Predicting the Breaking Intensity of Surfing Waves

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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 length 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.

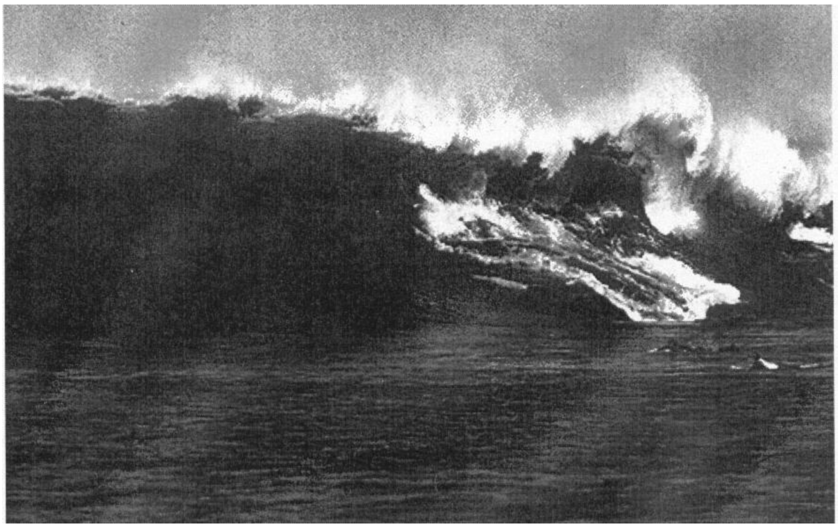

Plate 6.1. A wave collapsing as it breaks above the very steep seabed of Todo Santos reef in Mexico (after Sayce, 1997).

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).

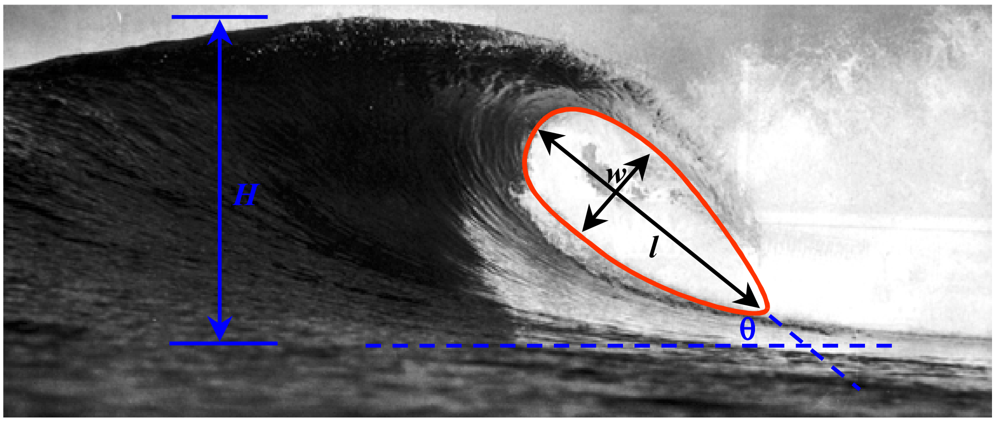

Figure 6.1. Curve fitting is applied to the forward face of a crest parallel wave image and used to calculate the vortex length (*l*), width (*w*) and angle (θ). *H* is the estimated wave height (after BLACK *et al.*, 1997).

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.

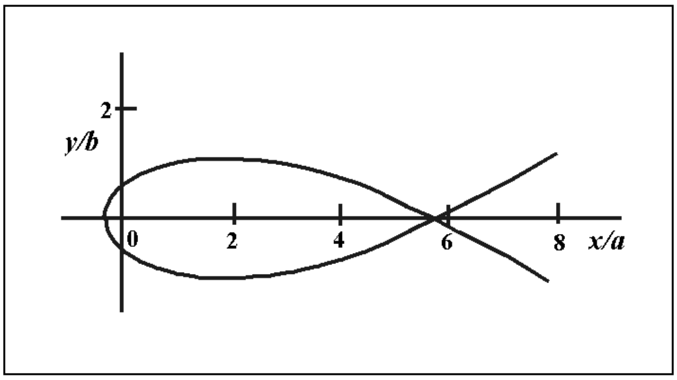

Figure 6.2. The profile of the cubic curve (LONGUET-HIGGINS, 1982).

