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Wave Group Effects on Breaker Height on a Uniform Slope

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ABSTRACT

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The maximum wave height that can be achieved during shoaling is of key importance in the design of coastal structures and the assessment of near shore currents and water levels. Previous investigations, upon which current design guidelines are based, have tended to focus on regular, monochromatic waves thereby neglecting group effects. Studies incorporating random wave testing include these group effects but may require prolonged testing periods to achieve the design condition. The shoaling transformations of wave groups as they progress into shallow water and break has been investigated in laboratory wave flume experiments. The water surface elevations were recorded by capacitance type wave probes. The type and position of breaking was recorded and video imaging used to observe wave kinematics during shoaling and breaking. Results show that the interaction of horizontal (intra-group) and vertical (depth-induced) energy fluxes plays a key role in the shoaling and breaking processes of the wave group. Notably, the evolutional stage of the wave group as it approaches a critical threshold depth facilitates the emergence of two distinct shoaling cases – an *early shoaling case* and a *delayed shoaling case*. These distinctive shoaling cases appear to cause significant variation in the wave breaking properties (breaker type and breaking position) and in the maximum depth limited wave heights (H_b/d) observed. In particular, the delayed shoaling case appeared to stabilise the wave groups, delaying breaking and yielding H_b/d ratios in excess of current design guidelines. These preliminary results indicate that current design guidelines based on monochromatic waves may underestimate the 'worst case' scenarios associated with wave groupiness with consequent implications for engineering design, coastal modelling and hazard mapping and planning.

ADDITIONAL INDEX WORDS: *Wave group, depth-limited wave breaking, shoaling, wave kinematics*

INTRODUCTION

The maximum wave height that can be achieved in a finite water depth is of key importance in the design of coastal structures and the assessment of nearshore currents and water levels. There have been many experimental, field and numerical studies investigating shoaling and breaking waves and the effect that wave and seabed properties have on these processes. However, most laboratory investigations have tended to focus on idealised wave trains consisting of regular, monochromatic waves.

To assess the maximum breaking wave height possible in water of limited depth, two key parameters are required: a breaking wave height and a water depth at the breakpoint. The exact definitions of breakpoint, wave height and water depth remain ill defined and have been subject to significant interpretation by past investigators.

The breakpoint of a wave may be defined several ways. Classical wave theories state that breakpoint is reached when the velocity of particles within the waveform reach the local wave speed. Other definitions of breakpoint include: the point at which the wave cannot further adapt to the changing bottom configuration and starts to disintegrate; the point where the horizontal component of the water particle velocity at the crest becomes greater than the wave; the point where the wave height reaches a maximum; the point where the radiation stress begins to decrease; the point where part of the wave front becomes vertical. While a universal definition of breakpoint has not been agreed, SMITH & KRAUS (1990) suggested that the point at which the wave front becomes vertical to be a practical definition.

Additionally, the depth at breakpoint is subject to broad interpretation. BLACK AND ROSENBERG (1992) discuss the influence various definitions of water depth at breakpoint may have on breaking ratios. These definitions include: the mean depth over the entire recorded time series (d_m); the mean depth over the cycle of the wave being considered (d_w); the water depth below the trough of the wave being considered (d_t). Additionally, the presence of wave groups' causes fluctuation in water level as they propagate (MEI ET AL, 1995) further complicating the above definitions. Black and Rosenberg found that the effectiveness of various established breaking criteria depends on the definition of water depth used. The authors felt that there was a need for a consistent definition of the water depth. When carrying out experiments within a laboratory wave flume, a still water level (d_s), observed without the presence of waves is a practical assumption.

