ON THE INFLUENCE OF WAVE GROUPS ON SHOALING AND BREAKING WAVES

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Determining the largest wave height *H* which can occur in water of depth *d* without breaking is a fundamental reference quantity for the design of coastal structures. The ratio of breaking height (H_b) to depth (H_b/d), is known as the breaker index and has been the subject of much research over the past 150 years. Current design guidelines are based on investigations which, predominantly used monochromatic waves, thereby neglecting group effects. Groupiness or height modulation in wave trains is inherent to the free propagation of waves in deep water. Whilst our understanding of the formation and propagation of wave groups remains limited, significant progress has recently been made in the prediction of the onset and strength of breaking of wave groups in deep water. Recent two-dimensional laboratory studies have also shown that wave group effects have a marked affect on wave shoaling and breaking, influencing both the position and form of the breaking waves. These studies have used idealised wave spectra to generate modulating wave groups which are repeatable on a characteristic wave group time scale. Some scenarios yielded breaker indices up to 35% systematically above current design guideline values.

Due to limitations of conventional wave probes when used near and within the breaking zone, a laser induced fluorescence (LIF) technique has recently been developed at the Water Research Laboratory. The technique yields high spatial and temporal resolution measurements of propagating wave forms from deep water, through the breaking region and inner surf zone. This technique has been verified using conventional capacitance wave probes and high resolution digital video images with resolution of better than 0.05mm obtained giving errors less than ±0.1 mm.

Extensive investigations using repeatable wave groups and incorporating the LIF technique have been completed for a uniform bed slope of 10:1 in which the location of a shoaling bed was incrementally adjusted along the wave tank. In this manner, the shoaling and breaking properties of individual waves within the group could be carefully examined. It was observed that, as a wave group encounters a sloping bed, the behavior of the shoaling wave group is critically affected by the spatial phasing of the group relative to the bed. A critical depth between $L_0/5 > d > L_0/8$, where L_0 is the deepwater wavelength, has emerged as the primary factor delineating two types of group shoaling. When a wave crest is coincident with the group energy maximum at this critical location, wave breaking tends to occur earlier, in deeper water and in a more gentle manner. However, where there is coincidence of a wave trough with the group energy maximum at this depth, *delayed shoaling* is observed. Notably, delayed shoaling stabilises the waves within the group, delaying the initiation of breaking and can yield H_b/d ratios up to 38% greater than present design guidelines. Our results show that present design guidelines based primarily on monochromatic waves are not conservative when wave group effects are considered.

INTRODUCTION

The stability of coastal structures is critically dependent on the height of the impacting incident waves. For example, the unit mass of rock armour specified by design codes based on the Hudson formula (USACE, 2003) exhibits a wave height cubed dependency. Conventionally, design is based on the maximum wave height which can be achieved in water of limited depth.

Defining this maximum wave height has been the subject of several

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significant investigations over the past century. McCowan (1894) theoretically derived a maximum wave height on depth ratio (the so-called *breaker index*) prior to breaking of 0.78 above flat beds. A constant value of the *breaker index* was found to be inadequate on steeper slopes by Iversen (1952). Subsequent studies by Galvin (1969), Goda (1970), Weggel (1972) and Smith and Kraus (1990) further refined breaker index values for waves and beds of varying steepness and slope, with Weggel (1972) producing design curves based on his own and earlier published investigations (Figure 1). These studies form the basis of modern design guidelines (Goda, 2000 and USACE, 2003) which define the breaker index according to wave steepness (height and length or period) and bed slope (see also Rattanapitikon and Shibayama, 2000).

The original raw measurement data (Figure 1) show significant scatter, with data points evident above the recommended design curves although, in the absence of turbulent perturbations, monochromatic waves should always break consistently in the same manner and in the same location. Goda (2007) identifies an inherent variability in wave breaking and breaker index of 6 to 14% depending on bed slope with steeper slopes exhibiting greater scatter.

Additionally, there are a number of intrinsic problems associated with the application of these guidelines. These include the definitions of both the wave break point and the depth at breakpoint (Shand *et al.*, 2007) and, perhaps most crucially, that these investigations have tended to focus on idealised wave trains consisting of regular, monochromatic waves therefore neglected possible group or irregular wave effects.

Effects of irregular waves are discussed by Goda (2007), with the indices for regular waves suggested as an upper limit. A further difficulty is that a statistical measure of wave height must be employed for analysis of irregular waves. Goda found ratios based on significant wave height (H_{sig}/d) were approximately 30% lower than for regular waves at the outer boundary of the surf zone.