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.

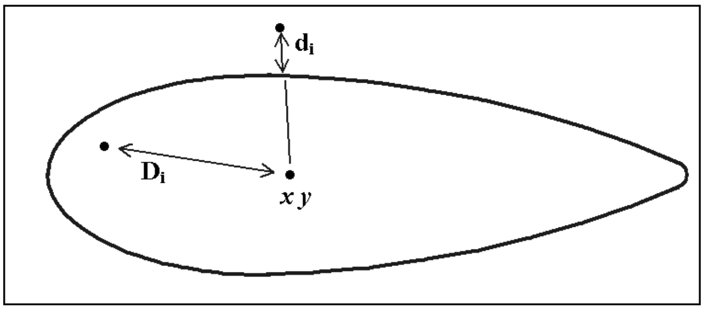

Figure 6.3. The error is derived from the mean-squared distance (Equation. 6.4) of digitised points from the fitted curve, where D_i is the distance from the mean *x* and *y* position and d_i is the distance from the fitted curve (after SAYCE 1997).

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).

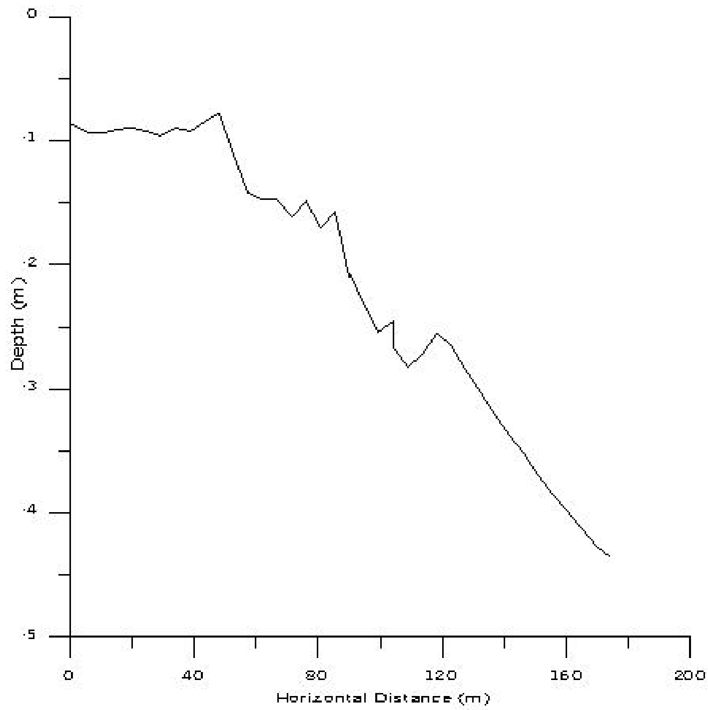

Figure 6.4. Example of seabed gradient profile created by digitising a bathymetry grid and then plotting using GRAPHER software (V. 1.3 1993-1996 Golden Software, Inc.).

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.

