Image-based Study of Breaking and Broken Wave Characteristics under Partial Standing Wave Field and Validation of the Surface Roller Model

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Abstract: This study focuses on the breaking and broken wave characteristics under partial standing wave field in front of a vertical seawall. Laboratory experiments were first performed to represent such phenomena. A physical model of a vertical seawall installed on the mild slope was made in the wave flume. Image-based measuring technique was newly developed and applied to capture the surface water fluctuations as high-resolution data sets both in spatial and temporal domains. By analyzing the high-resolution data, behaviors of partial standing waves are successfully captured in front of the seawall. Comparisons of obtained data with and without seawall clearly show the difference in breaking type, positions of breaking points and cross-shore distributions of wave height and mean water level. Obtained experimental data was then used to validate the applicability of Boussinesq wave model coupled with the widely-used surface roller breaking model. It is found that although surface roller breaking model reproduces the basic characteristics of breaking and broken waves under partial standing waves, it tends to overestimate the energy dissipation in front of the seawall due to the excess energy dissipation of reflected waves especially near the seawall where standing waves are dominant.

Keywords: breaking and broken waves; vertical seawall; partial standing wave field; surface roller breaking model

1. Introduction

Coastal and ocean engineers are devoted to improve the understanding on surf zone and swash zone hydrodynamics in order to facilitate the development of economical and social activities in the coastal region. The most notable phenomena in the surf zone is the process of non-linear wave breaking on the near shore beach. Ocean waves, when entering the shallow water near shore, undergo significant change of its profile and start to break when their amplitudes reach a critical condition. After the breaking, broken wave crest deforms to forward-leaning profile and yields surface roller that first evolves and then collapses in front of the wave crest. Coastal structures such as seawalls have been widely used for shore and harbor protections. Waves are reflected by those structures and interacting with incident breaking and broken waves. Due to the presence of wave breaking, incident wave height is not equal to reflected wave height and complex partial standing waves are formed in front of the structures. Study and predictive skills of such complex breaking and broken wave field in the vicinity of the coastal structure are essential for better evaluations of the surrounding scour and beach erosion.

There are a number of laboratory experiments carried out to investigate the near shore wave characteristics over various bed configurations. But most of the studies were performed for progressive waves e.g., [1,2]. In these studies, reflected waves from structures are not considered and reflection from the bed slope is neglectable. Some studies e.g., [3,4] used bed configurations which take consideration of the reflected wave from structures. Even in these studies, the main concern was the hydrodynamic characteristics of the structures and the breaking phenomena were not considered or focused on. They just generated partial or pure standing waves on a horizontal bottom without wave breaking on the bed slope. One difficulty of experimental measuring the breaking and broken characteristics under partial standing field is that the positions of antinodes are uncertain due to the nonlinear wave transformation on the slope. Therefore, the limited numbers of traditional wave gauges widely used in wave flume experiments may not capture all the information of the wave characteristics in such phenomena and new measuring technique in the wave flume should be necessary.

In numerical analysis, predictions of complex wave fields requires to account for phase information of each wave and phase-resolved time-dependent wave model needs to be applied instead of phase-averaged wave model commonly developed based on energy balance equations. Among phase-resolving wave models, numerical models based on Boussinesq-type equations have been recognized so far as an efficient method of reproducing the combined effects of most wave phenomena of interest over complex bathymetries e.g., [2, 5-7]. Introducing appropriate breaking and broken wave models, these models can also accommodate computations of breaking and broken wave field near the shore. The most common approach is to add an ad-hoc dissipation sub-model to the momentum equation. Existing sub breaking models used to simulate the wave energy dissipation can be categorized into three main types based on different analogies: (1) friction type [8,9], (2) eddy viscosity type [10-13], (3) surface roller type [2,14]. Although Boussinesq models attached with above mentioned breaking models have been successfully applied to investigate various practical problems, these existing breaking wave models are mainly developed based on the assumptions of progressive waves and thus applicability of these models to predict breaking and broken wave characteristics under partial standing wave field which has significant reflected wave components from structures is still unclear.