Defining the breakpoint according to depth has been the subject of extensive research during the latter part of the 20th century. This point is generally defined by the ratio of breaker height (H_b) to breakpoint water depth (d_b). The point of breaking according to solitary wave theory was found to depend on initial wave steepness and beach slope. For very flat slopes, a breaking ratio of 0.78 was originally derived by MCCOWAN (1894). While this value may hold for very flat slopes, it was found to be inaccurate for steeper slopes during extensive laboratory testing of monochromatic waves by IVERSEN (1952). Based on Iversen's findings, WEGGEL (1972) derived a series of critical conditions of wave breaking based on wave steepness and beach slope. For beaches of negligible slope, this reduces to 0.78. Further experimental and field studies by GODA (1970), SMITH AND KRAUS (1990), BLACK AND ROSENBERG (1992), NELSON AND GONSALVES (1992) and others, derived breaker ratios in the range of 0.55 to 1.2.

Current design guidelines based on the works of WEGGEL (1972) present H_b/d values at breakpoint as a function of bed slope and wave steepness (Figure 1). Note the considerable scatter in the experimental data and the lines of best fit, which are also presented in current design guidelines (for example, the Coastal Engineering Manual (CEM)).

RAPP & MELVILLE (1990) observed deepwater breaking of wave groups with strong energy density convergence. They concluded that this deepwater breaking was initiated by non-linear wave interaction. More recent studies by SONG AND BANNER (2002) and BANNER AND PEIRSON (2006) show that wave group energy fluxes play a key role in the initiation of deepwater breaking.

As wave groups propagate they can be observed to undergo a graduated series of oscillations. These include; the rapid oscillation associated with the individual wave propagation, a group oscillation incorporating patterns of localised crest maxima and trough minima associated with dispersive transmission processes (refer Figure 2) and a longer term oscillation associated with non-linear intra-group interactions resulting in convergences of wave energy within the group.

This wave energy convergence is the result of outer group waves transferring their energy to central waves. Convergence of wave energy density within an evolving wave group leads to the formation of locally-steep waves. This pattern of energy convergence results in the cyclic crest maxima and trough minima increasing in amplitude until a peak is reached. If the rate of wave energy convergence exceeds a critical threshold point, breaking is initiated. This threshold has shown to be a robust predictor of the onset of deepwater wave breaking in both numerical and laboratory experiments under a wide variety of wave conditions. Numerical studies by SONG AND BANNER (2002) found that energy density evolutions could be quantified with satisfactory accuracy using only the potential energy of the waveform. This enabled experimental studies to be carried out without the complex process of resolving the kinetic energies within wave groups.

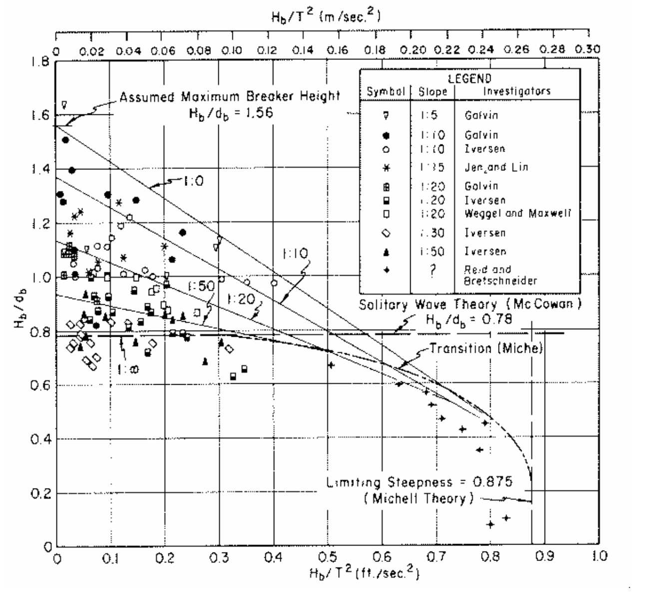

Figure 1. H_b/d_b as a function of wave steepness (WEGGEL, 1972)

