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Numerical modeling of wave runup on steep and mildly sloping natural beaches

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ABSTRACT

Runup on ocean beaches includes steady wave setup and oscillating swash, often decomposed into wind generated sea-swell (SS), and lower frequency infragravity (IG) waves. We show that the numerically fast, open-source numerical model 1D SWASH predicts accurately the bulk properties of runup observed on two natural beaches (one steep and one shallow sloped) for a range of incident wave conditions. The runup tongue shape was measured with a scanning lidar, and the waterline location was defined in both the observations and model with a 10 cm depth threshold. Runup is reasonably accurately predicted with energetic (e.g. 5 m significant height) incident waves, even though the assumption of 1D bound waves significantly overpredicts infragravity energy at the offshore boundary in 10 m depth. The model-data comparisons are limited by statistical chatter, often larger in runup than offshore because runup energy is concentrated in the relatively narrow infragravity IG band with low effective degrees of freedom.

1. Introduction

Wave runup contains steady and time-varying components. The steady component, wave setup, is driven by gradients in the wave-induced mean momentum flux (radiation stress) created by breaking waves in shallow water (Longuet-Higgins and Stewart, 1964). The oscillating component, swash, fluctuates about the mean setup, and is often divided into to two frequency ranges on ocean coasts: sea-swell (SS) (0.04–0.25 Hz) and a lower frequency (nominally 0.004–0.04 Hz) infragravity (IG) band. Observations and models suggest that the magnitude and relative importance of setup and IG and SS swash depend on beach bathymetry and incident wave conditions (e.g. Stockdon et al., 2006; Senechal et al., 2011; Stephens et al., 2010; Fiedler et al., 2015; Ruju et al., 2014; Raubenheimer and Guza, 1996). Accurate predictions of the runup are needed for warnings of erosion, flooding, and structural damage in extreme wave events.

Runup estimates based on parameterizations in terms of offshore wave parameters (e.g. Stockdon et al., 2006; Poate et al., 2016), for a sandy or gravel beach, respectively] are easy to compute, and may be the only alternative if bathymetric data are unavailable. However, errors are often sufficiently large e.g. 47 cm rms error for reflective conditions in Stockdon et al. (2006) to have practical consequences. For instance, a 20 cm difference in maximum wave uprush can be the difference between no and significant street flooding (Gallien, 2016).

Alternatively, runup can be estimated using numerical models that solve hydrodynamic equations. Increasingly complex, and potentially more accurate, models usually require more computational effort. Phase-averaged (sea-swell and IG waves are solved separately (Roelvink et al., 2009)) models are relatively fast, but omit important processes such as the effect of IG waves on SS waves in the inner surfzone, and predict runup poorly (Stockdon et al., 2014). Conversely, RANS models (e.g. Lara et al., 2011) resolve all wave processes in detail, but are impractical operationally owing to the prohibitive computation time. Further, the full complexity of RANS models may be unnecessary to predict runup. For instance, the phase resolving nonlinear shallow water wave equations (NLSWE), used in many models from the last century (e.g. RBreak, Kobayashi and Wurjanto, 1992) are numerically tractable, capture shocks (Lax and Wendroff, 1960), and simulate the runup tongue accurately (Raubenheimer and Guza, 1996). However, NLSWE are nondispersive and restricted in utility by the need to initialize in water that is shallow for all wave frequencies (e.g. <2 m depth, Raubenheimer and Guza, 1996), a location frequently within the surfzone and much shallower than typically estimated with regional wave forecasts.

Phase-resolving Boussinesq (Lynett et al., 2002) and non-hydrostatic

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models (Zijlema et al., 2011; Ma et al., 2012) are dispersive, and can be applied in deeper water, but otherwise effectively reduce to the NLSWE (sometimes by actively disabling dispersive effects, (e.g. Tonelli and Petti, 2012; Smit et al., 2013; Tissier et al., 2012; Roeber and Fai Cheung, 2012)). These models are a viable compromise between computational effort and accuracy. For instance, the non-hydrostatic SWASH model (Zijlema et al., 2011) has been successfully applied to accurately simulate nonlinear surfzone wave evolution (Smit et al., 2013; Rijnsdorp et al., 2014), wave runup (Ruju et al., 2014) and wave overtopping (Suzuki et al., 2017). Even so, comparison with observations predominantly consider 1D (normally incident waves only) flume data. Verification with field observations of runup (with directionally spread waves) for this class of models remains limited, and is important because 1D phase resolving models are used to estimate runup for evolving offshore conditions over large coastal reaches (e.g. Smith et al., 2012).

The (1D) assumption of normal wave incidence may reasonably approximate SS hydrodynamics in shallow water; waves incident from deep water refract to near normal incidence in shallow water, and nonlinear SS shoaling processes are weakly dependent on directional spread (e.g. Elgar et al., 1992). In contrast, the IG band – which often dominates the runup process – can be strongly directionally spread (Herbers et al., 1995) and contain alongshore propagating edge waves. The nonlinear dynamics of 1D and 2D IG waves can differ significantly (e.g. Sand, 1982).

Large computation times and uncertain physics in 2D phase resolving models preclude their effective use in regional simulations in the immediate future. Our objective is to test the accuracy of 1D SWASH for wave runup, as an alternative to widely used parametric models (e.g. Stockdon et al., 2006), or phase-averaged models (e.g. XBeach). The offshore boundary condition must be must be derivable from the frequency spectra of sea and swell typically provided by regional wave models or wave buoys.