In the present study, such breaking and broken wave characteristics under partial standing wave field were focused on. Laboratory experiments were first conducted in the wave flume with a vertical seawall installed on a mild slope. In order to obtain all the wave information, image-based measuring system was newly developed and applied to capture the water wave surface fluctuations with high resolutions both in time and space domains. For one case, progressive waves with the same incident wave conditions were performed without seawall on the slope in this study for comparisons. Moreover, obtained experimental data was used to check the applicability of existing widely-used surface roller breaking model since the surface roller model has more realistic physical meaning and relatively better prediction skills of breaking and broken waves compared to the other two breaking models. The performance of the surface roller breaking model under partial standing waves is clearly revealed in this study to enhance the insight of model application and future improvements.

2. Laboratory experiments

Laboratory experiments were first performed to investigate the characteristics of breaking and broken waves in front of a vertical seawall in the 2D wave flume of Coastal Lab at the University of Tokyo, which is 30m long and 60cm wide with transparent glass side walls mounted in steel frame.

2.1 Basic experimental setups

Figure 1 shows the basic experimental setups of the present laboratory experiments. A 1:30 sloping beach was made starting at around 12m from the wave maker in the wave flume. A vertical solid wall as a vertical seawall, which is widely used around the world as shore protection structures or as quay walls in harbors, was installed on the 1/30 slope and its horizontal distance from the wave maker is 19.795m. In order to capture all the information of surface fluctuations of breaking and broken waves in front of the vertical seawall, image-based measuring system was developed and applied to capture the wave characteristics with high resolutions both in time and space domains. Two video cameras were used to record successive still images of the instantaneous water surface boundary along the cross section of about 2m.
(2 steel frames of the wave flume) in front of the seawall in which the water and background were colored in blue and yellow, respectively. To ensure the high resolution of images, JVC HD cameras with resolution of 1920X1080 and frame rate of 30fps were used instead of high speed camera. Two spotlights were used to light up the measuring area. In order to synchronize two cameras, spotlights were turned off just before stopping the video recording in each experimental case.

Figure 1. Basic experimental setups.

2.2 Image-based data acquisition system

The recorded video images were converted to still images of each frame with high resolution pixel size of 1/1920m. Obtained images were first rectified based on the actual XY-square coordinate system on the glass wall of the flume. Eight reference points with known XY-square-coordinates on the glass wall were applied for this rectification. Rectification parameters, such as camera locations, angles, focal length and lens distortion, were estimated so that these parameters yield the minimum root-mean-square errors of estimated pixel coordinates at eight reference points with known coordinates.

The instantaneous surface water fluctuations in front of the seawall were estimated from the rectified still images. Based on the RGB-values in each pixel, the surface water boundary was detected through the following parameter,

\[ A = R + G - B \]

Since yellow color has larger values of both R and G while blue color has larger B but smaller values of R and G, computed A in Eq.(1) therefore should have larger value on the yellow background and smaller value on the blue water and should therefore be decreased abruptly at the air-water boundary. Figure 3 shows the downward vertical distribution of A along the vertical pixel line TT within an effective searching area as indicated in Figure 2. As seen in Figure 3, there is an abrupt decrease of A even at the surface of broken waves where the water color tended to be brighter than deep water. Under the present experimental setup, A was always greater than 200 on the yellow background while it was always less than 100 on the blue water even at the surface of broken waves where the water color tended to be brighter than elsewhere. This study therefore determined the surface water boundary condition of A by a single critical value, A=150, which is just between 200 and 100. Starting from the arbitrary points on the yellow background, the system search the pixel location in the vertical downward direction until A first goes below the critical value, A=150. Detected pixel coordinates at the water surface boundary were then transferred to the actual XY-coordinates on the glass wall of the flume.

Figure 4 compares the time-varying surface water fluctuations estimated by the present image-based measuring system and the ones measured by the wave gauge. It shows that, even under the breaking wave, the image-based system is able to capture overall surface fluctuations within acceptable errors (RMS error < 3mm).

Figure 2. A typical snapshot of the wave propagation and breaking on the 1/30 slope.

