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Simulating wave setup and runup during storm conditions on a complex barred beach

Alexandre Nicolae Lerma[a,*], Rodrigo Pedreros[a], Arthur Robinet[a,b], Nadia Sénéchal[b]

[a] BRGM (French Geological Survey), Risks and Prevention Division - Coastal Risks and Climate Change Unit, Orléans, France
[b] Université de Bordeaux, CNRS, UMR 5805-EPOC, Talence, France

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ABSTRACT

The purpose of this study is to assess the ability of the SWASH model to reproduce wave setup and runup in highly dissipative stormy conditions. To proceed we use data collected during the ECORS Truc Vert'08 Experiment, especially during the Johanna storm in the winter of 2007-008 (wave setup under H_s= 8.2 m and T_p= 18.3 s and runup under 6.4 m and peak period up to 16.4 s). We test different model settings (1D and 2D mode) and model forcing (spectral and parametric) to reproduce sensor measured wave setup at several locations in the nearshore area and video measured runup on two beach profiles. For the whole tested configurations, the wave setup is reproduced accurately. Results considering all the sensor locations in the near shore area in 1D and 2D are significantly correlated to the observations with respectively ρ^2=0.66 and 0.81; RMSE=0.13 m and 0.08 m without any significant bias. Observations and simulations of runup are investigated in terms of spectra and statistic component. 1D simulations produces an overall overestimation and no significant improvement is obtained by modifying the breaking parameters. The results for 2D simulations are fairly satisfactory reproducing significant swash height (S), but are significantly improved with spectral forcing than parametric with respectively ρ^2=0.73 and 0.71, RMSE=0.19 m and 0.43 m. Generally, the model reproduces accurately the infragravity component but tends to overestimate the incident component, leading to an overestimation of the energy density for moderate wave conditions and more accurate results for higher-energy wave conditions. Results in 2D with spectral forcing show a saturation of the infragravity component with a threshold around H_s=4 to 5 m, which is comparable to the observations collected at Truc Vert Beach. As regards the conventional statistical parameter for runup estimation ($R_{2\%}$) three methods are applied to derive the 2% exceedence value for runup from observed and simulated shoreline vertical elevation time series. When $R_{2\%}$ is based on the sum of wave setup and half of the significant swash height, results provided by the model are close or even better than estimations provided by empirical formulas from the bibliography. Defining $R_{2\%}$ as the exceeded 2% values of the time, derived considering the cumulative distribution function of the entire water-level time series also provide fairly good results. Results using only runup maxima time series are less satisfactory. In the two last cases, $R_{2\%}$ is slightly underestimated for moderate wave condition$_s$ (H_s < 4 m; $T_p \approx$ 14 s) and overestimated for higher-energy wave conditions. Generally results shows that where extreme wave conditions are concerned, the model setting must be considered carefully because the simplification of 1D (rather than 2D), or the use of parametric wave description (rather than spectral), can be a source of significant inaccuracy or overestimation in simulated run-up values.

1. Introduction

On beaches, accurate estimations of water levels reached during storm conditions are critical to assess changes in the beach face and dune front morphology (e.g. Ruggiero et al. [1]) or to quantify overtopping processes (e.g. Van der Meer and Stam, [2]). The main manifestation of swash zone processes on open beaches is the time-varying vertical position of the water's edge, known as runup. This is made up of a (quasi) steady component above the still water level (the wave setup) and a fluctuating component that varies in time, the swash. For years, reliable setup and runup estimations for realistic cases through process-based modeling were limited by the complexity (and the non-linearity) of the hydrodynamic processes within the surf zone and their interaction with the beach morphology. To address this difficulty, empirical formulations to estimate setup and runup were derived using statistical approaches and/or parametric models, thus

* Correspondence to: 3 avenue Claude Guillemin 45100 Orléans, France.
E-mail address: a.nicolaelerma@brgm.fr (A. Nicolae Lerma).

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providing synthetic tools for coastal engineers and managers (e.g. Stockdon et al. [3]).

