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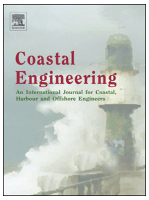

Estimating surfzone wave transformation and wave setup from remote sensing data

Raúl P. Flores [a,c,*], Patricio A. Catalán [a,d,e], Merrick C. Haller [b]

[a] Departamento de Obras Civiles, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile
[b] School of Civil and Construction Engineering, Oregon State University, Corvallis, OR, USA
[c] Department of Civil and Environmental Engineering, University of Washington, Seattle, WA, USA
[d] Centro Nacional de Investigación para la Gestión Integrada de Desastres Naturales, FONDAP/1511007, Santiago, Chile
[e] CCTVal-Centro Científico Tecnológico de Valparaíso, Basal Project FB021, Valparaíso, Chile

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ABSTRACT

The spatial distribution of wave roller dissipation is derived from optical remote sensing observations in a laboratory setting and is used to estimate wave transformation and radiation stress forcing through the surfzone. The methodology relies on direct measurements of the size of individual wave breaking rollers in an irregular wave field via remote sensing. The wave roller measurements are used to calculate the roller energy, roller dissipation, and the roller component of the radiation stress. These hydrodynamic quantities then serve as input into the wave energy flux and cross-shore momentum balances in order to derive the wave height transformation and mean water level profiles. The accuracy of the methodology is shown to be very good through comparison with in situ data. In addition, the mean water level profile reproduces the transition zone lag and maximum water level at the most shoreward measuring point. Overall, it is demonstrated that the methodology can be successfully applied to irregular waves and can be used to estimate both wave transformation and radiation stress forcing through the surf zone.

1. Introduction

Nearshore hydrodynamics is strongly influenced by wave dissipation, which results not only in the attenuation of waves as they propagate, but also transfers momentum, thus forcing mean flows and changing mean water levels (e.g. Longuet-Higgins and Stewart, 1964; Longuet-Higgins, 1970). In fact, previous work has shown that surf zone hydrodynamics can be sensitive to the details of wave dissipation, for example in the prediction of wave setup (Holman and Sallenger, 1985; Raubenheimer et al., 2001; Stephens et al., 2011). Holman and Haller (2013) argued that a direct measurement of wave energy dissipation is equivalent to measuring the mean flow forcing in the nearshore. However, measuring wave breaking, or more precisely, wave breaking dissipation, is a difficult task. On one hand, it exhibits a significant spatial and temporal variability, making it difficult to obtain data with sufficient spatial coverage with in situ instruments. Moreover, the surf zone can be a harsh environment that is potentially hazardous for instruments and operators. On the other hand, the signal of wave breaking is prominent in many remote sensing modalities, such as acoustic (Melville et al., 1988), optical (e.g. Lippmann and Holman, 1989; Holman and Stanley, 2007), microwave (e.g. Lewis and Olin, 1980; Catalán et al., 2014), and infrared (e.g. Jessup et al., 1997; Carini et al., 2015). Remote sensing also offers the opportunity to collect data nonintrusively over large spatial domains and long dwell times. However, obtaining quantitative wave information from remote sensing signals often requires sensor-specific image processing techniques, owing to differences in the transfer function between the imaged sea surface, and the produced image to be analyzed. Although the existence of a transfer function may introduce some limitations in the use of remote sensors, for instance, due to the dependence on environmental parameters such as wind or visibility, or intrinsic such as the sensor and imaging resolution, the benefits of using them make them an appealing and typically low cost and safer alternative to in situ sensors.

Lippmann and Holman (1989) first demonstrated that the bright intensity features in optical time exposure images (i.e. 15 min average) corresponded to expected maxima in the bulk wave dissipation, as is often found over sand bars. Later approaches related the remote sensing signals to the dissipation occurring in the wave roller, with the original conceptual model of the wave breaking roller being given by Duncan (1981) and Svendsen (1984a). For example, Aarninkhof and Ruessink (2004) demonstrated that the optical intensity magnitude could be calibrated against wave roller dissipation, once active breaking signals were separated from those of remnant foam.

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* Corresponding author at: Departamento de Obras Civiles, Universidad Técnica Federico Santa María, Casilla 110-V, Valparaíso, Chile.

E-mail addresses: raul.flores@usm.cl (R.P. Flores), patricio.catalan@usm.cl (P.A. Catalán), merrick.haller@oregonstate.edu (M.C. Haller).

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The approach of Haller and Catalán (2009) was to make direct measurements of the size of the wave rollers (using monochromatic waves), which could then be related to the wave roller energy and dissipation through the model of Duncan (1981) and Svendsen (1984a). The methodology required minimal calibration and the derived dissipation was validated against the observed wave transformation of monochromatic waves in a laboratory surfzone, based on the assumption that dissipation and shoaling were the dominant wave transformation processes. Catalán et al. (2011) demonstrated that wave roller measurements could also be made with field data using multi-sensor fusion. In that case, the wave rollers were identified and measured through a fusion of optical and X-band radar data. However, they did not have in situ data to validate against. Finally, Carini et al. (2015) demonstrated successful wave roller measurements using an infrared sensor and found good correspondence with both in situ and model-based estimates of dissipation on a field beach.