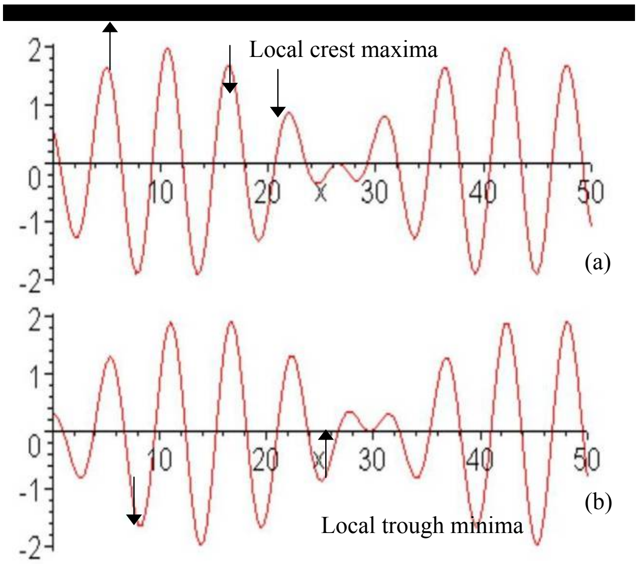

Figure 2. Examples of local crest maximum (a) and trough minimum (b) in an idealised evolving wave group.

Additional studies by SONG AND BANNER (2004) and DACK AND PEIRSON (2005) of waves breaking on horizontal beds show that while intra-wave group interactions and local energy convergence remain a key factor in initiating wave breaking, bed effects also start to have influence. These bed effects appear to stabilise the wave group, distorting the critical rate of energy convergence which dictates when breaking is initiated and enabling larger waves to occur prior to breaking.

This present study aims to expand the work of DACK AND PEIRSON (2005) on the interaction between intra-group non-linear interactions and shoaling transformations prior to breakpoint. It is anticipated that the relative phasing of these horizontal (intra-group) and vertical (shoaling) energy fluxes plays a key role in defining the breaking type, breaking position and breaker height index.

METHODS

This study aimed to test the effect of the relative phasing of an evolving wave group on shoaling and breaking on a plane slope within controlled laboratory conditions. This was achieved by generating a wave group of predetermined form at one end of a wave flume and allowing it to propagate while adjusting the bed position to regulate the relative group phasing at breakpoint.

Equipment

Laboratory experimentation was carried out in the 0.6m wave flume located at the University of New South Wales Water Research Laboratory (WRL) in Manly Vale, Sydney. The wave flume used has maximum dimensions of 30m in length by 0.6m in width and 0.9m in height. The flume has a solid bed, glass sidewalls and an open top and incorporates a synthetic absorption beach comprised of a perforated sloping bed and horsehair beach (refer Figure 3).

The paddle used to generate waves within the flume is a progressively flexible plate, fixed near the base of the flume. The paddle is fronted by a synthetic damping mat to reduce high frequency secondary waves and turbulence and is driven by a servo-controlled actuator. This setup allows precise waves and wave group structures to be generated with excellent short and long-term stability.

An adjustable plywood bed was constructed to facilitate wave shoaling and depth-limited breaking. This bed was free-moving in the horizontal axis, along the wave flume and so could be positioned at any location relative to the evolution of the wave group.

Capacitance type wave probes were used for observing the free water surface at discrete spatial locations along the flume. The experimental setup incorporated an array of six probes, configured in two in-line sets of three probes per line. The arrangement of the probes enabled repeat acquisition of wave data at any longitudinal location within the flume to an accuracy of approximately 5mm. The water surface position was recorded at a frequency of 125Hz, corresponding to readings every 0.008 seconds.

Testing of probes in static water yielded accuracies with maximum deviations of ±0.3mm and a standard deviation of 0.06mm. Linearity over the probe's 200mm range was normally ±1%.

Testing regime

The laboratory program was primarily concerned with assessing the shoaling and breaking processes of wave groups. However, to preserve a control situation, the testing regime included simulations carried out with monochromatic wave structures.

