Wave behaviour in the inner surf zone

Hannah POWER and Michael HUGHES

Abstract: The inner surf zone is a critical component of models that are used to predict nearshore wave behaviour and beach morphodynamics. However, wave behaviour in the inner surf zone is poorly understood. Water surface elevation data from eight field deployments were combined to produce a total data set of over 105 hours. This data was analysed to accurately characterise wave behaviour in the inner surf zone. Contrary to the current hypothesis, the wave height to water depth ratio, $\gamma$, in the inner surf zone was not constant, but increased rapidly in the shoreward direction. Some data runs had $\gamma$-values that were close to one, a factor more than twice as large as the commonly quoted value. This observation was used to modify the existing conceptual model for wave behaviour in the surf zone, by defining two new sub-regions in the inner surf zone: (1) the approximately constant $\gamma$ zone and (2) the rapidly increasing $\gamma$ zone. As waves progressed from the constant $\gamma$ zone to the increasing $\gamma$ zone, they became increasingly non-linear. This suggests the increasing importance of amplitude dispersion as waves move into shallow water. It is therefore important to use theoretical models that are based on the non-linear shallow water theory and/or bore equations (or similar) in order to accurately describe the physics.

Keywords: nearshore waves, beaches, inner surf zone, surf saturation, bores

Introduction

Wave behaviour in the inner surf zone is a critically important component of models that are used to predict water levels and coastal inundation and, therefore, assess coastal management options. While much attention has been focused on wave behaviour in the regions on either side of the inner surf zone, the outer surf zone and swash zone, there has been limited research specifically on the inner surf zone.

The inner surf zone consists of very shallow water depths, as it is the region of the surf zone immediately seaward of the shoreline. Waves in the inner surf zone are very effective at suspending sediment thus suspended sediment concentrations and therefore sediment transport rates in this region are usually large (Aagaard and Masselink, 1999). Consequently, the inner surf zone is an important link in the exchange of sediment between offshore bars and the beach face. The dynamics of the inner surf zone also have a direct impact on nearshore water levels and the dynamics of the swash zone, where the impacts of beach erosion are most pronounced (Hughes and Turner, 1999). The morphodynamic behaviour of the inner surf zone is therefore a key component of the total beach system, and our presently inadequate understanding of wave behaviour in this zone is the primary motivation for this study.

The current conceptual model for surf zone waves includes an outer and inner surf zone (Svendsen et al., 1978). In this model, the outer surf zone consists of breaking waves with decreasing wave height to water depth ratios ($\gamma = H/h$ where $H$ is wave height and $h$ is water depth) and rapidly changing wave shape, and the inner surf zone consists of bores with constant wave height to water depth ratios, $\gamma$, and slowly changing wave shape. Bores form when sufficient energy cannot be dissipated by gentle spilling and bottom friction and must be dissipated by more turbulent breaking (Svendsen and Madsen, 1984; Svendsen, 1984).

Another change that occurs as waves move from deep to shallow water is that waves become increasingly non-linear in their behaviour. This behaviour can be characterised by the Ursell parameter, $U_r$:

$$U_r = \frac{HL^2}{h^3}$$

where $L$ is wavelength (e.g. Svendsen, 2006). In deep water, where waves are generally sinusoidal, $U_r << 1$, but as waves shoal, they become increasingly non-linear, which leads to an increase in $U_r$ (Aagaard and Masselink, 1999).

The majority of the literature currently assumes that $\gamma$ is constant across the whole of the inner surf zone. However, this assumption is based on a small number of studies and many of these studies have considerable limitations, including limited spatial coverage close to the shoreline, small data sets and significant error margins (see Komar, 1998, for review). Therefore, in order to improve coastal models and achieve more accurate predictions of
beach change, a better understanding of wave behaviour in shallow water depths is necessary.

Pressure sensor data was used to investigate how $\gamma$-values and other indicators of wave behaviour change in the inner surf zone. This study demonstrates that, contrary to the current conceptual model of waves of roughly constant form extending across the entire inner surf zone, waves change markedly close to the shoreline with rapidly increasing values for wave height to water depth ratios, and wave non-linearity.

Methods

To investigate wave behaviour in the inner surf zone, field data from a wide range of beach types was required. The data used in this paper was collected on eight different beaches with beach slopes ranging from 0.019 to 0.082 and inner surf zone wave heights (and periods) ranging from 0.24 to 0.77 m (6.94 to 10.28 s). Table 1 shows the location, date, beach slope, maximum root-mean-square wave height ($H_{rms}$) and mean wave period ($T$) in the inner surf zone for each deployment. The details of the experimental design varied slightly depending on the beach type and the conditions on the day. In general, pressure sensor data was collected from several cross-shore locations for 4-6 hours from low tide to high tide in order to obtain data from a large range of water depths.

