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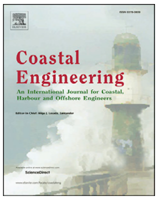

On the influence of wave breaking on the height limits of two-dimensional wave groups propagating in uniform intermediate depth water

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ABSTRACT

The empirical non-dimensionalisation of Nelson (1994) for determining wave height limits are critically reviewed using data assembled from recent studies of wave groups propagating in water of constant depth in the laboratory. The limiting wave height to water depth ratios of marginally breaking deep and intermediate water waves remain within 10% of Nelson's values. However, it is shown that the effect of wave grouping can produce waves in shallower water that are at least 30% greater in height than the limit proposed by Nelson (1994). The present study supports use of limits based on McCowan (1894) and Miche (1944) for coastal engineering design for marginal breaking waves and strongly-breaking deep water waves. Three-dimensional and more strongly breaking waves in shallower water may yield wave heights higher than those measured during this study.

The present study provides more robust and universal characterisation of breaking in transitional water than previously determined by geometric wave observations. Using the same measurement techniques as those of Saket et al. (2017), we have investigated the breaking threshold proposed by Barthelemy et al. (2018) but for different classes of unforced unidirectional wave groups in intermediate water depths. The threshold parameter $B_x = U_s/C$ (where U_s is the horizontal surface water particle velocity at the wave crest and C is the wave crest point speed) which distinguishes breaking from non-breaking waves was found to be 0.835 ± 0.005 with the experimental uncertainty of each data point of ± 0.020. This threshold is applicable to water depth to wavelength ratios as low as 0.2 including the deep water conditions investigated by Saket et al. (2017). No dependence on peak spectral wavenumber was found.

1. Introduction

Waves at the transition to breaking are the critical design condition for marine and coastal structures (Silvester, 1974, *p.* 379*ff*). The quest to determine a reliable means of determining the onset of wave breaking has spanned 135 years since Stokes (1880) developed the first theoretical prediction of wave breaking. Over the past half century, many criteria have been proposed to determine the onset of wave breaking in intermediate water (wavelengths between twice to 25 times the depth) with major contributions by Iversen (1952), Galvin (1969), Goda (1970), Weggel (1972) and Nelson (1994).

Based on local wave properties, theoretical criteria for the onset of breaking can be segregated into three categories: kinematic, dynamic and geometric criteria (Wu and Nepf, 2002). Although the kinematic breaking criterion or geometric wave properties have been traditionally used as indicators of breaking onset in deep or shallow water, these criteria have largely failed and are not universally applicable (Melville, 1994; Banner and Peirson, 2007; Perlin et al., 2013). Dynamic criteria based on energy flux rates show more promising ability in characterising the onset of wave breaking (Song and Banner, 2002; Banner and Peirson, 2007; Tian et al., 2008; Perlin et al., 2013; Derakhti and Kirby, 2016).

Barthelemy et al. (2018) have recently proposed a breaking onset threshold based on a local threshold of wave energy flux in the crest region of a steep wave using numerical simulations of fully-nonlinear 2D and 3D wave packets in deep and intermediate water. For unforced water surfaces, this threshold can be defined as $B_x = U_s/C$ and maximises at the surface. Here, U_s is the horizontal water surface particle speed in the wave propagation direction (x) and C is the wave crest point speed. Once the ratio B_x at the wave crest point (used interchangeably with the 'crest maximum elevation' throughout this paper) exceeds a critical threshold,

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the wave will progress to a breaking state. With a value of 0.855 ± 0.005, Barthelemy et al.'s threshold was found to be robust for long- and short-crested waves from deep to intermediate water for so-called Class 3 waves (chirped, focussing wave packets, Song and Banner, 2002).

Saket et al. (2017) investigated the breaking onset threshold of Barthelemy et al. (2018) in the laboratory for two-dimensional unforced and wind-forced wave groups in deep water. Both Class 3 and Class 2 (wave groups developing due to sideband instabilities) were investigated. Using a state-of-the-art thermal image velocimetry (TIV) technique to measure the velocity in the surface skin, they found that the threshold for the onset of breaking was 0.840 with an experimental uncertainty of ±0.016 and robust for different classes of waves in the absence and presence of wind.

Seiffert and Ducrozet (2016) examined numerically the breaking parameter proposed by Barthelemy et al. (2018) for modulated, chirped and random waves in deep water. They found that the onset of breaking threshold to be robust for different types of wave groups with a value between 0.84 and 0.86.

The so-called breaker index $(H/d)_b$ (CERC, 1984) is fundamental to coastal engineering design methods and has been extensively investigated for waves propagating over horizontal beds. Here, H is the wave height, d is the mean water depth and the subscript b denotes the value at breaking. Theoretical calculation by McCowan (1894) showed that the maximum value of H/d prior to breaking of a solitary wave in shallow water is 0.78, which is commonly used in coastal engineering design for horizontal and very gentle bed slopes. Miche (1944) theoretically showed that the limiting wave steepness at breaking (H_b/λ_b) in intermediate water depth could be approximated using:

$$\frac{H_b}{\lambda_b} = 0.142 \tanh\left(\frac{2\pi d_b}{\lambda_b}\right), \tag{1.1}$$

where λ is wavelength. Beyond the limit (H_b/λ_b), wave breaking will occur. Yamada et al. (1968) revised the value determined by McCowan (1894) to be 0.8261 (Goda, 2010). More recent theoretical investigations for steady waves are presented in Longuet-Higgins and Fox (1996). Weggel (1972) used monochromatic waves to investigate experimentally wave breaking as a function of wave steepness and submerged beach slopes and developed a suite of design curves. Experimentally, he found a breaker index of 0.78 in transitional water of constant depth. Further major laboratory studies and field observations on steeper slope showed that in shallow water the breaker index depends on the steepness and beach slope (Iversen, 1952; Galvin, 1969; Goda, 1970; Weggel, 1972; Nelson, 1994).