Recently, Díaz Méndez et al. (2015) demonstrated that wave transformation estimates derived through remotely-sensed dissipation (in their case, from radar observations of the frequency of wave breaking) can be successfully used to estimate the radiation stress forcing as well. In the present work, the methodology of Haller and Catalán (2009) is applied to irregular wave conditions on a laboratory beach using optical remote sensing observations. The cross-shore variation of wave roller dissipation is then utilized in the wave energy flux balance in order to determine the cross-shore profile of wave height. Next, roller energy and the roller contribution to the radiation stress are calculated directly from the roller measurements and, along with the wave-induced radiation stress, are used to estimate the mean water level variation from the cross-shore momentum balance. The wave transformation and mean water level profiles are validated against in situ measurements. At present, the methodology assumes that the incident wave energy and the surf zone bathymetry are known quantities, although methodologies for obtaining these via remote sensing, as in Díaz Méndez et al. (2015), could be added as well at a future date.

The paper is organized as follows: in Section 2 the cross-shore energy flux and momentum balances including roller effects are briefly presented. Section 3 describes the experimental setup and data sources. Data processing procedures and results for wave height transformation and wave setup using the proposed algorithm are presented in Section 4, and a discussion of these results follows in Section 5. Finally, Section 6 presents conclusions and perspectives on future work.

2. Background

2.1. Wave transformation: wave and roller energy balances

One approach to model nearshore hydrodynamics is to estimate the evolution of time averaged wave properties, thus removing the need for an accurate description of small scale processes such as turbulence. Despite its overall simplicity, this approach is well suited for estimation of statistical properties such as wave height and mean water level profiles, at low computational costs. Here, wave heights are obtained using two coupled differential equations describing the wave and roller energy balances, in a similar way as Haller and Catalán (2009). Assuming a stationary wave field, the wave (Battjes and Janssen, 1978, e.g.) and roller energy balances read (Deigaard, 1993; Nairn et al., 1990; Stive and De Vriend, 1994)

$$\frac{\partial}{\partial x}\left(E_w C_g\right) = -D, \tag{1}$$

$$\frac{\partial}{\partial x}(2E_r C) = D_{br} - D_r, \tag{2}$$

where x is the along ray coordinate, D is the total wave energy dissipation, C_g is the wave group speed and E_w is the organized wave energy. In Eq. (2), E_r is the roller energy, C is the carrier wave phase speed, D_{br} is the wave breaking dissipation, and D_r is the roller energy dissipation.

Although other dissipation mechanisms, such as turbulence, might be considered in D, here it is assumed that wave breaking dissipation is the dominant mechanism, $D \approx D_{br}$ (Battjes and Janssen, 1978; Thornton and Guza, 1983), thus coupling Eqs. (1) and (2). E_w is taken from linear theory as

$$E_w = \frac{1}{8}\rho g H_{RMS}^2, \tag{3}$$

where ρ is the water density, g is the gravitational acceleration and H_{RMS} is the root-mean-square wave height.

Roller energy is taken from Svendsen (1984b) as

$$E_r = \frac{\rho_r A C}{2T}, \tag{4}$$

where $\rho_r \approx \rho$ is the average density of the roller (here assumed constant and equal to sea water density), A is the cross-sectional area of the roller and T is the wave period. In deriving this expression, it was assumed that the roller propagates with the wave at its phase speed. Roller dissipation is given by (Duncan, 1981; Deigaard, 1993)

$$D_r = \frac{\rho g A \sin\theta \cos\theta}{T} = \frac{2gE_r}{C}\sin\theta\cos\theta, \tag{5}$$

where θ is the angle of inclination of the roller, which controls the amount of wave energy storage in the roller and its size. Eqs. (1) and (2) can be solved using a finite difference scheme initialized at the offshore boundary, with a known value of H_{RMS} and setting E_r equal to zero (no wave breaking). The system is closed by the specification of D_{br}, usually parameterized in terms of H_{RMS} (Battjes and Janssen, 1978; Thornton and Guza, 1983; Alsina and Baldock, 2007). Alternatively, substituting Eqs. (1) and (5) into (2) and rearranging yields

$$\frac{\partial}{\partial x}\left(E_w C_g\right) = -\frac{\partial}{\partial x}(2E_r C) - \frac{2gE_r}{C}\sin\theta\cos\theta, \tag{6}$$

where it can be seen that in solving for the wave energy flux (and hence the wave height), it is required to know the phase speed C, and hence the bathymetry; and the roller energy E_r. The roller energy is determined directly from the observations using Eq. (4). The traditional approach is to provide a model for A dependent on other known quantities (Svendsen, 1984b; Dally and Brown, 1995, e.g.). Haller and Catalán (2009) avoided the use of wave-breaking dissipation parameterizations by relating the cross-sectional roller area to a remote sensing observable, therefore directly estimating E_r from data. The ratio A/L (where L is the roller along-slope length) was determined to be nearly constant by (Duncan, 1981) for wave rollers in equilibrium

$$\frac{A}{L^2} = 0.11 \pm 0.01, \tag{7}$$

which suggests that roller geometry is self-similar. L can be related on geometrical terms to the horizontal projection of the roller, L_r. Haller and Catalán (2009) implemented the procedure outlined above for monochromatic wave fields, obtaining good agreement with experimental H_{RMS} profiles, with $\theta \sim 12.6$–$20°$.

2.2. Mean water level: the cross-shore momentum balance

Inclusion of the roller is relevant because it affects the overall forcing in the nearshore through its contribution to radiation stresses (Svendsen, 1984b). The cross-shore momentum balance can be considered to be dominated by radiation stress and mean water level (setup) gradients, as supported by laboratory (Stive and Wind, 1982; Dally and Brown, 1995) and field studies (Lentz and Raubenheimer, 1999;

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