Monochromatic water waves are inherently unstable due to sideband frequency instabilities and wave trains must, over time and space, form groups (Benjamin and Feir, 1967; Hwung and Chiang, 2005). Recent studies have highlighted the role of wave groups in deepwater wave breaking due to convergences in wave energy density (Rapp and Melville, 1990; Song and Banner, 2002; Banner and Peirson, 2007). These convergences are inherent to the groups themselves rather than due to depth or subsurface current effects.

Such fluctuations have also been found to influence breaking properties in shallow water (Peirson et al, 2007; Shand et al, 2007). Using idealised group spectra and by judicious selecting the spatial phasing of group evolution relative to shoaling, breaker indices up to 35 and 27% higher than design guidelines were observed on 5:1 and 10:1 sloped beds respectively.

A number of experimental limitations were identified, principally related to the use of spatially discrete capacitance wire wave probes. Wave breaking, as defined by the front wave face becoming vertical, could not be accurately determined. Instead the position of maximum wave height was used to define the break point, along with the depth at that point according to still water level. Additionally, due to the intrusive nature of measurements, instrument distortions and disturbances to the underlying waveform were possible and there were significant difficulties in measuring broken waves within the surf zone.

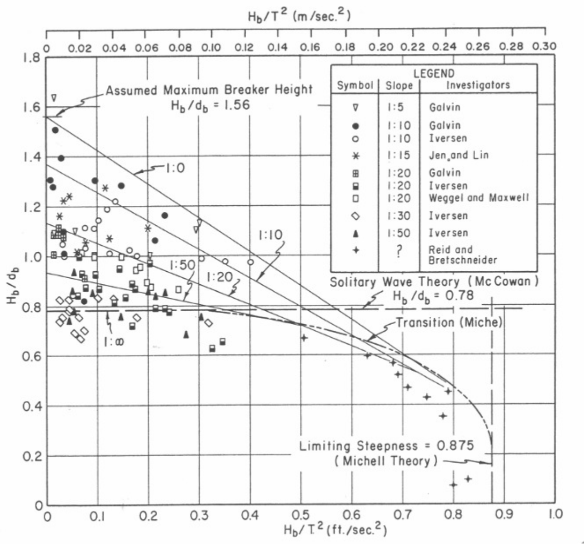


Figure 1. H_b/d_b ratios as a function of wave steepness and bed slope. Curves of best fit form the basis of modern design guidelines. (Weggel, 1972)

These limitations in the application of capacitance and resistance type probes to wave breaking measurements are well recognised. They remain however, the most widely used laboratory instrumentation due to their low cost and ease of use. More recently, ultrasonic sensors have provided an alternative and unintrusive measurement but they have significant limitations when measuring highly curved surfaces and steep waveforms within the rapidly evolving breaking and surf zones. Both types of instruments provide only a discrete spatial point measurements.

More recently, with the availability of high resolution and affordable CCD cameras, optical techniques have been developed (Govender and Mocke, 2002; She and Cannings, 2007). These techniques visualise the flow at the tank sidewalls, allowing more complete descriptions of the evolving surface. However, additional problems such sidewall meniscus effects and direct sidewall influence on the waveform limit the accuracy of such techniques. Mukto et al (2007), Kimmoun and Branger (2007) and Sue et al (2007) use laser sheets to illuminate a section of profile within the centre of the tank thus removing sidewall problems. However, these techniques have tended to be limited to deepwater where a shallow bed does not obstruct an upwardly directed laser sheet or, in the case of Sue et al (2007) where a downward directed sheet is employed, to slowly evolving waveforms.

This present study uses a new and novel technique to capture the water surface position continually during wave shoaling, breaking and within the surf zone. This technique is used to examine the influence of deep water wave group evolution on the breaking process and possible implications for the existing breaker index guidelines.

METHODOLOGY

Testing facilities

Laboratory experimentation was carried out at Water Research Laboratory (WRL) in Manly Vale, Sydney. A wave tank was used with dimensions of 30m in length by 0.6m in width and 0.9m in height. The tank has a solid bed, glass sidewalls and incorporates a synthetic absorption beach comprised of a perforated sloping bed and horsehair beach (Figure 2).

The paddle used to generate waves within the tank is a flexible, cantilevered plate, fixed near the base of the tank (Banner and Peirson, 2007). 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 tank and so could be positioned at any location relative to the evolution of the wave group to an accuracy of approximately 5 mm.

