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An empirical model for infragravity swash on barred beaches

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ABSTRACT

Idealized computational simulations with the nearshore model XBeach were carried out for a series of barred beach configurations in order to quantify the impact of nearshore bars on infragravity swash. Results show that nearshore bar systems reduce infragravity swash energy at the shoreline. The amount of swash reduction was found to correlate with both bar depth and rip width, when a rip channel is present. In order to develop a generalized empirical model for significant infragravity swash for barred beaches, the simulations were used to extend the empirical swash model of Stockdon et al. (2006) to include bar characteristics. The developed empirical model relates significant infragravity swash to incident wave conditions and nearshore bar depth. With respect to Stockdon et al. (2006), this new model improves predictive skill by reducing root-mean-square error by 50% for the computational simulations and by 15% when applied to a range of field data.

1. Introduction

Beaches are an important line of defense for coastal communities. It is well known that subaerial topography, such as beach width and dune height, plays a large role in protecting coastal communities from the adverse impacts of beach erosion. However, the bathymetric characteristics of the nearshore region also play a role in wave-induced beach erosion (Ruggiero et al., 2001). Likewise, it is important to understand how nearshore bathymetry influences wave processes at the beach face, which drive sediment transport. Specifically, the uprush of individual waves, where the maximum vertical elevation above the still-water level is termed runup, is known to contribute to beach and dune erosion (e.g., Ruggiero et al., 2001). Runup comprises both the quasi-steady wave setup, along with other contributions to mean water level, plus instantaneous swash.

As studied here, swash is defined as the vertical variance in instantaneous water level about the mean water level. Research has shown that empirical parameterizations of swash generally result in less scatter than similar parameterizations of runup, since variations in wave setup by definition are not included (e.g., Holman, 1986). Parameterizations of swash generally include some combination of wave height, wavelength, and local beach slope (e.g., Holman and Sallenger, 1985; Stockdon et al., 2006). These parameterizations do not include variables that describe local nearshore bathymetric features such as bars; therefore, these parameterizations do not account for the relative impact of local bathymetric features on swash.

In this paper, we aim to describe infragravity swash dependence on nearshore bar characteristics by using numerical simulation and analysis of infragravity swash on a series of idealized barred bathymetries.

2. Background

Depending on local bathymetric conditions, beaches can be described as either dissipative or reflective, or one of four intermediate states (Wright and Short, 1984). Of the intermediate bathymetric states, the longshore bar-trough state is the most dissipative due to wave energy dissipation over the bar as waves break. Normally, waves will cease breaking over the deeper trough, and break once again on the beach face. Swash motions at the shoreline are often described for two distinct wave frequency (f) ranges, infragravity ($f < 0.05$ Hz) and incident ($f \geq 0.05$ Hz) (e.g., Holman and Sallenger, 1985). Ruessink et al. (1998) found that dissipative beach states are dominated by infragravity swash motions, while reflective beach states are dominated by incident energy. Further, infragravity swash motions are unsaturated, since an increase in incident offshore wave height leads to an increase in infragravity swash energy (Raubenheimer and Guza, 1996). Therefore, infragravity swash motions become even more important during large wave events, as the energy in large incident waves is dissipated before reaching the shoreline.

An early idea about swash amplitudes was given by Miche (1951), who suggested that the swash amplitude should be proportional to the standing wave component of a progressive monochromatic wave. Hunt (1959) built upon this idea, and provided a parameterization that describes swash as a function of wave height, wave steepness, and beach slope. Guza and Thornton (1982) introduced a definition for the significant swash, calculated as 4σ, where σ^2 is the total variance

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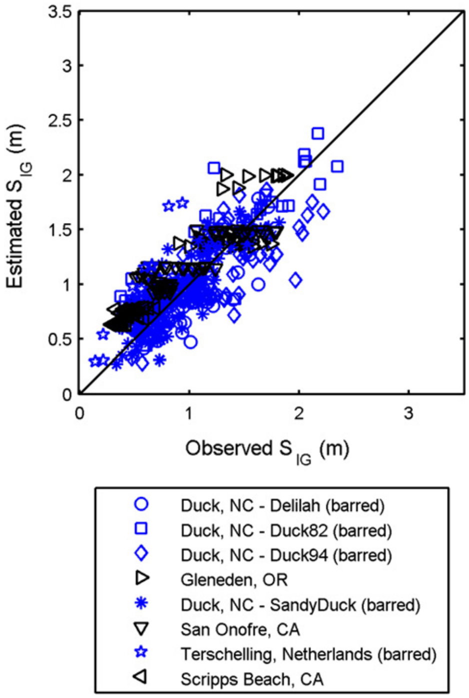

Fig. 1. Observed significant infragravity swash (S_{IG}) versus S_{IG} predicted using Eq. (2) when $A = 0.07$ (estimated S_{IG}); the line represents an exact match between observed and estimated S_{IG}. Observations shown are from eight field experiments on five beaches given in Stockdon and Holman (2011).

