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Parameterization of geometric characteristics for extreme waves in shallow water

Hongzhou Chen[a,b,*], Xiaocheng Tang[a], Junliang Gao[c], Guoxi Fan[d]

[a] *School of Civil Engineering and Architecture, Northeast Electric Power University, Jilin, 132012, China*
[b] *State Key Laboratory of Coastal and Offshore Engineering, Dalian University of Technology, Dalian, 116024, China*
[c] *School of Naval Architecture and Ocean Engineering, Jiangsu University of Science and Technology, Zhenjiang 212003, China*
[d] *School of Engineering, Ocean University of China, Qingdao, Shandong, 266100, China*

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ABSTRACT

This study presents an empirical parameterization of wave steepness and asymmetries used in the characterization of extreme waves in nearshore environment. A large amount of experimental datasets is analyzed for determining possible values of the wave geometric parameters. Results indicate that the steepness and asymmetries of extreme waves increase with water depth become shallower. For the data used here, the local relative wave height H_s/d play a crucial role in determining the geometric parameters of extreme waves different from that in deep water. A set of empirical formulas developed based on data analysis establish relationship between the wave geometric parameters and other parameters of engineering interest. Specifically, the first formula expresses the extreme wave steep as a function of the local relative wave height. The second formula defines the skewness and asymmetry for extreme waves as a function of the local Ursell number. From comparisons of the fitted results for different bottom slope, it is shown that the bottom slope has a negligible effect on the variations in crest-rear steepness, mean steepness and horizontal asymmetry, but obviously affects the crest-front and vertical asymmetry of extreme waves.

1. Introduction

The breaking of ocean waves is a common occurrence and is a crucial element in many oceanographic coastal and ocean engineering problems (Ramberg and Griffin, 1987). As a critical limit state, extreme waves are usually accompanied by breaking events. Obtaining a full understanding of such wave breaking and the ability to predict its onset have become the key research areas in these fields. Based on this issue, some criteria, based on extreme waves, have been proposed to predict the onset of breaking and breaking severity of surface waves. The traditional kinematic mechanism simply states that breaking occurs when the horizontal crest particle velocity U exceeds the phase speed C (Stokes, 1880; Nepf et al., 1998; Wu and Nepf, 2002). Along with this mechanism is the breaking criterion that involves the particle acceleration, breaking occurs when $dU/dt > -0.5g$ (Longuet-Higgins, 1963). However, application of this criterions to irregular waves is complicated due to the difficulty in measuring crest particle velocity and unable to accurately define the phase velocity for irregular waves (Tian et al., 2008). So, these criteria play a limited role in the evolution of nonlinear irregular wave fields (Perlin et al., 2013). To avoid complex calculation while retaining suitability for application in shallow water, geometric criteria, which typically use limiting steepness and local wave geometry as characteristic parameters are more widely used to predict breaking onset.

Stokes (1880) were the first to theoretically predict that a regular stationary wave is symmetrical and becomes unstable and breaks only if the angle between two lines tangential to its surface profile at the wave crest is 120°, which corresponds to a wave steepness of $kH/2 = 0.443$, where $k = 2\pi/L$ is the wave number, H is the wave height and L is the wave length). However, with decreasing water depth, gravity waves become nonlinear, and their geometry becomes horizontally asymmetric due to wave-crest steepening and wave-trough flattening (Nielsen, 1992; Drake and Calantoni, 2001). Moreover, the wave also exhibits fore-aft asymmetry because of wave-crest front-face steepening (Toffoli et al., 2010; Perlin et al., 2013). So, it is inappropriate to use symmetric wave theory to describe the onset of wave breaking. Considering the special geometry of extreme waves before breaking, Longuet-Higgins (1952) investigated the statistics of extreme waves in a random sea and implied that breaking occurs when the wave height is 0.12–0.14 times the

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[*] Corresponding author. School of Civil Engineering and Architecture, Northeast Electric Power University, Jilin, 132012, China.
E-mail addresses: 379988848@163.com, chenhongzhou@mail.dlut.edu.cn (H. Chen).

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wavelength. Kjeldsen and Myrhaug (1979) first investigated the individual limiting wave geometries through field observation in the Norwegian Sea. They explained that the total wave steepness $\varepsilon = H/L$ is not sufficient for asymmetric waves and the crest front steepness (ε_f), as well as the crest rear steepness (ε_r) should be analyzed (detailed expressions of these parameters could be seen in section 2). Statistical results show that the ε_f is between 0.32 and 0.78 and ε_r range of 0.26–0.39. Inspired by their research, Duncan (1981, 1983) measured the limiting wave height (H) and wavelength (L) of steady breaking waves in the laboratory and found the limiting steepness to be 0.31. Ramberg and Griffin (1987) observed that the mean of H/gT^2, where H is the limiting wave height, T is the wave period and g is gravitational acceleration, associated with spilling breakers was 0.021, corresponding to a limiting mean steepness of 0.41. Bonmarin (1989) observed breaking-wave profiles from a moving carriage and measured a mean steepness increased from approximately 0.25 to 0.55. Subsequent research concentrated on incipient wave breaking due to dispersive focusing and found that breaking could occur at a much lower steepness, from 0.15 to 0.22 (Rapp and Melville, 1990; Yao and Wu, 2004). Recently, Babanin et al. (2010) observed breaking waves due to modulational instability and found that the limiting steepness increased from incipient breakers at about 0.40 to final breakers at 0.44.