Monochromatic waves were created of specified wave height and initial wave number. Two different monochromatic wave forms were tested. These corresponded to monochromatic waves of moderate ($ak = 0.15$) and high ($ak = 0.3$) steepness where a is the wave amplitude and k is the wave number.

Following monochromatic wave testing, wave groups corresponding to the 'Case II' type waves described by SONG AND BANNER (2002) were generated and tested. The structure of these wave groups is described by Equation 1. This preliminary study incorporated only one group structure known as a recurrent group. This group converges with local crest maxima and trough minima increasing in amplitude to near breaking before diverging.

Testing of this group structure in deep water (Banner and Peirson, 2006) showed positions of maximum energy density convergence. Testing was focussed around these values, with the bed being first positioned with wave breaking occurring at a location of local crest maxima at x = 13.7m. The bed was then incrementally moved forward within the flume and testing repeated until breaking occurred at the previous location of local crest maxima. This encompassed a complete crest maxima- trough minima cycle. A summary of testing parameters is shown in Table 1.

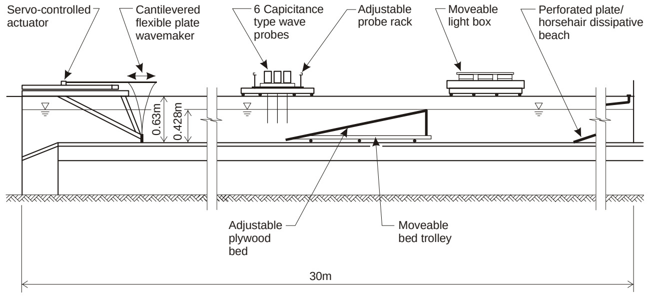

Figure 3. Wave tank elevation

$$\eta = a_o \cos(k_o x) + \varepsilon a_o \cos(\frac{N+1}{N} k_o x - \frac{\pi}{18}) \qquad (1)$$

Where

η = the surface water level deviation
a_0 = wave amplitude
k_0 = initial wave number = $2\pi/L_0$
L_0 = initial wave length = $T^2 g/2\pi$
T = wave period
x = distance in the direction of propagation from the wave paddle
ε = parameter to control group structure
N = an integer controlling the number of waves produced by the wave paddle

Table 1. Summary of testing parameters and experimental conditions

Case 2 N=5 (recurrent)		**Experiment**	**Bed Toe Position (m)**
T_1 (s)	0.6696	A	10.6
T_2 (s)	0.73656	B	10.4
T_{mean} (s)	0.70308	C	10.2
$L_{0(mean)}$ (m)	0.771	D	10.05
a_1 (m)	0.0143	E	10
a_2 (m)	0.016	F	9.8
θ_1	0	G	9.74
θ_2	0.1745	Mono(s=0.3)	10.64
Bed Slope	10:1	Mono(s=0.15)	10.64

RESULTS AND ANALYSIS

Water surface elevation as a function of time was collected for each horizontal probe position. This data was analysed to extract maximum crest and minimum trough elevations with respect to the mean water level. The minimum trough elevation was inverted giving an absolute value. Values were then non-dimensionalised with respect to the mean deepwater wavelength. Maximum crest and trough amplitudes are presented in Figures 4a and 4b with respect to absolute position within the flume as well as relative to the sloping bed crest location. Additionally, data sourced from a previous deep water study (BANNER AND PEIRSON, 2006) is included for comparison. From this maxima and minima, maximum wave height was calculated. Checks were carried out to ensure that the maximum crest and minimum trough belonged to the same wave. As the still water depth at each horizontal location was known, a maximum H/d ratio could be calculated for each position. H_{max}/d ratios at selected depths were extracted for each experimental case and are presented in Table 2.

This procedure was repeated for each incremental bed position, giving a complete data series for a full local crest maxima – trough minima group evolution cycle.