Figure 3. Downward vertical distribution of A along the vertical pixel line TT within the searching area as indicated in Figure 3.
2.3 Experimental wave cases and results

Table 1 enlists the experimental wave cases and conditions. In the table, $T_i$, $h_o$, $H_i$ is the incident wave period, the water depth near wave maker and the incident wave height over the horizontal bottom. Five typical regular wave cases were introduced and incident wave conditions and water depth near the wave maker were selected respectively in each of experimental cases. For case 1, progressive waves with the same incident wave conditions were also performed in this study without the presence of seawall on the slope for comparison.

<table>
<thead>
<tr>
<th>Case</th>
<th>$T_i$ (s)</th>
<th>$h_o$ (cm)</th>
<th>$H_i$ (cm)</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.2</td>
<td>30</td>
<td>4.8</td>
<td>Without seawall</td>
</tr>
<tr>
<td>2</td>
<td>1.4</td>
<td>30</td>
<td>4.4</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1.6</td>
<td>30</td>
<td>4.2</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1.2</td>
<td>31.5</td>
<td>5.5</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1.6</td>
<td>31.5</td>
<td>5.1</td>
<td></td>
</tr>
</tbody>
</table>

Figure 5 (a)-(e) shows the time-spatial distributions of extracted surface water level, $\eta$, standard deviation of the surface water fluctuations, $\sqrt{\eta^2}$, mean water level, $\bar{\eta}$, for each wave case. In Figure 5, origin of the horizontal axis is set at the location of seawall and the vertical axis is time. This figure shows the parameters for 30s starting from the first wave generated from wave maker was captured by the camera. $\bar{\eta}$ and $\sqrt{\eta^2}$ were computed as equation (2) and (3) based on the extracted surface water level data of each single wave period so that time-variation of these values as waves propagate, break, hit the seawall and finally form partial standing waves can be observed.

$$\eta = \frac{1}{N} \sum_{i=1}^{N} \eta_i$$  \hspace{1cm} (2)$$

$$\sqrt{\eta^2} = \sqrt{\frac{1}{N} \sum_{i=1}^{N} (\eta_i^2 - \bar{\eta}^2)}, \quad N = T_i \times 30$$  \hspace{1cm} (3)$$

As indicated by the red color of $\sqrt{\eta^2}$ in Figure 5, antinodes of standing wave features can be successfully captured by the present image-based measuring system in front of the wall for each wave case. This complex cross-shore distribution of the wave characteristics can be hardly captured by the traditional wave gauges since the position of the antinodes varies based on the incident wave conditions. For each wave case, the positions of antinodes remains same which implies steady partial standing waves formed in front of the vertical seawall and positions of antinodes should be at $nL/2$ from the vertical seawall accordingly ($n=1,2,3,...$, $L$ is the partial standing wave length on the slope). It was also observed that waves started to break around the antinode which is $3L/2$ from vertical wall for Case 1, Case 2 and Case 4 and around the antinode which is $L$ from vertical for Case 3 and Case 5. Mean water level $\bar{\eta}$ is rapidly elevated at the beginning and then went down to reach equilibrium state due to formation of partial standing waves.

Further comparison was made between Case 1 with seawall and the progressive wave case with the same incident wave conditions without seawall to check the influence of the reflected waves from the seawall. Figure 6 shows typical pictures of breaking wave phenomena where waves started to break for Case 1 and the progressive wave case. As seen in this figure, breaking type is somehow changed due to the presence of the seawall. Significant reflection from the structures caused plunging breaking behaviors for Case 1 while spilling breaking type was observed and validated by the surf similarity parameter proposed by Battjes for the progressive wave case with the same incident conditions. Figure 7 shows the comparisons of the cross-shore distributions of (a) $\sqrt{\eta^2}$ and (b) $\bar{\eta}$ at every 1/30s around $t=20$sec for one wave period for Case 1 and the progressive wave case. As seen in this figure, $\sqrt{\eta^2}$ was really increased around antinodes in Case 1. Mean water level $\bar{\eta}$ of Case 1 also had antinodes and was lower than the progressive wave case between antinodes and wave setup of Case 1 was not obvious near the seawall. This feature complies with the results presented by Longuet-Higgins and Stewart. They found that the mean surface level of standing waves is slightly raised at the antinodes and correspondingly lowered at the nodes by analysis of the radiation stresses. Figure 8 shows the time-spatial distributions of $\sqrt{\eta^2}$ for Case 1 and the progressive wave case. As indicated by the red color in the figure, formation of antinodes which increased wave height also made the breaking points of Case 1 further from the vertical wall than the progressive wave case.
Figure 5. Time-spatial distributions of extracted surface water level, standard deviation of the surface water fluctuations and mean water level for (a) case 1 (b) case 2 (c) case 3 (d) case 4 (e) case 5.
3. Experimental wave cases and results

This section aims to further investigate the overall performance of conventional widely-used surface roller breaking model under the present partial standing wave field through the comparisons of obtained experimental data and numerical results.