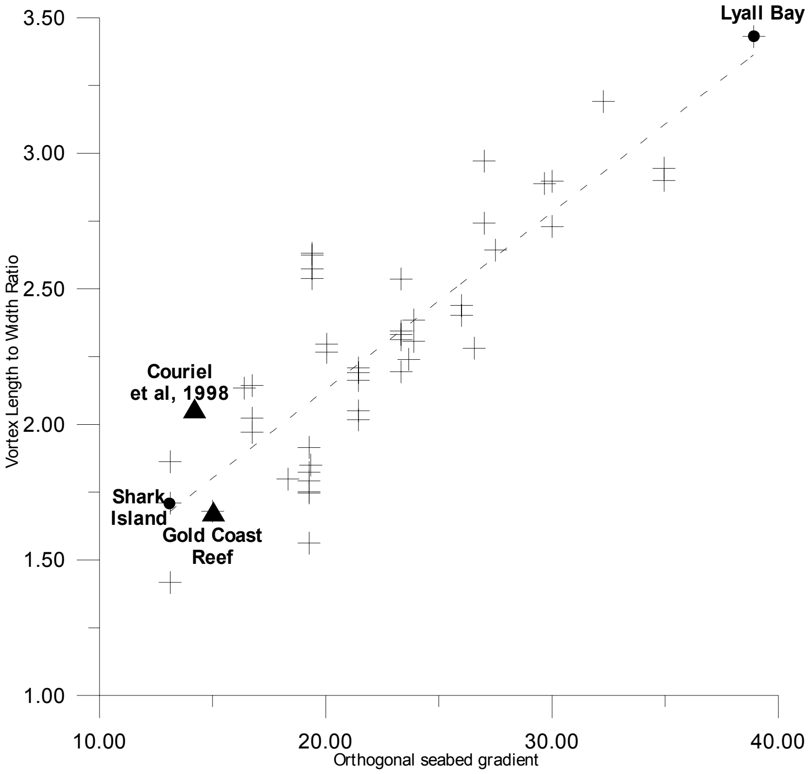

Figure 6.5. Orthogonal seabed gradient versus the ratio of vortex length to vortex width ($R^2 = 0.71$). The orthogonal seabed gradient (given as the horizontal distance to one vertical unit) is the gradient along the direction of wave propagation. Additional data points are the Gold Coast artificial 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.

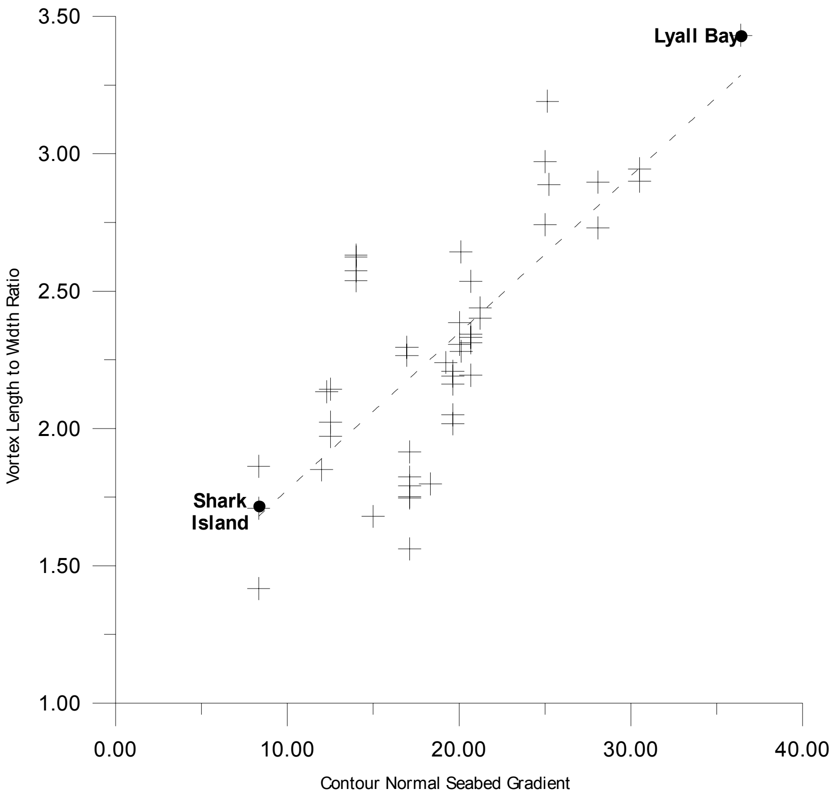

Figure 6.6. The relationship between the contour normal seabed gradient and the ratio of vortex length to vortex width ($R^2 = 0.57$). The contour normal seabed gradient (given as the horizontal distance to one vertical unit) is the steepest possible seabed gradient.