DISCUSSION

From the experimental observations of water surface position and breaker location and type, a number of trends can be noted. These include, most significantly, the emergence of two distinct shoaling cases – an *early shoaling case* and a *delayed shoaling case*.

Based on the plot of crest and trough maxima and minima (Figure 4), it can be observed that in deep water (x/Lo < ~15), the cyclic trends of wave groups tested in this study are in good

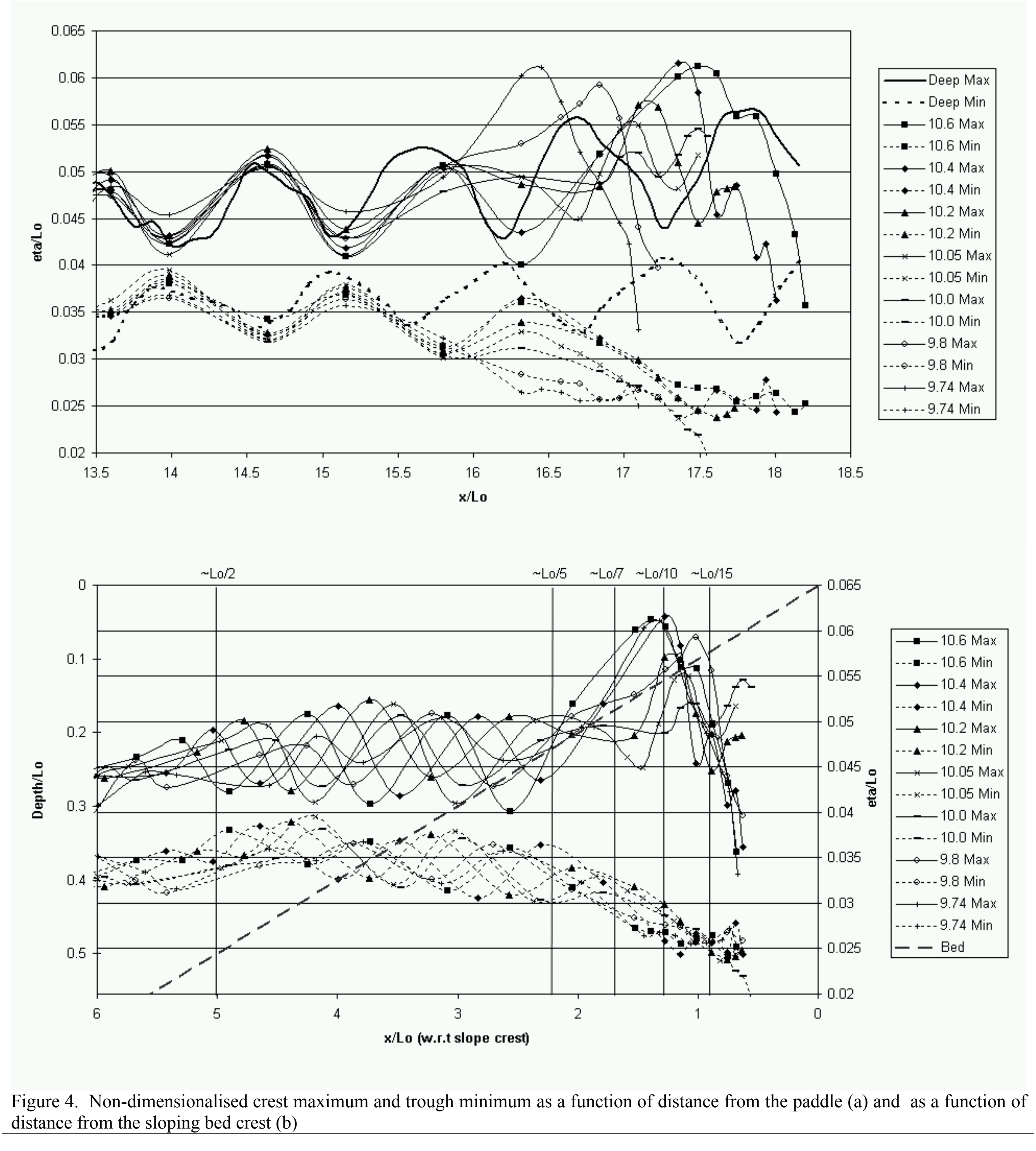

Figure 4. Non-dimensionalised crest maximum and trough minimum as a function of distance from the paddle (a) and as a function of distance from the sloping bed crest (b)

agreement with wave groups tested in previous deepwater studies. This is important as it demonstrates good repeatability and robustness of experimental method and also that reflections and other contamination which may be caused by the sloping bed are not having significant effect.

However, once the groups enter shallow water and begin to shoal at around $L_0/2$, deviations from the deep water cycle begin to occur. Primarily, the amplitudes of crest and trough maxima and minima begin to reduce, i.e. the group begins to stabilise. This may be observed at the local crest maxima at x/Lo = 15.7 – 16. This becomes more noticeable in depths less than $L_0/4$ with increased suppression of the local crest/trough maxima/minima.

Two Shoaling Cases

The relative phasing of the group (i.e. whether the group is approaching a crest maxima or trough minima) as it reaches approximately this depth appears important in determining the future evolution of the wave group. Between the depths of $L_0/5$ and $L_0/7$, groups approaching a crest maxima (i.e. experiments A, B, F and G) depart from the deep water cycle and the crest maxima continues to grow in amplitude, while the trough minima continues