Data processing

Time series analysis was used to analyse all the data sets. Data were analysed in 15 minute runs to ensure stationarity with respect to tidal water level, and filtered in a two-step filtering process. Firstly, the data were filtered using a low-pass finite impulse response filter to remove instrument noise. Secondly, data were high-pass filtered using a moving average filter to isolate short waves (sea and swell). The length of the filter ($f_L$) was defined by:

$$f_L = \frac{f_c}{f_s}$$

where $f_c$ is a cut-off frequency and $f_s$ is the sampling frequency. Frequency spectra were calculated to enable the cutoff frequency to be chosen for each data run. This typically occurred at $\geq 0.075$ Hz.

A total of 105 hours of data were analysed as part of this study. This resulted in the analysis of over 43,000 waves from a total of eight different beaches.

This far exceeds any one data set that has previously been used to investigate the inner surf zone.

Results

The data presented in this paper are separated into deployments that represent a period in time of about 0.5 to 1 tidal cycle. This is because offshore wave conditions were approximately constant for those periods of time. The tidally varying wave level, combined with several sensors located across the surf zone, was beneficial as it increased the range of water depths in which wave behaviour could be measured.

In the majority of deployments the water depth decreased continuously with distance across the surf zone towards the shoreline. It is therefore assumed that trends between wave parameters and decreasing water depth also generally represent trends associated with distance travelled in the shoreward direction. Potential limitations to this assumption are addressed in the discussion.

Variation in $\gamma$-value

The wave height to water depth ratio, or $\gamma$-value, that was used in this study was calculated using the method that is most commonly used in the literature, $\gamma = \frac{H_{rms}}{h}$ . This uses the root-mean-square wave height ($H_{rms}$) and mean water depth ($h$), where $H_{rms}$ is estimated using

$$H_{rms} = \sqrt{8m_o}$$

where $m_o$ is the variance of the water surface elevation record (e.g. Masselink and Hegge, 1995; Sellenger and Holman, 1985; Sellenger and Howd, 1989; Thornton and Guza, 1982; Thornton and Guza, 1983; Wright et al., 1982). This estimation of $H_{rms}$ has been shown to be within 20% of the true $H_{rms}$ value (Thornton and Guza, 1982). A wave-by-wave analysis of the records based on zero down-crossings produced similar results to those reported here.

In all 8 deployments the $\gamma$-values in the surf zone increased in a shoreward direction (Fig. 1). The rate at which the $\gamma$-values increased varied between deployments. In all cases $\gamma$ slowly increased in the shoreward direction in the deeper water depths of the inner surf zone and then rapidly increased in the shallower water depths close to the shoreline. In the deeper water depths, where $\gamma$ increased slowly, $\gamma$-values were around 0.35-0.45, which is consistent

Table 1. Beach slope ($\tan \beta$), maximum $H_{rms}$ and mean period ($T$) in the inner surf zone for all deployments. All locations are in New South Wales, Australia unless otherwise stated.

<table>
<thead>
<tr>
<th>Location</th>
<th>Date</th>
<th>$\tan \beta$</th>
<th>Max. $H_{rms}$</th>
<th>Mean T</th>
</tr>
</thead>
<tbody>
<tr>
<td>Whangamatta, New Zealand</td>
<td>29/11/99</td>
<td>0.037</td>
<td>0.59</td>
<td>8.80</td>
</tr>
<tr>
<td>Seven Mile Beach (South Coast)</td>
<td>19/11/02</td>
<td>0.028</td>
<td>0.24</td>
<td>8.57</td>
</tr>
<tr>
<td>One Mile Beach</td>
<td>06/05/04</td>
<td>0.044</td>
<td>0.47</td>
<td>9.97</td>
</tr>
<tr>
<td>Elizabeth Beach</td>
<td>11/05/04</td>
<td>0.034</td>
<td>0.38</td>
<td>10.28</td>
</tr>
<tr>
<td>Avoca Beach</td>
<td>17/11/04</td>
<td>0.082</td>
<td>0.62</td>
<td>8.90</td>
</tr>
<tr>
<td>Vejers Beach, Denmark</td>
<td>07/10/06</td>
<td>0.019</td>
<td>0.77</td>
<td>6.94</td>
</tr>
<tr>
<td>Boomerang Beach</td>
<td>24/04/07</td>
<td>0.023</td>
<td>0.46</td>
<td>9.51</td>
</tr>
<tr>
<td>Seven Mile Beach (Central Coast)</td>
<td>26/04/07</td>
<td>0.028</td>
<td>0.63</td>
<td>9.21</td>
</tr>
</tbody>
</table>