3.1 Model descriptions

Time-resolving Boussinesq-type wave models are widely used to simulate the wave propagation and transformation in the surf zone. In this study, the Boussinesq equations with an improved linear dispersion relation documented by Madsen and Sorensen were used as the governing equations of the wave model for present numerical analysis.
\[ \eta_t + P_x = 0 \]  
\[ P_t + \left( \frac{P^2}{d} \right)_x + gd\eta_x + \psi_1 + \frac{1}{2}f_\omega (P/d)^2 + F_{br} = 0 \]

where subscripts \( x \) and \( t \) denote differentiation with respect to space and time, \( d=h+\eta \) is the total water depth, \( h \) is the still water level, \( \eta \) is the instantaneous water surface elevation, \( g \) is the gravity acceleration and \( P \) is the depth-integrated velocity components; \( \psi_1 \) is wave friction factor. \( P_1 \) is the Boussinesq terms as dispersion parameters defined by

\[ \psi_1 = -\left( B + \frac{1}{3} \right) h^2 P_{xx} - Bgh^3 \eta_{xxx} - hh_x \left( \frac{1}{3} P_{xx} + 2Bgh\eta_{xx} \right) \]

where the value of the coefficient \( B \) is determined by matching the resulting linear dispersion relation with a polynomial expansion of Stokes first order theory combined with use of Padé’s approximant. By this approach the value \( B=1/15 \) was found and the resulting phase celerity was shown to be in excellent agreement with Stokes first order theory in deeper water.

Furthermore, \( F_{br} \) is an ad hoc momentum term to account for energy dissipation due to breaking and broken waves. Different types of breaking models have different formulations of \( F_{br} \). In the present study, surface roller type breaking model \cite{14} are focused on since roller model has more realistic physical meaning and relatively better prediction skills. They \cite{14} successfully applied this surface roller model attached with above Boussinesq equations for regular progressive waves over sloping beach. The corresponding \( F_{br} \) for surface roller type breaking model is expressed as

\[ F_{br} = \delta \left( \frac{c-P}{d} \right)^2 \left( 1 - \frac{\delta}{d} \right)^{-1} \]

Following Sorensen et al, the thickness of the surface roller \( \delta \) in \( F_{br} \) and breaking criteria is then determined by the heuristic geometrical approach as:

\[ \frac{\partial \delta}{\partial t} = f_\delta \left( \frac{\partial \eta}{\partial t} - c \tan \phi \right) \quad \delta \geq 0 \]

\[ \tan \phi = \tan \phi_0 + (\tan \phi_0 - \tan \phi_0) \exp \left[ -\ln \left( \frac{2(t-t_0)}{t_{1/2}} \right) \right] \]

where \( f_\delta \) is the roller shape factor, \( c \) is the wave celerity, \( t_0 \) is the time of start of breaking and \( t_{1/2} \) refers to a time scale for the development of the roller and is defined as a fraction of a wave period, \( \tan \phi_0/2 \) is initial breaking slope and \( \tan \phi_1/2 \) is a terminal breaking slope. The default values of these parameters were also suggested by Sorensen et al.