to decrease in amplitude. This appears to be the location where shoaling transformations replace intra-group interaction as the dominating factor influencing energy fluxes. These groups will here forth be referenced to as early shoaling groups. This state of evolution continues until breakpoint is reached.

Groups approaching a trough minima between $L_0/5$ and $L_0/7$ (i.e. experiments C, D and E) continue towards this minima before the crest increases in amplitude very rapidly prior to breaking. In these cases of phasing, it appears that the energy fluxes within the group remain dominated by intra-group interactions for longer before the shoaling process takes over. These groups will be referenced to as delayed shoaling groups.

Table 2 Maximum H/d ratios

Non-dimensional Depth	**$L_0/2$**	**$L_0/5$**	**$L_0/7$**	**$L_0/10$**	**$L_0/15$**
Depth (m)	0.385	0.154	0.11	0.077	0.051
Experiment					
A	0.16	0.42	0.62	0.82	0.90
B	0.17	0.41	0.61	0.72	1.05
C	0.17	0.41	0.58	0.77	1.10
D	0.16	0.42	0.53	0.79	1.16
E	0.16	0.40	0.54	0.79	1.15
F	0.16	0.41	0.57	0.85	1.02
G	0.15	0.41	0.61	0.77	0.89
Max difference	*0.02*	*0.02*	*0.08*	*0.13*	*0.27*
mono (steep)	0.16	0.38	0.52	0.83	N/A
mono (moderate)	0.10	0.24	0.36	0.58	1.01

Maximum H/d ratios

In deeper water, the non-dimensional Hmax/d value is governed by the state of group evolution, fluctuating depending on the crest and trough maxima cycles. At $L_0/5$, groups approaching a crest maxima have a higher H_{max}/d (refer Table 2). As the maximum wave height of these groups continues to increase as they shoal, so does their respective H_{max}/d ratios. However, between $L_0/10$ and $L_0/12$, groups which were delayed in their initial shoaling processes begin to exceed these early shoaling groups in terms of H_{max}/d. By $L_0/15$, the delayed shoaling groups have significantly higher H_{max}/d ratios.