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 32º to 57º. 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).

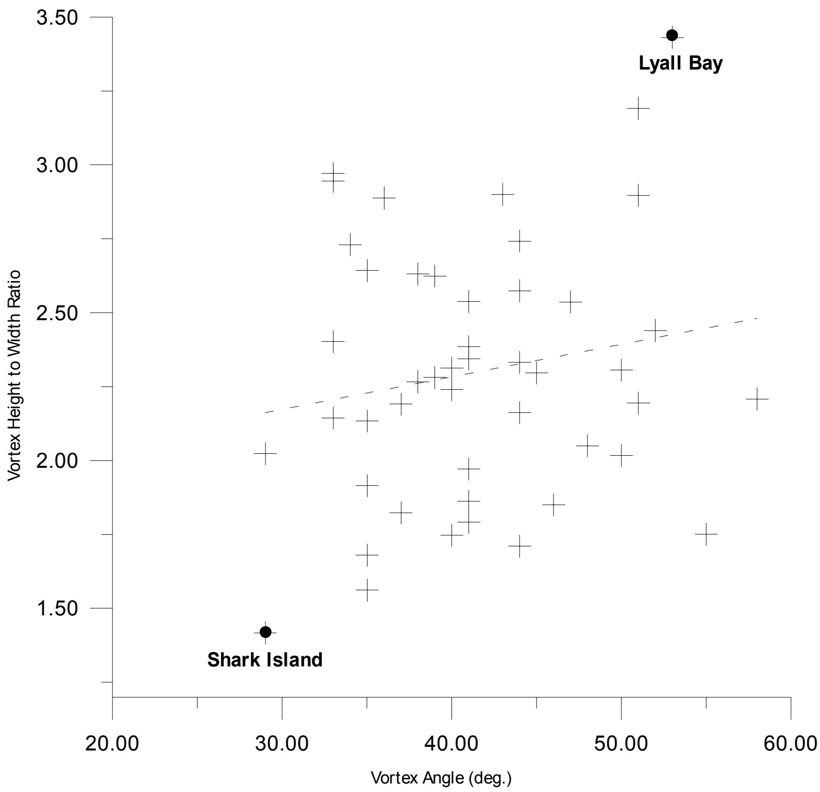

Figure 6.7. Wave vortex angle vs the ratio of vortex length to vortex width ($R^2 = 0.03$).

