VARIATION OF WAVE ROLLER SLOPE IN THE SURF ZONE

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Although the concept of breaking wave roller has been widely used in parametric surf zone modelling, the key physical parameter, wave roller slope, was not well understood and often simply assumed as a time- and space-independent constant. Based on an experimental analysis of breaking wave roller evolution, we found that the actual roller slopes are greater than those commonly used. Moreover, the roller slope is cross-shore variable with a peak at the breaking point. Applying the observed roller slopes into the conventional wave energy and momentum balance equations leads to improved calculated results of roller length evolution and wave setup. This implies the importance of an appropriate parameterization of space-dependent wave roller slope in modelling of surf zone processes.

Keywords: wave breaking; roller; cross-shore variation; surf zone

INTRODUCTION

The breaking wave roller is the aerated white water region which rides the underlying wave and stays stationary relatively to the wave crest (Svendsen 1984). After wave breaks, the roller exhibits a rapid growth in size and energy within a short distance, and then gradually decays further into the inner surf zone. This phenomenon modifies the distributions of energy, mass and momentum fluxes over the beach profile and affects surf zone dynamics. The effects of breaking wave roller evolution have been widely considered to improve the predictions of surf zone processes and to explain the spatial lag between breaking point and wave setup and wave-induced currents in the transition surf zone (e.g., Nairn et al. 1990; Apotsos et al. 2007; Zheng and Tang 2009).

In the theoretical formulation of roller evolution, roller energy is controlled by both the feed of wave breaking dissipation and its own energy dissipation due to the shear stress at the interface between roller and the underlying wave. Here, the roller slope is a key parameter affecting the amount of roller energy dissipation, and therefore affecting the roller energy evolution. Although the direct measurements of roller slope have been reported in literatures (Duncan 1981; Govender et al. 2002), most numerical studies treated it as a calibration parameter and various values have been used. These include the most often used values of 0.1 (Nairn et al. 1990; Dally and Brown 1995; Reniers and Battjes 1997; Ruessink et al. 2007; Apotsos et al. 2007), and 0.05 (Walstra et al. 1996; Ruessink et al. 2001). It is noted that most of these studies calibrated the roller slope based on the model-data comparisons of setup and wave-induced currents, rather than direct comparisons of roller characteristics. Haller and Catalán (2009) performed an experimental study of breaking wave roller length evolution over a barred beach. They noted that higher values (0.24-0.35) of roller slope better reproduced the measured roller length. However, existing studies treated the roller slope as a time- and space-independent constant. This assumption may not be physically appropriate since the roller slope is highly related to wave transformation and therefore would be expected to be variable under different wave conditions and at different spatial locations. In general, clear physical insights of the actual roller slope value and its variation pattern across the surf zone are still lacking, which are potentially important for the further improvements of surf zone modeling. This motivates the present study.

We used the experimental data of Haller and Catalán (2009) to analyze the roller slope variation from the breaking point to the inner surf zone. The measured roller slopes are then applied in the conventional phase-averaged wave energy and momentum equations to calculate the roller length evolution and wave setup. The validity of the present finding of space-dependent roller slope will be discussed based on the comparisons between the modeled and measured roller length and wave setup.

EXPERIMENTAL DATA ANALYSIS

In the experiment of Haller and Catalán (2009), the evolution of breaking wave roller length across the surf zone over a fixed barred beach was directly measured with the remote sensing technique. Water

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surface elevation was also measured by six in-situ wave gauges. The remote sensing observations showed obvious growth, equilibrium, and decay phases of the roller, induced by wave breaking and recovery above bar crest and trough as observed by wave gauges. Three cases, named 'run 33', 'run 37' and 'run 38' are considered in this study, involving various incident regular wave heights (0.37 m, 0.51 m, 0.47 m), wave periods (8 s, 5 s, 6 s), and breaking types (plunging, spilling, spilling). The average bed slope is 0.042. Because the roller length across the surf zone was directly measured in this experiment, it is possible to perform a more rigorous test for the effects of roller slope on the various phases of roller evolution.

The wave roller slope (β) is calculated as the average wave front slope from the zero-up crossing of surface elevation to the wave crest. The wave crest elevation and the time duration of wave front were obtained from the wave gauge time-series. The wave crest elevation was also considered in the calculation of nonlinear wave celerity in the surf zone. Fig. 1 shows the cross-shore variations of the measured wave crest elevation, measured roller slope and the bathymetry for three experimental test cases. Following features are found:

- The dominant wave breaking occurs on the bar crest and the secondary breaking occurs close to the shoreline, while wave recovery can be observed on the bar trough.
- The roller slope is not a constant over the profile, and it peaks at the dominant breaking point and decreases towards the shore.
- The roller slope ranges from 0.2 to 0.8, which is generally greater than the commonly used value of 0.1.
- The roller slope tends to approach a stable value around 0.2 in the inner surf zone.

