed coastal site*. Chapter 2 in "Mixing Processes in estuaries and coastal seas". C. Pattiaratchi (ed.). American Geophysical Union. p.29-58.

Black, K.; Andrews, C.; Green, M.O.; Gorman, R.M.; Healy, T.R.; Hume, T.M.; Hutt, J.; Mead, S.; Sayce, A. (1997). Wave dynamics and shoreline response on and around surfing reefs. Ist International Surfing Reef Symposium, Sydney, March 1997.

Black, K.P. (1997) *Wave refraction model WBEND.* Occasional Report, Centre of Excellence in Coastal Oceanography and Marine Geology, Department of Earth Sciences, University of Waikato, New Zealand. (in prep.)

Hutt, J.A. (1997) Bathymetry and wave parameters defining the surfing quality of 5 adjacent reefs. MSc thesis. Centre of Excellence in Coastal Oceanography and Marine Geology, Earth Sciences Department, University of Waikato. 170 pp.

McComb, P.; Black, K.P.; Atkinson, P. (1997). High-resolution wave transformation on a coast with complex bathymetry. Pacific Coasts and Ports'97, Christchurch, 7-11 September 1997.