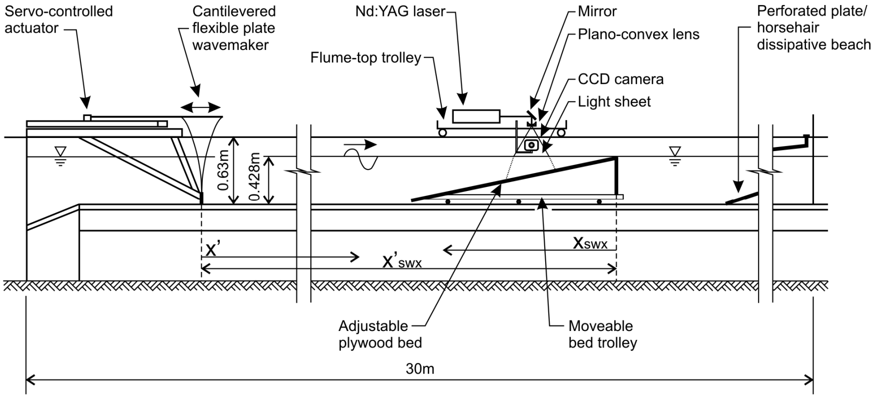


Figure 2. Schematic diagram of the experimental setup and reference notation.

Optical technique

A pulsed light sheet, orientated along and in the centre of the tank is produced by a high powered Nd:YAG laser system and plano-concave lens to form a light sheet approximately 3 mm by 120 mm along the tank centre line. The water is dosed with Rhodamine WT fluorescent dye and, once excited by the laser pulse, a sharp optical interface at the free-surface can be viewed obliquely.

A CCD camera is positioned outside the tank and slightly above the free surface ensuring the meniscus did not obscure the view of the laser sheet during any phases of wave-cycle. The free-surface is captured over a length of approximately 100 mm (Figure 3) before the camera and laser, mounted on a trolley, is redeployed along the tank and the process repeated.

The surface is then detected using a two-stage algorithm. First, a region of interest is established at the free surface excluding spurious splashes, reflections or intensity dropout. The surface is then determined to sub-pixel resolution using the intensity gradient. Corrections are applied for camera lens and perspective distortions (i.e. images are rectified to a vertical plane and georeferenced) and for laser sheet geometric variations. Surface resolution is found to 0.2 pixels (0.05 mm) with accuracy estimated at ±0.45 pixels (0.11 mm). Comparison to capacitance probes in deepwater shows agreement in measured wave heights to within 2%.

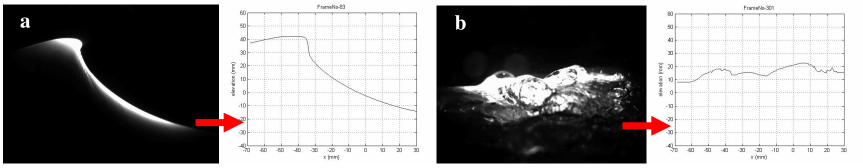


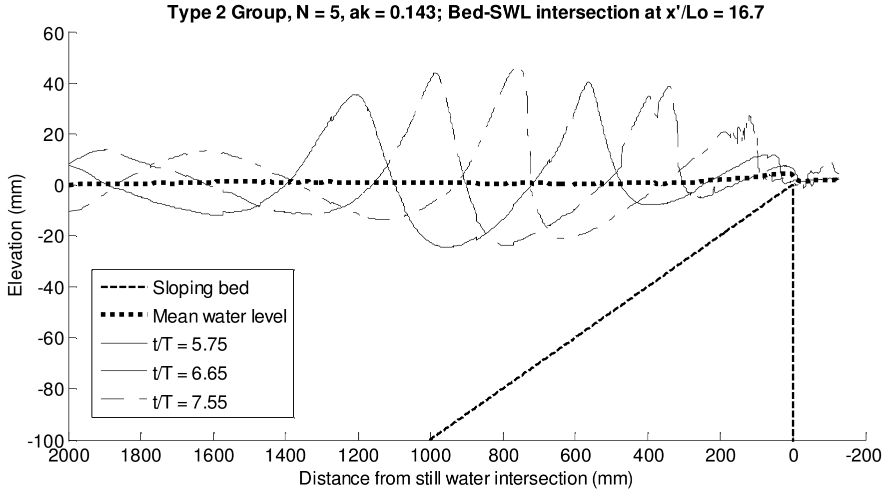
Figure 3. Examples of surface profile detection at breakpoint (a) and within the surf zone (b)

Due to the repeatability of the groups being generated, adjacent video series can be phased relative to one another and their profile series combined (Figure 4). This exemplary figure depicts the free surface at three instants in time, with waveforms observed to shoal to breakpoint, splash-up following breaking and propagate through the surf zone as a near vertically faced bore. A record of this type is valuable for examining detailed aspects of wave shoaling including wave-length/number evolution, breaking and post-breaking behavior and may have many future applications including numerical model calibration and verification. Additionally to profile analysis, time-series at any spatial locations, analogous of capacitance probes or pressure transducers may also be extracted.