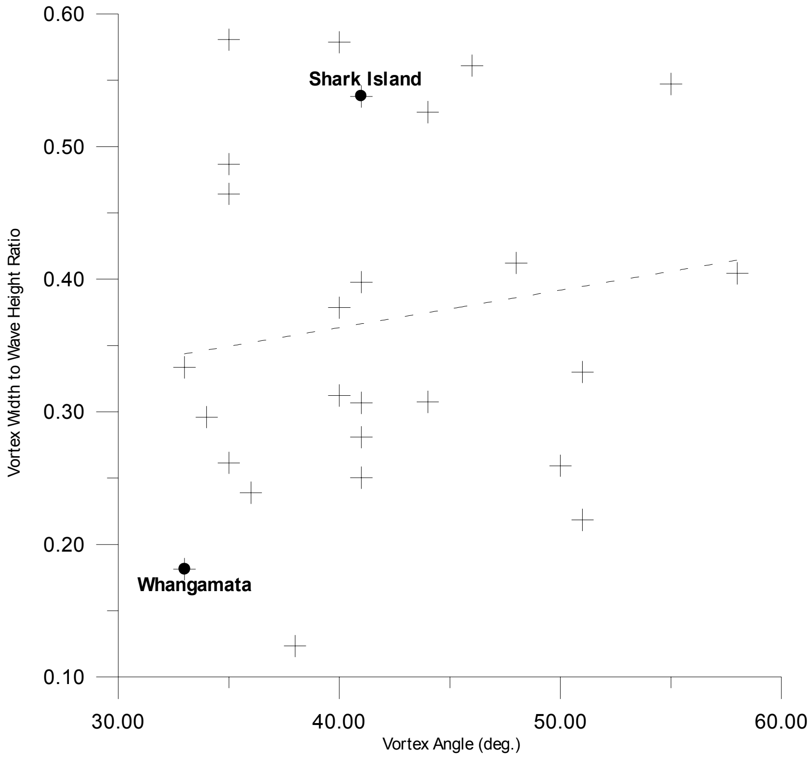

Figure 6.8. Wave vortex angle vs the ratio of vortex width to wave height ($R^2 = 0.02$). Wave height for the Lyall Bay video image could not be estimated, and so Whangamata is shown as the break with the lowest seabed gradient.

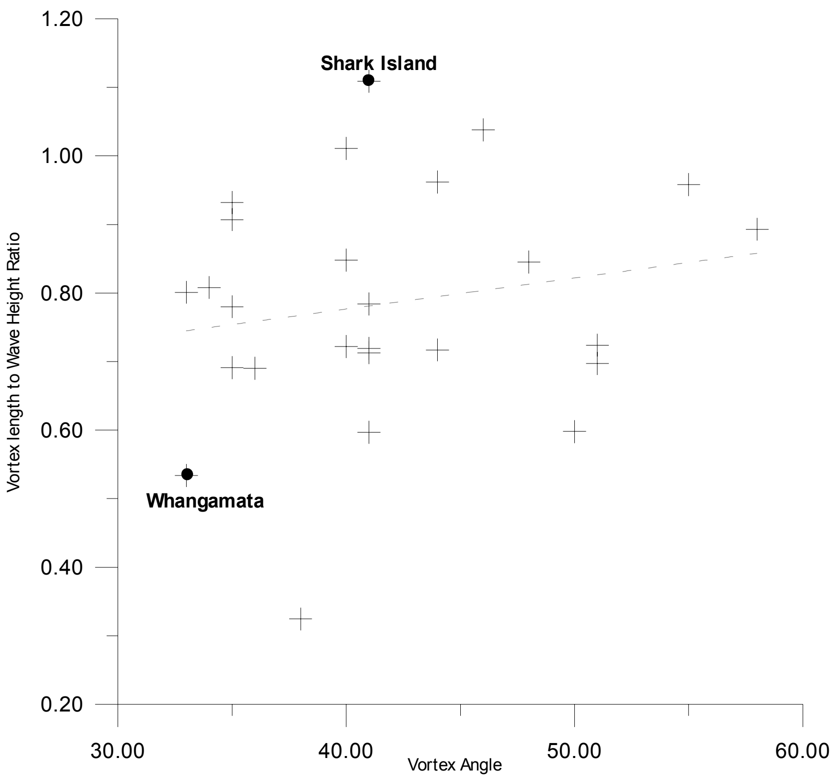

Figure 6.9. Wave vortex angle vs the ratio of vortex length to wave height ($R^2 = 0.03$). Wave height for the Lyall Bay video image could not be estimated, and so Whangamata is shown as the break with the lowest seabed gradient.

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).