of the swash power spectral density ($PSD(f)$). In this approach, a statistical measure was used to describe the highest expected swash excursion as a linear function of significant wave height. Stockdon et al. (2006) studied swash motions by utilizing data from nine different field experiments spanning a wide range of bathymetric conditions, including locations with and without nearshore bars. Significant infragravity swash (S_{IG}) was calculated for all the datasets as follows:

$$S_{IG} = 4\sqrt{\sum_{f=0\text{Hz}}^{0.05\text{Hz}} PSD(f)df}. \tag{1}$$

Stockdon et al. (2006) found that S_{IG} is best parameterized by offshore wave height (H_o) and wavelength (L_o):

$$S_{IG} = A(H_oL_o)^{0.5} \tag{2}$$

where A is a fit constant. Estimated S_{IG} using Eq. (2) versus observed S_{IG} is given in Fig. 1 for selected[1] field data reported in Stockdon and Holman (2011) and used in Stockdon et al. (2006). For the data shown, $A = 0.07$ with an $R^2 = 0.68$. Eq. (2) predicts S_{IG} for these field data sets with a root-mean-square error (RMSE) of 0.26 m and a small bias, mean error $= +0.07$ m. Wave conditions during these field experiments ranged from $4 \text{ m} \leq (H_oL_o)^{0.5} \leq 35 \text{ m}$, and nearshore bars were present during four of the eight experiments shown.

Swash has been shown to depend on environmental variables such as offshore wave height and wavelength as well as local beach slope. While the effects of nearshore bars have not previously been considered explicitly, Stockdon et al. (2006) stated that the dissipation of offshore waves by bars may lead to scatter in empirical relationships that describe swash. Furthermore, infragravity swash is expected to be an indicator of beach erosion potential, as infragravity wave motions at the shoreline have been shown to be a main source of beach erosion (Ruggiero et al., 2004). Finally, Van Gent and Giarrusso (2005) showed via numerical simulation that the amount of infragravity wave energy generated during wave breaking is sensitive to nearshore bathymetry. Specifically, the authors showed that the percentage of total wave energy at low frequencies depends not only on incident wave conditions but also on the ratio between offshore wave height and water depth within one wavelength of the coast. In this paper, through analysis of idealized numerical simulations, and starting with the Stockdon et al. (2006) formulation (Eq. (2)), we develop a generalized empirical model for explicit estimation of infragravity swash, S_{IG}, as a function of nearshore bar characteristics.

3. Methods

The goal of this paper is to provide a parameterization of significant infragravity swash that extends the Stockdon et al. (2006) parameterization by including variables that describe nearshore bar dimensions. Numerical simulations with XBeach (eXtreme Beach behavior; Roelvink et al., 2010) are used to model infragravity swash over two idealized bathymetry classes: (1) no nearshore bar (hereafter NO BAR) and (2) alongshore-uniform nearshore bar (hereafter BAR). Simulated swash data are then analyzed to develop a parameterization for infragravity swash energy as a function of bar parameters that may be readily measured from high-resolution bathymetry. The following describes the development of the idealized bathymetries, the computational model, model implementation, and data analysis methods.

3.1. Idealized bathymetry

In order to better control bathymetric variables and to remove impacts of alongshore bathymetric variation, a series of idealized bathymetric conditions were used. This allows isolation of the specific impact of bar geometry on infragravity swash. Longshore bar-trough beach states tend to form in areas with moderate breaking wave heights and tidal ranges (Wright et al., 1986). Panama City Beach, Florida, USA, located on the Gulf of Mexico (Fig. 2, top) satisfies these conditions. High-resolution bathymetric lidar data (Irish and Lillycrop, 1999; Wozencraft and Lillycrop, 2006) from this region, collected in 2009 (Fig. 2, bottom), is used as the basis for developing the bathymetric scenarios for numerical simulation. Review of the lidar data reveals a pronounced longshore bar-trough beach state.

The lidar data were analyzed to quantify alongshore variations in the cross-shore position (distance from shoreline to bar crest, x_B) and bar-crest depth (h_B). For this site, h_B was found to linearly correlate with x_B, with $R^2 = 0.88$ (Fig. 3). Based on this correlation and the range of h_B and x_B within the Panama City Beach dataset, 12 pairs of h_B and x_B were identified for simulation (Table 1). Given that infragravity energy is often assumed to be released during wave breaking (e.g., Battjes et al., 2004), we hypothesize that the impact of the nearshore bar on infragravity swash will diminish with increasing h_B. Thus, the case of deeply submerged bars, as would occur during extreme surge events, is not considered here.

In order to create alongshore-uniform bathymetry for each of the 12 BAR scenarios, a barred beach profile was developed by fitting a piece-wise equation to representative cross-shore profiles extracted from the lidar data. The piece-wise function splits the cross-shore profile into four sections. An equilibrium profile, $h(x) = Bx^{2/3}$ (Dean, 1977), was fit from the shoreline to the deepest section of the trough, two sine curves were used to describe the bar, while a second equilibrium profile, utilizing a virtual origin, was fit to the portion of the profile offshore of the seaward extent of the bar. This piece-wise fit effectively smoothens the cross-shore profile by omitting small-scale bathymetric variations. Each of the 12 BAR profiles was created from lidar profiles representative of the specific bar height and distance to bar, with the

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[1] While Stockdon and Holman (2011) also report field data Agate Beach, OR, a barred beach, no bathymetric data on the bars exists for the time period of the experiments (P. Ruggiero, personal communications). Thus, all but the Agate Beach data set are included in this analysis.