Testing regime

Initial testing using this new methodology for data abstraction was restricted to three monochromatic wave structures to provide control situations and an idealised group spectra. This group spectra consists of two discrete frequency bands selected to ensure group modulation and the production of repeatable groups. This repeatability enables testing to incorporate group effects without the need for long testing regimes often required to characterise group behavior.

Monochromatic waves were produced using pre-specified wave heights and length. The three different monochromatic wave forms tested corresponded to waves of low (*H/Lo* = 0.035), moderate (*H/Lo* = 0.07) and high (*H/Lo* = 0.09) steepness where *H* and Lo are the deepwater wave height and length.



Type 2 Group, N = 5, ak = 0.143; Bed-SWL intersection at x'/Lo = 16.7

Figure 4. Examples of profile series obtained by combining individual video records

The wave group structures used correspond to the 'Case II' type waves as described by Song and Banner (2002). In deepwater, the maximum and minimum (z_{max} and z_{min}) elevations of the group envelope can be observed to fluctuate between alternative positions of local maxima or minima (refer Figure 5). These occur when a wave crest or trough is coincident with the group envelope maximum and represent positions of maximum local energy density convergence. The amplitude of these local maxima and minima can be observed to increase with distance along the tank as the non-linearity within the envelope increases until either a point of recurrence or breaking is reached, after which local maxima and minima amplitudes decrease. Wave steepness was selected to produce a recurrent type group, with testing focused around the positions of maximum energy density convergence.

The position of the sloping bed is first selected with the bed-swl intersection (x'_{swx}) located coincident with a local trough minima point (as observed in deepwater) at x/Lo=16.55. Following data acquisition, the sloping bed is moved incrementally along the tank. This enables the spatial phase of the group evolution relative to the initiation of shoaling to be incrementally adjusted and differences in shoaling and breaking patterns observed. The bed was moved in increments of 0.1 m or approximately 0.12Lo with a total of 11 positions over 1.0 m (or ~1.2Lo) captured. As this range captured more than a complete minima to minima cycle around the location of most highly grouped behaviour, it is likely to capture the most important scenario.

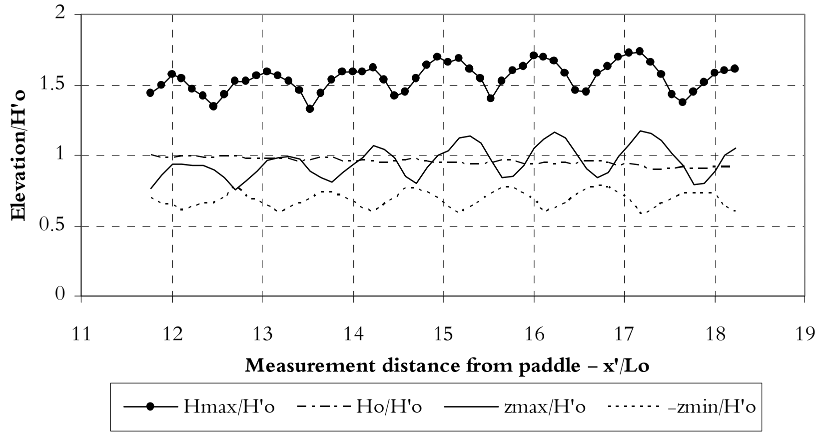


Figure 5. Deepwater wave evolution of a Case 2, N=5, recurrent-type group as a function of the initial, energy-based significant wave height (H'o). Note that measurements were taken without the sloping bed in place.

RESULTS AND DISCUSSION

Key information including the maximum wave height (H_{max}), maximum crest and minimum trough elevations (z_{max}, z_{min}), the energy-based significant wave height ($Ho=4\sqrt{\eta^2}$), the mean water level (mwl), and H_{max}/d ratio are extracted at a spatial resolution of 10 mm. The position and manner of wave breaking was also recorded for each wave within the group allowing evaluation of H_b/d with respect to still or mean water level.