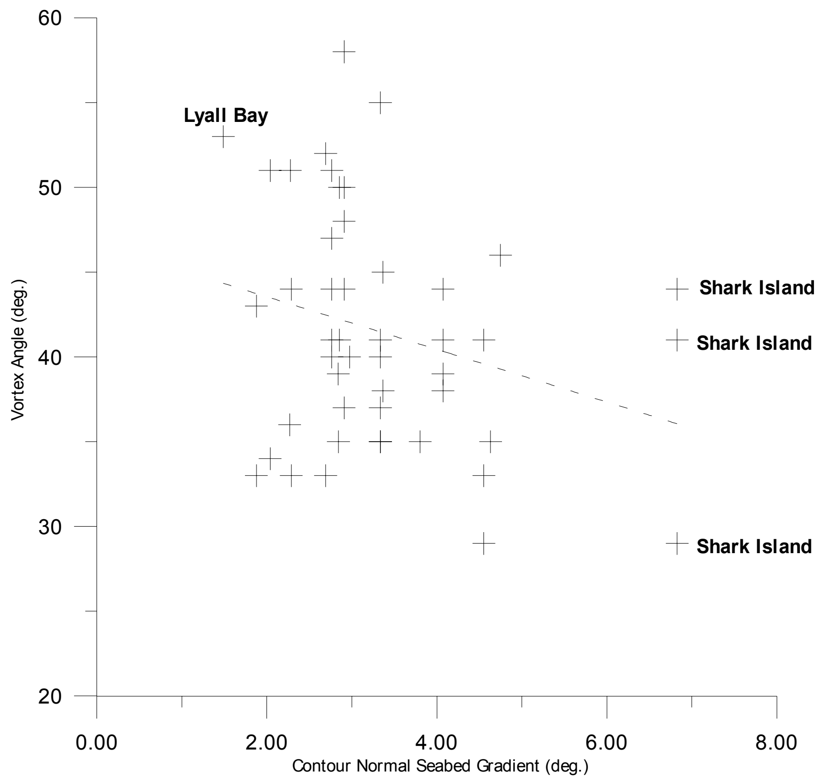

Figure 6.10. Contour normal seabed gradient (expressed as an angle (deg.)) vs the vortex angle (R^2 = 0.07).

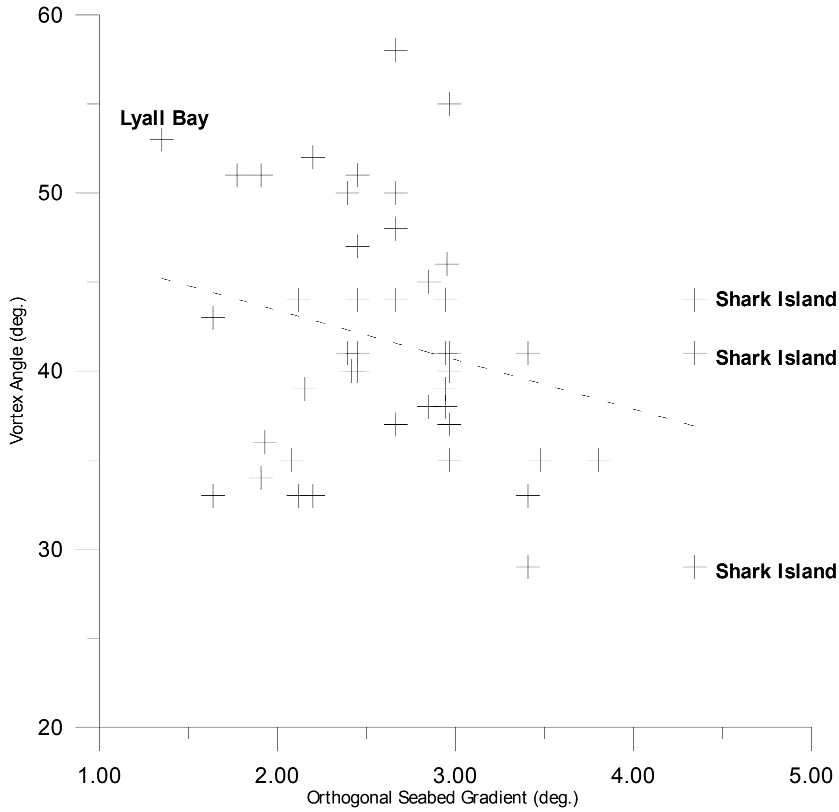

Figure 6.11. Orthogonal seabed gradient (expressed as an angle (deg.)) vs the vortex angle (R^2 = 0.07).

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 32º to 57º. This is a smaller range than that found by SAYCE (1997) and SAYCE *et al.* (1999) of 10º to 55º. 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^o while this study recorded angles from $29\text{-}44^o$. 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.

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