DEVELOPMENT OF A WAVE ROLLER AREA MEASUREMENT METHOD IN THE LABORATORY SURF ZONE

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INTRODUCTION
With the occurrence of wave breaking in shallow water, an air-entraining turbulent region appears ahead of the wave crest, known as the wave roller (Duncan, 1981). The wave roller provides an energy flux at the water surface, and this energy flux is directly proportional to the roller area. Therefore, accurate quantification of the roller area is crucial for predicting the hydrodynamics in the surf zone. Over the past half-century, some researchers have provided in-lab observational data on wave roller area (Duncan, 1981; Govender, 2002). Other researchers calculated roller area data by measured current velocity (Okayasu et al., 1987; Tomasicchio, 2006). However, existing measurement data for roller area remain relatively scarce. To address this gap, the authors conducted in-lab experiments and developed a measurement method to efficiently acquire roller area data in bulk.

EXPERIMENTAL SETUP
The experiments were conducted using the wave tank at the State Key Laboratory of Hydraulic Engineering Intelligent Construction and Operation at Tianjin University. A schematic diagram of the experimental setup is shown in Figure 1. In the experiment, waves were generated at the wave generator at the left end of the tank, traveled through a horizontal region of 10.4 m before reaching the uniform slope region, where they broke and formed wave rollers. The water depth in the horizontal region was 0.3 m. The uniform slope region had two configurations, 1:20 and 1:40, constructed using steel frames and gray plastic sheets. The experiments were conducted with both regular and irregular waves. The wave heights (or significant wave heights) used in the experiments were 0.025, 0.050 and 0.075 m, while the periods (or mean periods) were 0.9, 1.1 and 1.3 s.

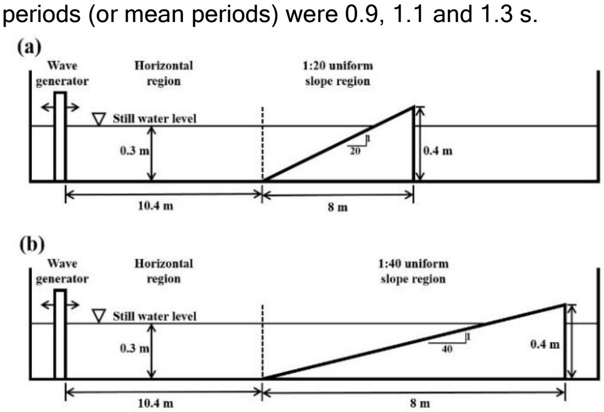

Figure 1 – Schematic diagram of the wave tank with (a) 1:20 and (b) 1:40 slopes.

MEASUREMENT METHOD
The image acquisition system for the experiments employed two high-intensity light-emitting diode (LED) sources for illumination. One source, equipped with a square diffuser box, was positioned behind the wave tank, directly facing it. The other source, with a spherical diffuser box, was positioned in front of the wave tank at a 60° angle to the normal of the glass wall. This LED lighting arrangement is commonly referred to as the shadowgraphy technique, as it renders bubbles as dark shadows against a white background (Ryu et al., 2005). A high-speed camera was employed for image capture at a framing rate of 50 fps.
The captured images were initially processed using the time stack technique. The time stack technique involves extracting vertical pixel lines at specific positions from all frames of a single acquisition and stacking them side by side (Govender, 2002). Subsequently, the measurement of the roller area is obtained from the time stack images using the thresholding method. The key point of the thresholding method is segmenting the image into two groups of pixels, i.e., object and non-object pixels, by applying a specific threshold value (Bakhoday-Paskyabi et al., 2016). In this study, pixels with brightness values less than the given threshold were identified as the wave roller. With limited data, manual threshold identification is common; however, for larger datasets, automated threshold identification through computer algorithms becomes necessary. Following the methods of Kleiss and Melville (2011) and Bakhoday-Paskyabi et al. (2016), we opted to derive the threshold from the cumulative distribution function (CDF):