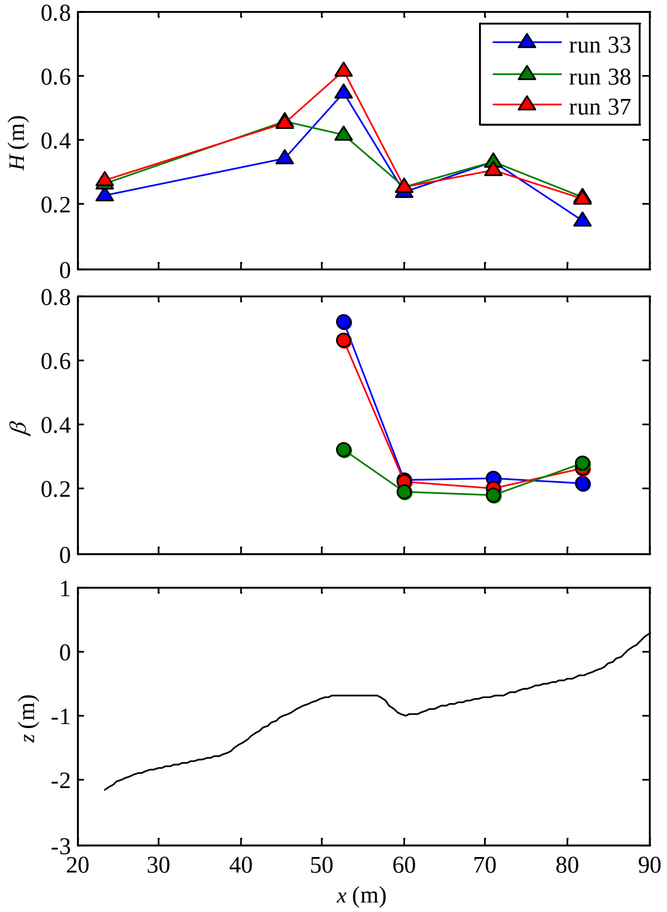

Figure 1. Cross-shore variations of the measured wave crest elevation, measured roller slope and the bathymetry for three experimental test cases.

NUMERICAL SIMULATION

Regarding that the measured roller slope is space-dependent across the surf zone, it is thus interesting to investigate whether the roller slopes with better physical meaning will lead to improved numerical results. In this section, we input the measured roller slopes into the conventional phase-averaged energy and momentum equations of breaking waves to calculate the roller lengths and compare them with the measurements. The energy and momentum equations can be written as (Nairn et al. 1990; Stive and De Vriend 1994)

$$\frac{\partial\left(2E_r c\right)}{\partial x}=-\frac{\partial\left(E_w c_g\right)}{\partial x}-\frac{2gE_r\sin\beta}{c} \qquad (1)$$

$$\frac{\partial S_{xx}}{\partial x}+\frac{\partial\left(2E_r\right)}{\partial x}+\rho g\left(h+\overline{\eta}\right)\frac{\partial\overline{\eta}}{\partial x}=0 \qquad (2)$$

$$E_\mathrm{w}=\rho g\overline{\eta^2} \qquad (3)$$

$$E_\mathrm{r}=\frac{\rho Ac}{2T} \qquad (4)$$

$$c=\sqrt{\mathrm{g}(h+\eta_c)} \qquad (5)$$

where E_r is the roller energy, E_w is the wave energy, c is the wave celerity, c_g is the group velocity, β is the roller slope, S_{xx} is the wave radiation stress, ρ is the water density, g is gravitational acceleration, h is the still water depth, $\overline{\eta}$ is the wave setup, η_c is the wave crest elevation, A is the roller area, T is the wave period, x is the horizontal coordinate.

The roller length (L_r) is calculated using the empirical relationship of Duncan (1981):

$$L_r=\cos\beta\sqrt{A/0.11} \qquad (6)$$

The wave energy, radiation stress and wave celerity are calculated with the measured time-series of water surface elevation. Therefore, wave nonlinearity is taken into account. The measured roller slopes are used in Eq. (1). There is no tuning parameter in these equations and the outputs are the cross-shore variations of roller length and wave setup. The Finite Difference Method is used to solve the equations.

Fig. 2 shows the cross-shore variations of the measured wave height, measured roller slope, calculated and measured roller length, calculated and measured wave setup and the bathymetry for run 33. Following points are highlighted:

- The growth and decay cycles of roller are clearly observed. The measured roller length rapidly increases from zero to a maximum value after the dominant wave breaking over the bar crest, and then decreases with wave recovery over the bar trough. The roller length increases again due to the secondary wave breaking, and then decreases close to the shoreline.
- If $\beta = 0.1$ is used, the roller length is overestimated in the entire surf zone and the roller decay near the shoreline is not captured.
- If the measured β is used, the roller length is very well simulated for both the magnitude and the cross-shore variation pattern.
- The use of the measured β produces greater wave setup in the surf zone, and fits better with the measurements.