### 3.1 Validation of the surface roller model

Figure 9 shows the comparison between experimental and numerical results of standard deviation of surface fluctuations, \( \eta' \), and mean water level, \( \bar{\eta} \), for all cases. Parameters, i.e., \( \sqrt{\eta'} \) and \( \bar{\eta} \), were computed from the measured or computed time series of water surface fluctuations of the last ten wave cycles after waves reached to periodic equilibrium state. As seen in this figure, surface roller model can reproduce the basic characteristics of breaking and broken waves and partial standing waves. The model results also have antinodes of \( \sqrt{\eta'} \) and \( \bar{\eta} \) and their positions agree well with the experimental data. However, mean water level, \( \bar{\eta} \), in the breaking and broken waves near the seawall is tended to be overestimated and wave setup was obviously observed while \( \sqrt{\eta'} \) is tended to be underestimated near the seawall. It is also noted that the variation range of cross-shore distribution of computed \( \sqrt{\eta'} \) between antinodes and nodes is smaller compared to the ones of measured data. The results of model is somehow more like the ones of progressive waves with lower wave height and higher mean water level near the seawall as shown in Figure 7.
In order to further investigate the performance of the surface roller model under partial standing wave field, computed surface water fluctuations were separated into incident and reflected components for case 1. This study use the separation method presented by Mizuguchi validated by the results from linear wave theory applied to the numerical results. Advantages of Mizuguchi’s method is that it requires only the data sets of water surface fluctuations at several locations and thus this method can be applied to the present experimental cases. Although the method is based on the assumption that wave profile is conserved within certain distance, it was confirmed, through the comparisons of results of the Mizuguchi’s method and the ones by well-known separation techniques using both surface water fluctuations and water velocities, that Mizuguchi’s method yields reasonable separation of incident and reflected wave components even when the method is applied to the data on the slope.

Figure 10 shows the separated incident wave height and reflected wave height obtained from experimental data and numerical results of surface roller model for case 1. As seen in this figure, the cross shore incident wave height is relatively captured well by the surface roller model while reflected wave is really underestimated. This clearly reveals that the existing surface roller breaking model overestimate the wave energy dissipation due to the excess energy dissipation of reflected waves. Smaller computed reflected waves also bring about smaller variation range of cross-shore distribution of computed $\sqrt{\eta^2}$ as mentioned in Figure 9. It is also noted that the reflected waves predicted by the model decreases very quickly especially near the seawall at the right part of the figure where standing waves were dominant, i.e., reflection rate is relatively larger, compared to experimental data while reflected waves predicted by the model decreases mildly away from the seawall at the left part of the figure where standing wave is not dominant, i.e., reflection rate is relatively smaller. This indicates that excess energy dissipation of reflected waves by surface roller model mainly happened near the seawall where standing waves were dominant. The roller model must take the whole partial standing wave field as progressive wave and thus simulated energy dissipation happens both in incident waves and reflected wave while observed data sets indicate that dissipation of reflected waves is not obvious compared with the dissipation of incident waves.
4. Conclusion

Image-based measuring system was successfully developed and applied to the wave flume experiments to capture the water wave surface fluctuations in front of the seawall as high-resolution data both in time and space domain. Behaviors of steady partial standing wave field in front of the seawall was captured by the present system. Formation of several antinodes, which can hardly be captured by the wave gauges, were clearly observed in standard deviation of surface fluctuations computed from the high-resolution data. Mean water level is rapidly elevated in the beginning and then goes down to reach equilibrium state. Comparisons of obtained experimental data with and without seawall clearly show the difference in breaking type and cross-shore distribution of standard deviation of surface fluctuations and mean water level. Formation of antinodes which increases wave height also makes the breaking points of the case with seawall further from the vertical wall than the progressive wave case.

Obtained experimental data was also used to check the overall applicability of surface roller breaking models attached to Boussinesq wave model under partial standing wave field. The present surface roller model can capture the basic characteristics of breaking and broken waves and partial standing waves. However, by separating the incident waves and reflected waves, it is clearly revealed that the existing surface roller breaking model overestimates the wave energy dissipation due to the excess energy dissipation of reflected waves especially near the seawall where standing waves are dominant. The more standing the wave is, the more poorly the model predicts. For future research, improvements should focus on the reducing the energy dissipation of reflected waves especially near the structures when applying the conventional breaking models for accurate simulation of the breaking and broken waves under partial standing waves. Most likely introduction of an ad-hoc parameter as a function of reflection coefficient, which determine the extent of the standing wave, to the breaking term is useful.

Acknowledgements

The authors acknowledge the Fundamental Research Funds for the Central Universities of China (2016QNA4040).

References