Shoaling patterns

Differences in the shoaling patterns of the maximum wave height, maximum crest elevation and minimum trough elevation are evident within these data as the group phasing is varied relative to the shoaling region. Figure 6 illustrates the evolution of the H_{max}/d_{mwl} ratio as a function of water depth and changes in the bed position. At d=Lo/7, groups nearer a position of local crest maxima (those nearer the centre of the plot) have a higher maximum wave height and therefore a higher H_{max}/d_{mwl} index compared to those nearer a local trough minima (those nearer the edge of the plot). However, the groups nearer a crest maxima at this point tend to exhibit less growth in H_{max}/d_{mwl} as they continue to shoal compared to those groups nearer a trough minima whose H_{max}/d_{mwl} ratios increase dramatically in shallower water. Extreme examples of these differences occur with the bed-swl intersection located at x'_{swx} /Lo = 16.65, 17.2 and 17.7 from the paddle and these cases will be examined in greater detail.

The shoaling transformations of the group crest and trough maximums are examined in Figure 7. In deeper water of around $d=L_0/3.5$, while the phasing of $x'_{swx} = 17.2$ (nearing a local maximum) is opposite to $x'_{swx} = 16.65$ and 17.7 (nearing a local minimum), they both largely follow the deepwater record. As they move into shallower water, their evolution patterns deviate from that observed in deepwater as they begin to interact with the bed and the dispersive processes slow. While $x'_{swx} = 16.65$ and 17.7 reach a position of local maxima at around $d=L_0/5$, they continue to another position of local minima at around $d=L_0/6.5$ before increasing rapidly to a maximum at $d=L_0/10$. In contrast, $x'_{swx} = 17.2$ reaches a position of local maxima at around $d=L_0/6$ after which it continues to shoal to a maximum at around $d= L_0/7$. Shand et al (2007) termed these respective patterns *delayed* and *early* shoaling.

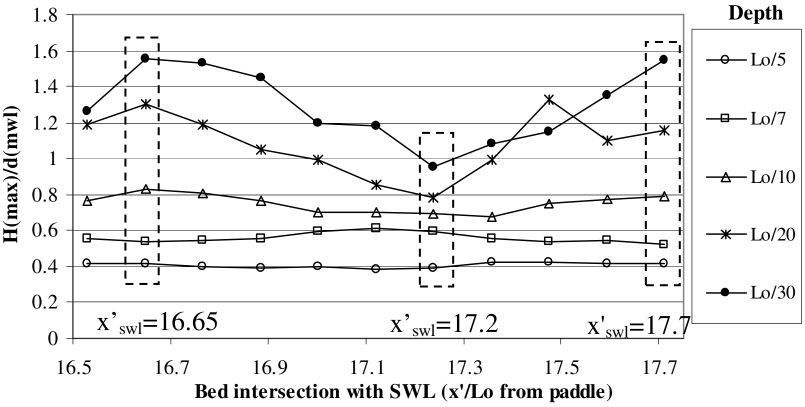


Figure 6. Evolution of the H_{max}/d_{mwl} ratio as a function of depth and group phasing

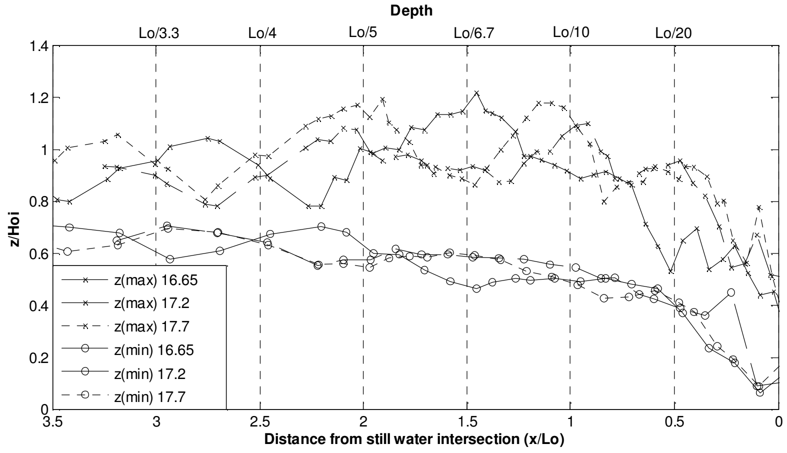


Figure 7. Differences in the shoaling patterns of the group maximum and minimum dependent on the group evolutional phase as shoaling in initiated.