2/ International Conference on Civil and Environmental Engineering, ICCEE-2008/ Oct. 2008/ Hiroshima University
Figure 1. \( \gamma = \frac{H_{rms}}{h} \) for each beach deployment, where \( H_{rms} \) is calculated using Eq. (3) and \( h \) is the mean water depth at (a) Whangamatta 29/11/99, (b) Seven Mile Beach (South Coast) 19/11/02, (c) One Mile Beach 06/05/04, (d) Elizabeth Beach 11/05/04, (e) Avoca Beach 17/11/04, (f) Vejers Beach 07/10/06, (g) Boomerang Beach 24/04/07, (h) Seven Mile Beach (Central Coast) 26/04/07.
with previous research. In the shallow water depths where γ increased rapidly, wave heights were almost equivalent to the water depth. The inflection point where there was a change from slowly increasing to rapidly increasing γ varied between deployments from 0.4-1.0 m water depth (Fig. 1).

Variation in wave shape

The Ursell parameter, $U_r$, was used to investigate the linearity of waves in the inner surf zone. To obtain the measurements necessary to calculate the Ursell parameter on a wave-by-wave basis, a zero down-crossing analysis was performed. Wave height was defined as the vertical distance between the wave crest and the preceding wave trough and wavelength was calculated using the shallow water approximation to linear wave theory. A two-sample, two-tailed t-test was conducted to determine if there were statistically significant differences between the two zones. The null hypothesis was that the there was no difference in the mean of $U_r$ between these two zones; the alternate hypothesis was that there was a difference.

The Ursell parameter, $U_r$, increased from the constant γ zone into the increasing γ zone (Fig. 2) and was significantly different between the two zones ($\alpha = 0.01$, p-value = 0). The values of the Ursell parameter were highly positively skewed in both the constant and increasing γ zones. To account for this, the values were log-transformed before conducting the t-test.

![Figure 2](image_url) Comparison of run means of the Ursell parameter ($U_r$) between waves in the constant γ zone (•) and waves in the increasing γ zone (○).

Discussion

This study examined numerous beaches to investigate wave behaviour in the inner surf zone. Wave height to water depth ratios, or γ-values, were calculated for each run, using root-mean-square wave height, $H_{rms}$, and the mean water depth, $h$. All of the 8 deployments analysed showed that γ was constant in the deeper water depths of the inner surf zone, but increased rapidly close to the shoreline (Fig. 2). This indicates that in the shallower water depths of the inner surf zone waves are not strictly depth limited. This suggests a need to revise the current conceptual model of the surf zone by dividing the inner surf zone into two regions: (1) the approximately constant γ zone which occupies the deeper water depths of the inner surf zone and (2) the rapidly increasing γ zone which occupies the shallower water depths (< 1.0 m) of the inner surf zone and extends to the boundary between the surf and swash zones (Fig. 3).

In the constant γ zone recognised in this study, wave energy is dissipated at a suitable rate to compensate for wave shoaling and ensure wave heights remain depth limited and γ-values are constant. In the increasing γ zone, however, energy apparently cannot be dissipated quickly enough through turbulent breaking and other mechanisms, and the reduction in wave height cannot keep up with the reduction in water depth. The inflection point observed between constant and increasing γ-values was used to define the boundary between the constant and increasing γ zones (Fig. 3). The depth where this boundary occurred varied between deployments.

Waves in the constant γ zone were characterised by mean γ-values for each deployment ranging from 0.25-0.60 (Fig. 3). The range of γ-values observed here corresponds to the range of γ-values published in the literature, which range from 0.32 (Sallenger and Holman, 1985) to 0.5 (Masselink and Hegge, 1995).

Waves in the increasing γ zone were characterised by mean γ-values as high as 0.99 for individual data runs. The increase in γ-values with decreasing water depth in this zone means that the short wave height will be non-zero at the shoreline. This is inconsistent with existing surf zone models that predict limited short wave energy at the shoreline and a predominance of long wave energy (e.g. Le Méhauté, 1962; Huntley et al. 1977). On all of the beaches in this study considerable short wave energy was observed at the shoreline to drive swash.

Increasing γ-values in a shoreward direction have been observed before, but not to the extent that was seen in this study. This may be due to a lack of observations in the shallower water depths of the inner surf zone in previous studies. For example, Sallenger and Holman (1985) observed an increase in γ-values from 0.32 to 0.42 as waves approached the shore and Sallenger and Howd (1989) observed an increase from 0.32 to 0.38. These increases were observed using data that was collected over a number of days and during different tidal water levels. Both studies attributed the increased γ-values to an increase in beach slope in the shallower water depths of the inner surf zone.

In this study the observed increase in γ with decreasing water depth in very shallow water is even more pronounced, but is unrelated to beach slope. The observed inflection point where γ-values begin to increase occurs at the same depth for data that was
Figure 3. Modified conceptual model of the surf zone showing the two sub-regions in the inner surf zone, the constant and increasing $\gamma$ zones, that were defined in this study. Observed mean values (and ranges) for $\gamma$ and the Ursell parameter ($U_r$) in each sub-region and the water depth ($h$) where the boundary between these two sub-regions occurs is also shown.