Here, we compare the state-of-the-art phase resolving model 1D SWASH with a unique set of detailed field observations (Fiedler et al., 2015) obtained with a range of incident wave conditions on a steep and a shallow sloped beach. Section 2 describes the field experiments and model formulation and setup. In Section 3, observed and modeled bulk statistics in the surf and swash zones are compared. The model sensitivity to friction and the offshore boundary condition, and the importance of statistical fluctuations, are discussed in sections 4. Section 5 is a summary.

2. Methodology

2.1. Field experiments

Wave measurements were collected on the US west coast at the steeply sloped Cardiff Beach, California (Winter 2012–2013) and at the low-slope Agate Beach, Oregon (Fall 2013, (Fiedler et al., 2015), Fig. 1). Bottom pressure and velocity measurements were obtained along a cross-shore transect from the shoreline to $\sim$ 10 m depth with pressure sensors and current meters sampling at 1–2 Hz.

Pressure sensors in shallow depths, buried to reduce flow noise and exposure to debris, were corrected for burial with poro-elastic theory (Raubenheimer et al., 1998) and surface corrected using linear wave theory to a maximum frequency of 0.25 Hz. At Agate, four co-located current meters and pressure sensors (PUVs) were deployed in 5–10 m depth (upward-facing and bottom mounted) and three were down-facing and mounted on tripods in the inner surf and swash zones (Fig. 1a). At Cardiff, the only PUV was in about 10 m water depth (Fig. 1b).

An elevated scanning lidar at the back beach obtained wave runup and subaerial beach elevation measurements, following (Brodie et al., 2015). At Cardiff, the lidar was mounted on 10 m tall scaffolding. Line scans were obtained for two 20-minute intervals every hour, with alternating frame scans of the beach and surrounding area for coordinate rectification. In the latter half of January 2013, lines scans were obtained at 50-minute intervals to capture the long-period, narrow-banded swell. A cliff-mounted lidar at Agate Beach acquired line scans for 50 min every hour. Lidar scans coincident with the instrument cross-shore transect were sampled at approximately 7 Hz, gridded at 0.1 m cross-shore resolution, and decimated to 1 Hz (Fiedler et al., 2015). The runup line was defined as the most shoreward location where the water depth was at least 10 cm. This threshold was chosen as the smallest accurate runup depth threshold at Agate owing to often noisy data in adverse field conditions (Fiedler et al., 2015). The same threshold was used at Cardiff for consistency. Runup thresholds are discussed in Fiedler et al. (2015).

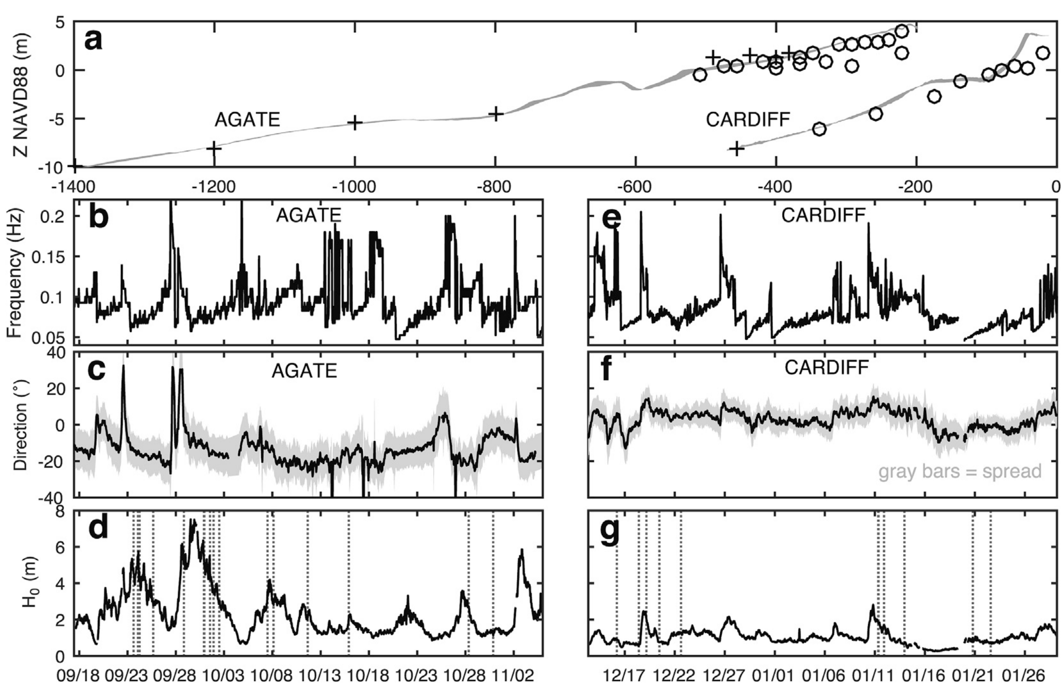

Fig. 1. (a) Depth versus cross-shore distance, and locations of pressure (o) and current (+) sensors at Agate and Cardiff Beach. (b–g) Offshore incident wave conditions at Agate (left) and Cardiff (right) versus time, (b,e) peak frequency, (c,f) mean direction, and (d,g) offshore wave height Ho. Dotted vertical lines in (d,g) denote test cases.