Wave breaking

The breaking position may be with respect to either distance from the bed-swl intersection (x_{swx}) or absolute distance from the paddle (x'). A true monochromatic or solitary wave would be expected to break in the same location relative to the bed regardless of bed position, whereas a wave breaking due to convergent group processes such as shown in Figure 5 would be expected to break in a constant absolute position, dependent only on the group evolution.

Figure 8 depicts the breaking position of the three largest waves within the group as defined by BP1, BP2 and BP3. While wave 1 and, to a lesser extent wave 3, break in relatively consistent locations with respect to the bed-swl intersection, wave 2 moves uniformly offshore. This implies that it breaks in a consistent absolute position before a critical depth is reached, in this case ~Lo/6, after which breaking cannot occur and the wave propagates inshore to break in a 'depth-limited' environment. This indicates a preference for the certain waves coincident with the group envelope maxima to continue to break on predefined points of local group maxima, approximately regardless of bed position, whilst other waves within the same group break in a more depth-limited fashion.

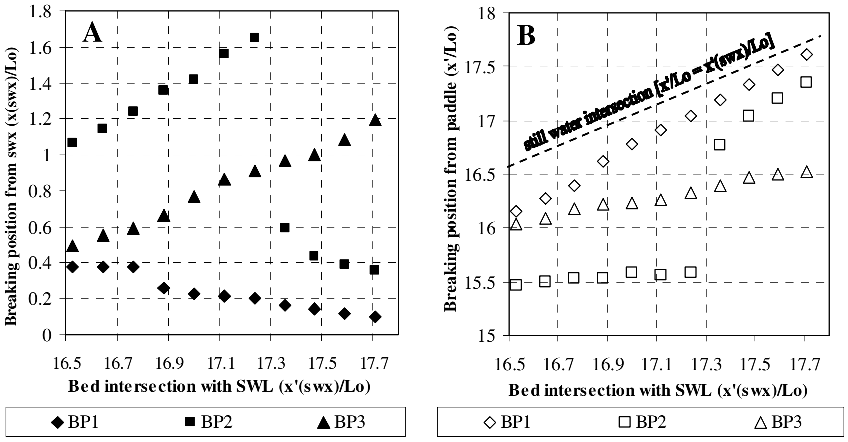


Figure 8. Wave breaking location with reference to the bed-swl intersection (A) or absolute position within the tank (B). Note the near constant absolute breaking position of wave 2 (BP2) in (B) before a rapid shift in location.

As the breaking position relative to the bed-swl intersection changes, the breaking type is also observed to vary (Figure 9). Waves shoaling more gradually and reaching a maximum further offshore (x'_{swx} = 17.2 – early shoaling) tend to break in a more gentle, spilling manner, while waves shoaling more rapidly, in shallower water (x'_{swx} = 16.65 and 17.7 – delayed shoaling), break in a more violent plunging fashion. This implies that variation in the breaking type is possible, even with identical offshore wave steepness and bed slope.

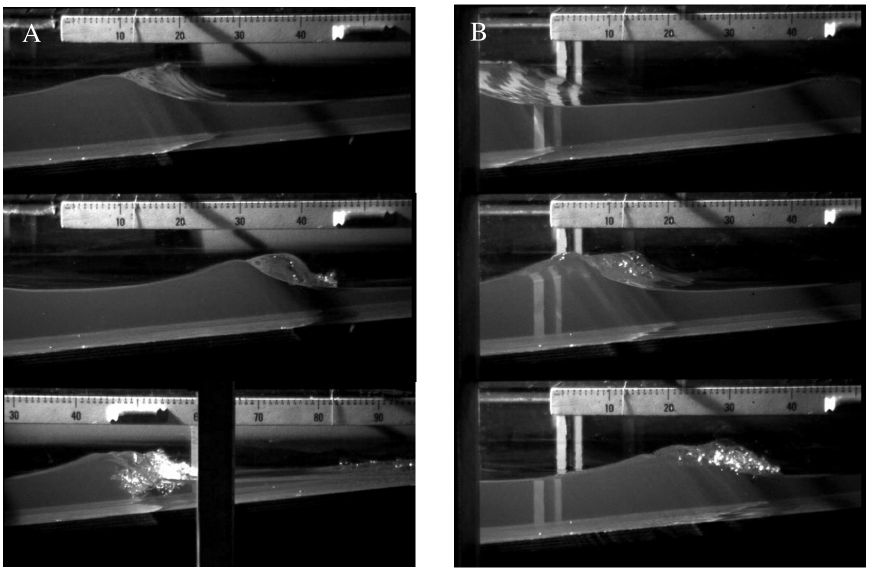


Figure 9. Breaking pattern for (A) $X'_{swx} = 16.65$ **(delayed shoaling) and (B)** $X'_{swx} = 17.5$ **(early shoaling)**