Wave behaviour in the subregions of the inner surf zone can be characterised by comparing values for the Ursell parameter from the two subregions (Fig. 3). As waves progressed from the constant to the increasing $\gamma$ zone, they became increasingly non-linear. The value of the Ursell parameter, $U_r$, increased rapidly reaching values of up to 118 for individual run means (Fig. 3). This corresponds to previous observations of the value of $U_r$ that showed that it generally increased as waves progressed across the surf zone (Cowell, 1982). The values measured in this study, however, were not as large as those reported by Cowell, who found values greater than 1000 close to the shoreline.

Large values of $U_r$ in the increasing $\gamma$ zone indicate that the waves in this zone were highly non-linear. As waves become increasingly non-linear the flow velocities become increasingly asymmetric, with the onshore flow velocity stronger, but of shorter duration than the offshore flow. This has important implications for sediment transport as it can lead to increased onshore sediment transport (Komar, 1998). Another important implication of increasing non-linearity is that waves become amplitude dispersive, i.e. wave speed varies with wave height. If waves are amplitude dispersive, the water under the crest of the wave will travel faster than the rest of the wave, as this is where the wave height is greatest, leading to a saw-toothed waveform. Therefore, in order to describe the wave behaviour in this zone, it is necessary to use a wave theory that accounts for amplitude dispersion, such as bore theory.

Limitations

While this study has shown that the wave height to water depth ratio, $\gamma$, is not constant across the inner surf zone, the results of this study are limited by the assumption that trends observed between wave parameters and decreasing water depth also represent trends associated with distance travelled in a shoreward direction. This is inherent in the way that data has been combined and presented in this study and in others (e.g. Sallenger and Holman, 1985; Sallenger and Howd, 1989), with parameters measured from widely varying tidal water levels being plotted against water depth.

While this is not problematic for beaches with approximately planar beach morphology, it is not as accurate for beaches with complex morphology such as bar-trough features. At a given water depth on a plane beach, the history of wave travel up to this depth is the same throughout a tidal cycle. However, on a beach with bar-trough morphology, the history of the wave travel to a given water depth can vary throughout a tidal cycle and across the profile. In addition to this, it is possible to have two points in the surf zone that have the same water depth, for example on the seaward and landward side of a bar. Despite having the same water depth, these two points occur at different horizontal positions and therefore different stages in the wave transformation process.

This limitation could be overcome in part by plotting parameters against distance from the shoreline, but as water depth exerts a greater influence, it is therefore still preferred as the independent variable. Also, a further problem arises with plotting parameters against distance from the shoreline in that the shoreline varies in both space...
and time. Due caution was exercised in relating wave behaviour to position in the surf zone by inference from the water depth, but some uncertainties remain in relation to the results of this and also previous studies. This limitation can only be overcome by deploying many pressure sensors across the surf zone at once to achieve high spatial resolution however, this was beyond the resources available to this study.

Another limitation of this study is the lack of data in the increasing γ zone compared with the constant γ zone (Fig. 1). More data points in the increasing γ zone would help to clarify factors such as the precise location of the seaward boundary of this zone and the range of Ursell values possible in this zone.

Future research
Contrary to current impressions, this study has shown that wave height to water depth ratios, γ-values, are not constant across the entire inner surf zone. However, the factors that affect the location where γ-values change from being approximately constant to rapidly increasing were not investigated. Previous studies have suggested that γ-values increase with increasing beach slope, but this was not the case in this study. The precise factors controlling the point at which γ-values increase, and hence define the boundary between the constant and increasing γ zones remains to be established.

The implications of constant and increasing γ-values were not investigated as part of this study. However, these differing conditions are likely to have important implications for flow velocities and therefore sediment transport in the surf zone, which ultimately affects beach morphology. Further investigation into these factors, combined with the results obtained in this study, has the potential to significantly improve broader scale morphodynamic and engineering models that would better inform coastal managers.

Conclusions
Wave height to water depth ratios, \( \gamma = \frac{H_{\infty}}{h} \), were calculated for 420 15-minute data runs from 8 deployments on different beaches with surf zone slopes ranging from 0.02 to 0.08. For all deployments, \( \gamma \) was approximately constant in the deeper part of the inner surf zone but rapidly increased as waves travelled into the shallow water depths close to the shoreline. In the increasing γ zone wave heights were almost equivalent to the water depth. The magnitude of the Ursell parameter was larger in the increasing γ zone.

Acknowledgements
The authors gratefully acknowledge Troels Aagaard, Tom Baldock, and Rob Brander for their help in collecting the field data.

References