Wave breaking properties

In all cases, the leading wave of the group as it approached breakpoint peaked offshore at a local crest maxima then decreased in amplitude before plunging in shallow water well inside the surf zone. The degree to which this wave decreased prior to breaking was dependent on the position of the last local crest maximum point with respect to the bed and the point at which shoaling becomes the dominant driver of energy convergence.

The breaking behaviour of the second wave of the group changed more significantly depending on the shoaling case approaching breakpoint. For the early shoaling cases, waves appeared to break in a spilling manner. In the case of the delayed shoaling groups, the second wave appeared to break in a plunging manner. For almost all cases, this second wave in the group was the largest breaking wave. These results infer that the type of breaking is influenced by more complex variables than simply the offshore wave steepness and bed slope and may go some way to explaining the considerable scatter observed in breaker-type diagrams.

The third wave in the groups propagated into shallower water than the second and appeared to more consistently break by plunging in all cases. Again, the size of the third wave compared to the second wave is a function of the relative phasing of the group and bed.

Breaking H/d ratios

Although breaking positions were estimated, their positional accuracy was limited as video analysis was not used comprehensively for this study. Positions of breaking are therefore approximate and small errors in defining horizontal breaking position correctly can result in large errors when defining breaking depth and H/d ratios.

Breaking H_b/d ratios are shown in Table 3. Ratios for the most offshore breaking wave of the group (in these cases, wave 2) ranged between 0.73 and 0.97. With the exception of one outlying test case (Experiment F), waves experiencing delayed shoaling typically had slightly higher H_b/d ratios to early shoaling waves, although their ratios were still, in general, lower than those predicted by the CEM or Goda design guidelines. However, the H_b/d ratio of the third wave in the group shows considerable variation, with a range of 0.9 to 1.36. The delayed shoaling groups exhibit ratios significantly in excess of either the early shoaling cases or design guidelines. Note that for Experiment C and D, breaking occurred outside the measurement area and maximum H_b/d ratios could not be obtained. For both the monochromatic wave cases, results were in reasonable agreement with design guidelines, although the CEM predicted a higher H_b/d ratio for the steeper case than was observed.

Whilst this study was intended only as a preliminary scoping study to assess whether relative phasing of group evolution has influence on shallow water breaking properties, a number of limitations were encountered. Most significant were limitations encountered when attempting to measure wave properties with high accuracy wave probes in very shallow water. These limitations resulted in measurements being truncated at quite an important position in the wave evolution process. As a consequence, some very shallow water values were not available.

Table 3: H_b/d ratios for the 2nd and 3rd breaking waves

	2nd wave			**3rd wave**		
Exp.	Exp	Goda	CEM	Exp	Goda	CEM
A	0.73	0.75	0.9	0.91	0.9	0.95
B	0.73	0.75	0.9	1.05	0.95	0.97
C	0.78	0.85	0.96	>1.18*	1.02	0.95
D	0.81	0.84	0.94	>1.13^{+}	1.07	0.95
E	0.81	0.83	0.92	1.36	1.07	0.95
F	0.97	0.92	0.96	1.02	0.95	0.98
G	0.75	0.82	0.92	0.96	0.93	0.97
Mono (steep)	0.8	0.84	0.92	-	-	-
Mono (mod)	1.03	1.02	1.01	-	-	-

* measurement did not extend into breaking position. Last recorded H_{max}/d ratio 1.18

$^{+}$ measurement did not extend into breaking position. Last recorded H_{max}/d ratio 1.13

Also, the uncertainty in defining the exact breaking location was problematic in defining exact H_b/d ratios.

Additional studies testing a greater variety of wave groups for a range of bed slopes is currently underway. Additionally, problems with measuring wave properties in very shallow water have been resolved with measurements now being extracted to the end of the bed. Video techniques for defining the precise breaking position have also been developed. Based on the results of these more comprehensive studies, more precise quantification of maximum attainable wave heights in shallow water may be possible.