The above findings confirm the validity of the space-dependent roller slope as proposed in this study. Results of the other two test cases are quite similar to those presented in Fig. 2, and are therefore not shown here.

It is clearly seen that the predicted results of roller length are improved with the input of measured space-dependent roller slopes. On the other hand, the improvements of wave setup prediction are relatively not that obvious. This indicates that the setup prediction is less sensitive to the roller slope. However, the significant difference in roller characteristics (e.g., roller length) implies that the roller slope may have non-ignorable effects on roller energy dissipation and the relevant surf zone dynamics. Numerical tests show that compared to the results with β = 0.1, the measured space-dependent β leads to significant increase in energy dissipation close to the breaking point. This explains the obvious overestimation of roller length by using $\beta = 0.1$. It is also found that this error seems to accumulate with distance across the surf zone. This could be of particular importance because the roller energy dissipation has been considered as the primary turbulence production source for the water column below the trough level, which in turn affects flow velocity profile and sediment transport (Mocke 2001; Zhang et al. 2009; Zheng et al. 2014).

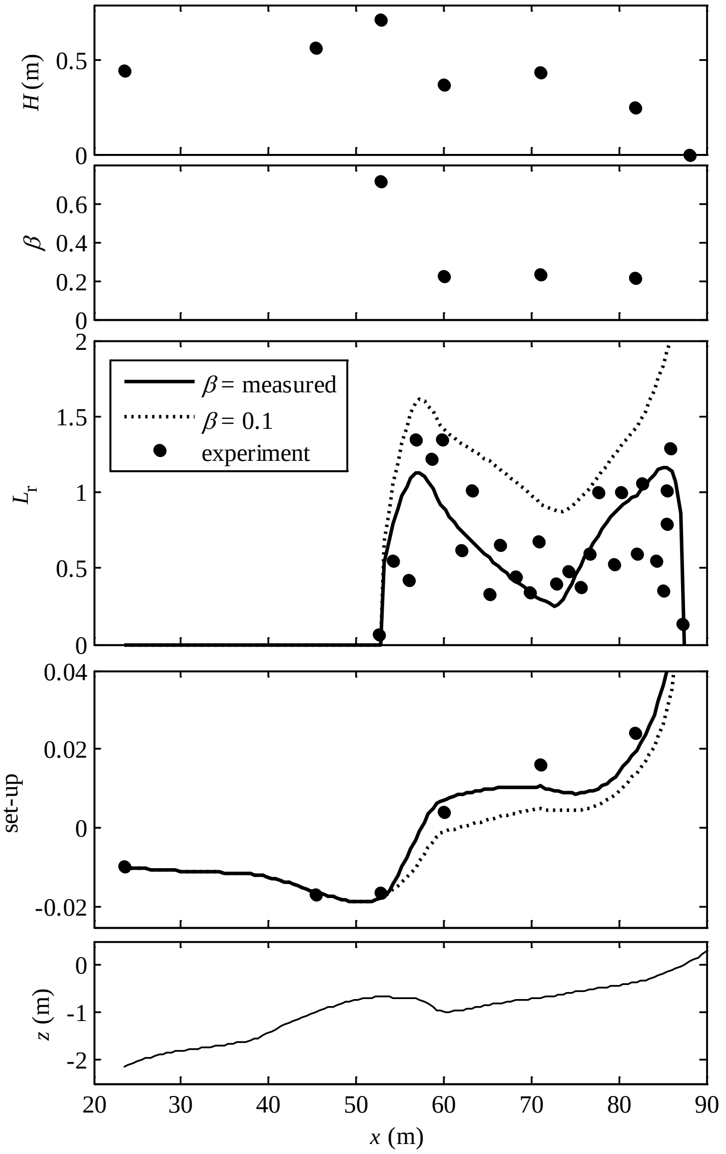

Figure 2. Cross-shore variations of the measured wave height, measured roller slope, calculated and measured roller length, calculated and measured wave setup and the bathymetry for run 33.

CONCLUSION

Based on the experimental data analysis and numerical simulation, this study investigates the actual value of breaking wave roller slope and its variation pattern across the surf zone. Results show that the wave roller slope ranges from 0.2 to 0.8. It is space-dependent, and it peaks at the breaking point and decreases toward the shore in the inner surf zone. This finding is different from the traditional assumptions of wave roller in both quantity and its spatial variation. Applying the measured roller slopes into the conventional wave energy and momentum balance equations yields improved simulations of roller length evolution and wave setup. It is demonstrated that the variation of roller slope is important for surf zone processes and deserves attention in surf zone modeling to achieve better physical representation and numerical accuracy.

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