Breaker indices

As breaking position and depth changes, so does the breaker index. Figure 10 presents the breaking wave height and H_b/d_{mwl} ratios for the three largest waves within the groups as a function of varying bed position. Breaker indices found for monochromatic waves and those recommended by design guides are also included. Depth according to mean water level (mwl) is used in preference to still water level (swl) as d_{swl} neglects setup within the surf zone and so results in unrealistically high indices in the inner surf zone. This discrepancy remains a problem when using existing guidelines, with setup contributions to water level within the surf zone often unaccounted for.

The dispersive nature of the wave groups is evident with the breaking height of the first wave (BP1) decreasing as the bed (and consequently the group) is moved further away from the paddle. The height of the second wave (BP2) increases to a maximum before abruptly decreasing when breaking ceases to occurs at a position of local maxima, as discussed above, and the breakpoint of that wave moves further inshore The third wave (BP3) increases in height as it acquires energy and replaces the second wave as the largest within the group.

The values of wave height and breaking index for waves two and three on the right hand side of the figure near match those of wave one and two on the left hand side illustrating the cyclic nature of this process.

Under certain group phasings, breaker indices exceed those recommended by the design guides. In particular, BP1 tends to exceed guidelines for most bed positions. This wave however, tends to be the smallest of the three, and breaks well inside the following two in relatively shallow water. Possible explanations include the effects of long waves beneath the group which may temporarily elevate water level above the recorded mean. This again would illustrate problems with defining breaker depth.

Of the larger waves, the cases related to delayed shoaling, as discussed earlier, show breaker indices above the design guides and monochromatic wave values. These guideline values are exceeded for certain scenarios by up to 38%. In the case of the early shoaling group, both indices are typically below either the design guides or monochromatic waves.

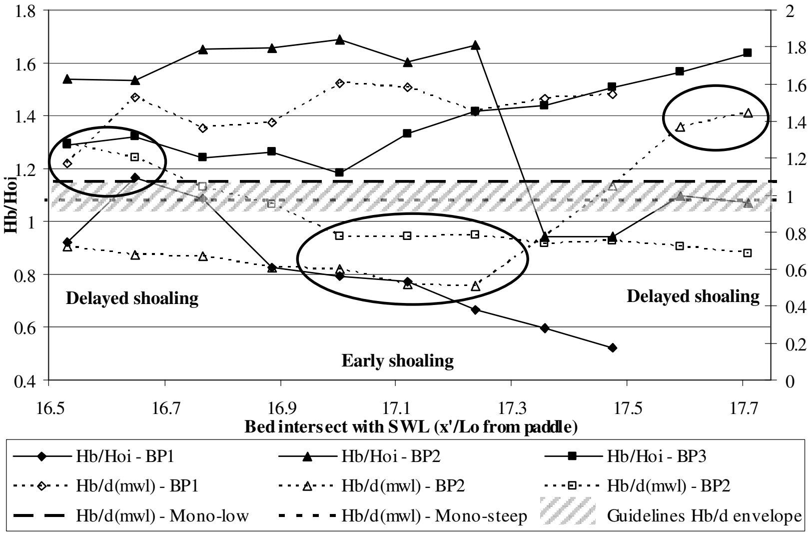


Figure 10. Breaking wave height and breaker index for the three largest waves within the group as a function of bed position, along with monochromatic and design guideline values.

This result shows a scatter in breaker index points for otherwise consistent offshore wave steepness and bed slope. However, a *worst case* scenario can be identified, and has the potential to be used in laboratory testing as a design case, thus removing the long testing regimes that irregular wave testing require to statistically achieve such extreme conditions.

CONCLUSIONS AND RECOMMENDATIONS

A new optical method for obtaining wave measurements within the laboratory has been developed by the authors enabling complete spatial descriptions of the free surface at high temporal resolution. This method has shown good agreement with conventional measurement techniques under low wave conditions and provided far superior performance within the steep breaking region and surf zone.