CONCLUSION

This study investigated the effect of the relative phasing of an evolving wave group on shoaling and breaking on a plane slope. Results of this study showed that the relative phasing of the group (i.e. whether the group is approaching a crest maxima or trough minima) as it approached a critical depth was important in determining the future evolution of the wave group. If the group was approaching a crest maximum at this critical depth, the maximum crest elevation continued to increase and the wave group continued evolving to breaking. This condition was termed an early shoaling case. If the group was approaching a trough minimum at this critical depth, shoaling was delayed, with the crest growing rapidly in shallow water before breaking. This condition was termed delayed shoaling. A summary of early and delayed shoaling case properties is presented in Table 4.

Table 4: Summary of early and delayed shoaling properties

Property	**Early Shoaling case**	**Delayed Shoaling case**
Group evolutional phase approaching L/5	Approaching local crest maximum	Approaching local crest minimum
Experiments in this phase	A,B,F,G	C,D,E
Shoaling becomes dominant transformation mechanism	~$L_0/5$	~$L_0/7$ to $L_0/8$
Shoaling transformation	Gradual	Rapid
Primary breaker type	Spilling	Plunging
H_b/d	Lower	Higher

These preliminary results indicate that current design guidelines based on monochromatic waves may significantly underestimate the ‘worst case’ scenarios caused by wave groupiness. Additionally, random wave testing may include these group effects but can require prolonged testing periods to achieve a ‘worst case’ situation. Judicious phasing of design groups strikes a balance between these wave modes and offers more time effective method of attaining design wave conditions.

LITERATURE CITED

BANNER, M.L. AND PEIRSON, W.L., 2006. Wave Breaking Onset and Strength for Two-Dimensional Deep Water Waves. *Submitted to Journal of Fluid Mechanics*.

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

DACK, D.A.J. AND PEIRSON, W.L., 2005. Depth-Limited Wave Heights Associated with Wave Groups Propagating onto Horizontal Beds. *Proceedings of 2005 Coasts and Ports Australasian Conference* (Adelaide, Australia), pp. 197-202.

GODA, Y., 1970. A Synthesis of Breaker Indicies. *Transactions of JSCE*, 2(2), 227-230.

IVERSEN, H.W., 1952. Waves and breakers in shoaling water, *Proceedings of the 5th Coastal Engineering Conference. American Society of Civil Engineers*, pp. 1-12.

MCCOWAN, J. 1894. On the highest wave of permanent type. *Philosophical Magazine*, Series 5, 38, 351-357.

MEI, C.C., STIASSNIE, M. AND YUE, D.K.-P., 2005. *Theory and Applications of Ocean Surface Waves. Part 2: Nonlinear Aspects.* Advanced Series on Ocean Engineering, 23. World Scientific, 506 pp.

NELSON, R.C. AND GONSALVES, J., 1992. Surf zone transformation of wave height to water depth ratios. *Coastal Engineering*, 17(1-2), 49-70.

RAPP, R.J. AND MELVILLE, W.K., 1990. Laboratory Measurements of Deep-Water Breaking Waves. *Philosophical Transactions of the Royal Society of London*, 331, 735-800.

SMITH, E.R. AND KRAUS, N.C., 1991. Laboratory study of wave-breaking over bars and artificial reefs. *Journal of Waterway, Port, Coastal and Ocean Engineering*, 177, 307-325.

SONG, J.-B. AND BANNER, M.L., 2002. On Determining the Onset and Strength of Breaking for Deep Water Waves. Part I: Unforced Irrotational Wave Groups. *Journal of Physical Oceanography*, 32, 2541-2558.

SONG, J.-B. AND BANNER, M.L., 2004. Influence of Mean Water Depth and a Subsurface Sandbar on the Onset and Strength of Wave Breaking. *Journal of Physical Oceanography*, 34, 950-960.

WEGGEL, J.R., 1972. Maximum Breaker Height. *Journal of the Waterways, Harbours and Coastal Engineering Division*, 98, 529-548.