$$H(k) = \sum_{i=0}^{k} h(i) \qquad (1)$$

where h is normalized image intensity histogram; and k is a brightness value between 0 and 1. Figure 2a shows a time stack image of a single period in a certain regular wave test. Figures 2b, 2c and 2d show the CDF and its first derivative $H'(k)$ and second derivative $H''(k)$, respectively. Pixels in the image with brightness values greater than 0.9 are identified as the white background and excluded from the statistics.
The authors explored 6 thresholds (Thresholds A-F) based on the function $H'(k)$, since $H'(k)$ tends to exhibit lower noise compared to $H''(k)$ (Fig. 2). Threshold F corresponds to the maximum value of $H'(k)$, representing the inflection point of the CDF. Thresholds A-E correspond to 20%, 40%, 60%, 80% and 90% of the maximum value of $H'(k)$, respectively. The Thresholds A-F were compared with those manually identified from 27 time stack images. The root mean square errors for Thresholds A-F were 0.051, 0.036, 0.025, 0.012, 0.010, and 0.055, respectively. The

results indicate that Threshold E has the best match with the manually identified thresholds.

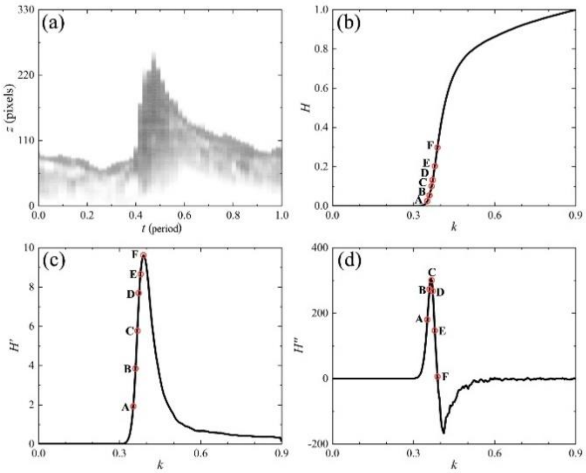

Figure 2 – (a) Time stack image of a single wave period, (b) CDF and its (c) first and (d) second order derivatives.

RESULTS AND CONCLUSIONS

Based on Threshold E, the authors processed the experimental images, obtaining measured data of wave roller area in bulk. Taking the test of regular waves with a wave height of 0.025 m and a period of 1.1 s on the 1:40 slope as an example, Figure 3a illustrates the measured wave height, while Figure 3b displays the measured wave roller area. After the waves break, the wave roller area rapidly increases from zero to a maximum value and then gradually decreases. The results indicate that the combination of shadowgraphy technique, time stack technique and thresholding method can effectively be applied to acquire wave roller area data in the laboratory surf zone.

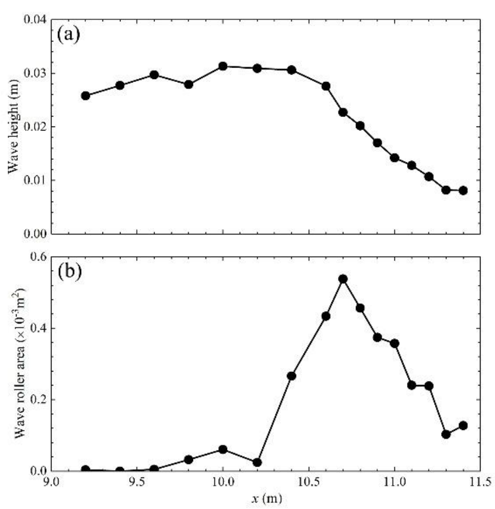

Figure 3 – Measured (a) wave height and (b) roller area in the test of regular waves with a period of 1.1 s and an incident wave height of 0.025 m on 1:40 slope. And x = 0 m represents the left end of the slope.

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