Using this method, key values of wave height, crest and trough amplitudes, and mean water levels are obtained for judiciously selected phasing of group evolution with respect to the initiation of shoaling.

By altering the phasing in this manner, variations in the shoaling and breaking properties of the group are observed. Results show that in spite of the groups breaking in ‘shallow’ water, deepwater processes continue have influence, with breaking occurring preferentially in locations where a wave crest is coincident with the group envelope maximum. At the extremes, groups approaching a position of local crest maxima at around $d=L_0/7$ continue to shoal to breaking in relatively deep water and in a more gentle spilling manner. Groups approaching a local trough minima at this depth however, experience a delay in shoaling, with breaking occurring in shallower water and in a plunging manner.

These two types of shoaling have been referred to as early and delayed shoaling cases. Due to differences in breaking position, variation in their respective breaker indices are also noted with early shoaling cases tending to exhibit breaker indices below that of monochromatic waves or design guides and delayed shoaling cases exhibiting indices above. In some cases, breaker indices up to 38% above design guides are observed, in good agreement with results of earlier studies.

The maximum wave height that can occur under depth limited conditions or breaker index, is defined by the existing design guidelines as a function of wave steepness and bed slope only. Our present results show that wave group processes induce significant fluctuation in breaking properties and consequently breaker index. This indicates that caution should be taken when using these parameters alone to classify breaker index or breaker type.

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REFERENCES

Banner, M. L. and W. L. Peirson (2007). Wave Breaking Onset and Strength for Two-Dimensional Deep Water Waves. J. *of Fluid Mech.* 585: 93-115.

Benjamin, T. B. and J. E. Feir (1967). The disintegration of wave trains on deep water. Part 1: Theory. J. *of Fluid Mech.* 27(3): 417-430.

Galvin, C. J. (1969). Breaker travel and choice of design wave height. *Journal of Waterways and Harbors Division* 95: 175-200.

Goda, Y. (1970). A Synthesis of Breaker Indices. *Transactions of JSCE* 2(2): 227-230.

Goda, Y. (2000). *Random Seas and Design of Maritime Structures*. Singapore, World Scientific Publishing Co. Pty. Ltd.

Goda, Y. (2007). Reanalysis of regular and random breaking wave statistics. *54th Japanese Coastal Engineering Conference*.

Govender, K., G. P. Mocke, et al. (2002). Video-imaged surf zone wave and roller structures and flow fields. *Journal of Geophysical Research* 107(0): 1-21

Hwung, H.-H. and W.-S. Chiang (2005). Measurements of wave modulation and breaking. *Measurement Science and Technology* 16: 1921-1928.

Iversen, H. W. (1952). Waves and breakers in shoaling water. *Proceedings of the 5th Coastal Engineering Conference*, American Society of Civil Engineers.

Kimmoun, O. and H. Branger (2007). A particle image velocimetry investigation on laboratory surf-zone breaking waves over a sloping beach. J. *of Fluid Mech.* 588: 353-397.

McCowan (1894). On the highest wave of permanent type. *Philosophical Magazine Series* 5(38): 351-357.

Mukto, M. A., M. A. Atmane, et al. (2007). A Particle-Image Based Wave Profile Measurement Technique. *Experiments in Fluids* 42: 131-142.

Peirson, W. L., T. D. Shand, et al. (2007). Augmentation of depth-limited wave heights within groups propagating onto offshore slopes of 1V:5H. *Australasian Coasts and Ports Conference*, Melbourne, Australia.

Rapp, R. J. and W. K. Melville (1990). Laboratory Measurements of Deep-Water Breaking Waves. *Phil. Transactions of the Royal Society of London* 331: 735-800.

Rattanapitikon, W. and T. Shibayama (2000). Verification and modication of breaker height formulas. *Coastal Engineering Journal* 42(4): 389-406.

Shand, T. D., W. L. Peirson, et al. (2007). Wave Group Effects on Breaker Height on a Uniform Slope. *Journal of Coastal Research* SI50: 767-772.

She, K. and P. Cannings (2007). Geometric Study of Monochromatic Wave Breaking on Beaches. *Journal of Waterway, Port, Coastal and Ocean Engineering* 133(5): 334-342

Smith, E. R. and N. C. Kraus (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 M. L. Banner (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.

Sue, L. P., R. I. Nokes, et al. (2007). Modelling of Underwater Landslide Induced Tsunami. *Australasian Coasts and Ports Conf.*, Melbourne, Australia.

USACE (2003). *Coastal Engineering Manual.*

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