Extensive work in the laboratory and in the field by Nelson (1985, 1994) found that the maximum wave height to water depth ratio for shallow water waves propagating over a horizontal bed could not exceed the value of 0.55. The differences between the findings of Weggel (1972) and Nelson (1994) are perplexing and remain controversial. Based on his experimental results, Nelson (1994) proposed a relationship to predict the limiting wave heights using a non-dimensional parameter F_c as follows:

$$(H/d)_{\max} = \frac{F_c}{22 + 1.82F_c} \tag{1.2}$$

F_c was adopted from Swart and Loubser (1979) and is defined as:

$$F_c = \frac{g^{1.25} H^{0.5} T^{2.5}}{d^{1.75}} \tag{1.3}$$

where g is the acceleration due to gravity and T is the wave period. Riedel and Byrne (1986) carried out a laboratory investigation using monochromatic and random trains over a horizontal bed flume. Their experimental study showed that the values of $(H/d)_b$ ranged from 0.44 to 0.54 with F_c between 49 and 150 for random waves and the largest value was 0.54 with $F_c = 150$. They concluded that the limiting ratio of 0.55 proposed by Nelson (1985) applies equally well to random waves. Note that their experiments were conducted in intermediate water depth and their measured value of H/d actually exceeded Nelson's curve by up to 15%. Gourlay (1994) measured the transformation of regular waves over a laboratory model of a coral reef. It was found that the largest wave height to water depth ratio never exceeds 0.55 for shallow water waves and the limiting wave height increases by increasing F_c or the bed slope. Massel (1996) evaluated the maximum possible wave height limit over a horizontal bed theoretically in intermediate water depths using monochromatic waves. The maximum wave height was found to be less than $0.6d$ which was seen as being in agreement with the limit proposed by Nelson (1994).

Dack and Peirson (2005) investigated whether the spatial development of wave groups can influence the breaker index. They carried out a laboratory experiment to investigate the breaker indices of uni-directional bimodal group waves propagating above a horizontal bed. They found a maximum breaking wave height to water depth ratio that exceeded Nelson's curve by 22%. They concluded that the intra-wave group interactions can play a key role in determining the initiation of wave breaking in intermediate water. Recently, Barthelemy et al. (2013) numerically extended this work using chirped wave groups propagating over a flat bed and found the value of $(H/d)_{\max} = 0.605$.

Given the developing support for the dynamically-based threshold for the onset of breaking proposed by Barthelemy et al. (2018), the present laboratory investigation has systematically investigated the onset of breaking of water wave groups propagating in intermediate and constant depth. The impact of wave groups on the breaker index is examined using both spatially-focussed and bimodal wave groups propagating over a horizontal bed. The implications for breaker-index-type characterisations have been quantified.

This present contribution is structured as follows. In Section 2 we describe the experimental methods used. The results are discussed in Section 3. We conclude with recommendations for engineering design.

2. Methodology

The experiments were carried out in the two-dimensional wave tank that was 30 m long, 0.6 m wide and 0.6 m deep with glass sidewalls and a solid floor located at UNSW Sydney, Water Research Laboratory (WRL) in Manly Vale, Australia. The tank configuration was identical to that used by Saket et al. (2017), except that the flexible wave paddle was replaced with a piston paddle system for intermediate depth conditions (Fig. 1). Three water depths $d = 0.35$ m, $d = 0.22$ m and $d = 0.19$ m were selected to generate intermediate depth water waves. The change in depth created the possibility of reflections from a sluice gate behind the paddle. To minimise the reflections from the sluice gate behind the paddle, flexible reticulated polyester-urethane foam was positioned between the paddle and the gate. The tunnel roof height above was reduced to 0.12 m for optical reasons and used as the support of the measurement apparatus. No wind was used during the present study, so that the fan and the honeycomb flow guide used by Saket et al. (2017) were removed from the tunnel. Otherwise, all configurations, dimensions and distances were identical to those of Saket et al. (2017).

The thermal image velocimetry technique developed by Saket et al. (2016) was used to measure the horizontal water particle velocities U_s at the crests of waves transitioning through the group maximum. The entire TIV system consisted of a thermal imaging camera, an irradiating source, a computer-controlled shutter, and a computer controlling the system components. Its operation is described in detail in Saket et al. (2016) and its validation for monochromatic waves is presented in Saket et al. (2017). Its configuration and all accompanying wave probe measurements to determine crest point speeds for this present study were identical to those used by Saket et al. (2017).

The wave generation signals used during this present study were selected to be identical to three deep water cases used by Saket et al. (2017). The shallowest Class 2 wave case with the water depth of