Although wave steepness plays a crucial role in describing extreme waves, it is simply defined as the relationship between wave height and wave length, hence it cannot represent the horizontal and the vertical wave crest asymmetries (Tian et al., 2008). Kjeldsen and Myrhaug (1979) introduced vertical asymmetry (asymmetry, A_s) and horizontal asymmetry (skewness, S_k) to better describe the geometry of breaking crests. They reported that the limiting vertical and horizontal asymmetry parameters as large as 2.0 and 0.9 respectively. Bonmarin (1989) measured photos that recorded the whole process of breaking and reported a vertical asymmetry range from 1.20 to 2.14 and a horizontal asymmetry range from 0.69 to 0.77.

The aforementioned studies have mainly concentrated on deep and intermediate water depths and relatively little research have been conducted in shallow water condition. However, breaking events in nearshore region seems more frequent and threaten coastal structures. Hence, a complete understanding of the mechanics of wave breaking in shallow water and the efficient prediction of its onset are important tasks for ocean engineering. The studies above generally conclude with either a set of critical parameter values or some change intervals, but do not include the specific evolutional process. So, as the primary motivation of the present research, the empirical parameterizations of geometric characteristics for extreme wave are developed. Moreover, many researches revealed that bottom topography has a vital effect on wave transformation in shallow water (Battjes, 1974; Dong et al., 2014), but this has been rarely considered in previous ocean wave studies. Therefore, the second objective of this paper is to assess the bottom slope effect on extreme waves.

Following the introduction, a brief description of wave geometric parameters is presented in Section 2. The experimental set-up, involving some validation and measuring procedure is introduced in Section 3. The results are presented in Section 4, and conclusions are given in Section 5.

2. Basic definitions of geometry parameters for extreme wave

As discussed in introduction, some distinct extreme waves were formed during the evolution of waves. Investigation on the characteristics of individual waves is an effective way to capture the features of extreme events. A well defined quantitative description of the geometry of extreme waves is a fundamental key to understanding and then predicting wave breaking (Kjeldsen and Myrhaug, 1979; Babanin et al., 2007). The statistics of wave steepness, and asymmetry are often used to depict extreme waves (Babanin et al., 2007; Toffoli et al., 2010; Perlin et al., 2013) and can be determined easily from the extracted individual profile (see Fig. 1). Nevertheless, Kjeldsen and Myrhaug (1979), Kjeldsen et al. (1980) have pointed out that the definition of limiting steepness using zero-downcrossing or upcrossing method will obtain different result. Toffoli et al. (2010) defined individual wave steepness which extracted by using zero-upcrossing method as crest-front steepness and downcrossing method as crest-rear steepness. In this study, both the front and the rear steepness are considered. Meanwhile, the mean steepness which considering both the front and the rear geometries of the extreme waves is also investigated. The detailed expression of this set of steepness is defined as follow:

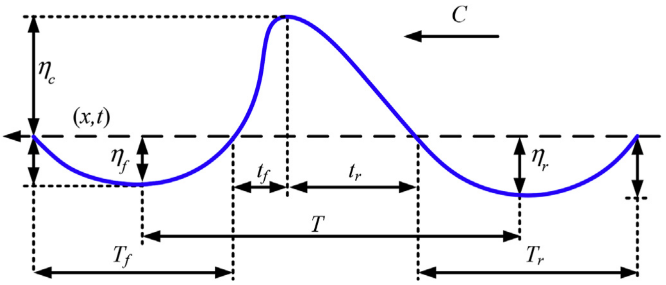

Fig. 1. Definition of local wave geometry.

Crest-front steepness:

$$\varepsilon_f = \pi \frac{\eta_c + \eta_f}{L_f} \tag{1}$$

Crest-rear steepness:

$$\varepsilon_r = \pi \frac{\eta_c + \eta_r}{L_r} \tag{2}$$

Mean steepness:

$$\varepsilon_m = \pi \frac{\eta_c + \frac{\eta_f + \eta_r}{2}}{L_m} \tag{3}$$

Following Kjeldsen and Myrhaug (1979) and Babanin et al. (2007), the horizontal asymmetry S_k (skewness) and vertical asymmetry A_s (asymmetry) are defined as:

$$S_k = \frac{2\eta_c}{\eta_f + \eta_r} - 1 \tag{4}$$

$$A_s = \frac{t_f}{t_r} - 1 \tag{5}$$

where above mentioned η_c, η_f, and η_r were the elevations of the crest, the front trough, and the rear trough, respectively; and λ_f, λ_r, λ_m were the local wave length determined from the dispersion relationship:

$$\frac{2\pi}{(T_f + t_f + t_r)^2} = \frac{g}{L_f} \tanh \frac{2\pi d}{L_f} \tag{6}$$

$$\frac{2\pi}{(T_r + t_r + t_f)^2} = \frac{g}{L_r} \tanh \frac{2\pi d}{L_r} \tag{7}$$

$$\frac{2\pi}{T^2} = \frac{g}{L_m} \tanh \frac{2\pi d}{L_m} \tag{8}$$

Here T_f,T_r,t_f,t_r and T represent time interval, d is water depth. It is noteworthy that the extreme wave steepness and asymmetry parameters are determined by wave probes. However, the measured profiles were a function of time, not space, and as such they do not represent exactly the geometry of the surfaces (Yao and Wu, 2006; Perlin et al., 2013). Therefore, the measured extreme wave profiles only provide some sort of average surface elevations (Ma et al., 2013).