The first parametric models were established in the mid-20th century using primarily laboratory measurements (Miche [4]; Iribarren and Nogales [5]; Hunt [6]; Battjes [7]). In recent decades, many studies have focused on developing new formulations based on field observations covering a wider and more realistic range of beach configurations (e.g., Guza and Thornton [8]; Holman and Sallenger [9]; Ruessink et al. [10]; Ruggiero et al. [11]; Stockdon et al. [3]).

However, given the complexity of deploying instruments and collecting field observations during storm periods, few setup and runup datasets associated with highly energetic conditions have been compiled (Sénéchal et al. [12]). The most energetic offshore wave conditions used so far to establish currently used empirical formulations for setup and runup have a maximum wave height and wave period of 4 m and 12 s, respectively (Holman [13]; Stockdon et al. [3]). Therefore, the use of existing empirical formulations during highly dissipative conditions caused by extreme offshore waves is questionable (Stockdon et al. [14]; Cohn and Ruggerio [15]).

In addition, recent studies show that fundamental questions remain about the interactions between waves and environmental parameters in highly dissipative conditions (Sénéchal et al. [12]; Guedes et al. [16]; Guza and Feddersen, [17]; Cox et al. [18]), especially on main mechanisms explaining infragravity wave dissipation close to the shore: infragravity wave breaking (Battjes et al. [19], Van Dongeren et al. [20], De Bakker et al. [21]) or energy transfer from infragravity to incident wave frequencies Hendersen et al. [22] and Thomson et al. [23].

Thanks to major developments and the wider availability of very large computing capacities, process-based numerical wave modeling now offers an alternative to the statistical and parametric approach. Recent studies (Stockdon et al. [14]; Cohn and Ruggerio [15]; Medellin et al. [24]) have underlined the value of using numerical models to reproduce wave breaking behavior and extend the application of setup and runup formulas to extreme wave conditions.

These studies are based on the use of various kinds of numerical models, such as Boussinesq model (Coulwave model, Lynett et al. [25]) in Park and Cox [26], phase-averaged process-based model (X-beach model, Roelving et al. [27]) in Stockdon et al. [14] or in Cohn and Ruggiero [15]). The phase-resolving non-hydrostatic wave model (SWASH, Zijlema et al. [28]) was already employed in studies focusing on runup and infragravity wave dissipation, but here again, most validation studies were performed in flumes (Ruju et al. [29], Rijnsdorp et al. [30]) or for a schematic 1D profile (Torres–Freyermuth et al. [31]; De Bakker et al. [21]). Applications in 2D with SWASH model were compared with field data only for moderate offshore waves (H_s < 2.5; T_p < 13 s, in Guimarães et al. [32]). Therefore, the use of process-based wave models for realistic cases and their validation against field data is still highly experimental, and even more so for high-energy wave conditions and complex bathymetry.

The purpose of this study is to use the data collected during the ECORS Truc Vert'08 Experiment (Sénéchal et al. [12]; Sénéchal et al. [33]; Pedreros et al. [34]), which at the moment is the most high-energy field dataset reported in the bibliography. We studied especially the highly dissipative conditions during the Johanna storm period in the winter of 2007/2008, to assess the ability of the SWASH model to reproduce wave setup (under maximum conditions: H_s=8.2 m and T_p= 18.3 s), and runup (under 6.4 m and peak period up to 16.4 s). We tested various model settings to reproduce this data and to preliminary discussed the dissipation behavior reproduced by the model.

We first describe the methods and materials used in order to estimate the abilities of the SWASH model to reproduce the field observations collected during the ECORS Truc Vert'08 Experiment (Section 2). Secondly, we present the results according to the different model settings (Section 3). Finally, we discuss these results in terms of limitations and prospects (Section 4).

2. Method

2.1. Model and settings

We used the SWASH 2.00A model (Zijlema et al. [28]), to simulate the wave propagation in the surf and swash zone. This model is a vertical multi-layered model based on non-linear shallow water equations (NLSW) including non-hydrostatic pressure, and provides a general basis for describing complex changes in rapidly varying flows. It is considered as a valuable tool to reproduce wave propagation, wave breaking, energy dissipation and energy transfer from the incident frequency band to the infragravity band (Rijnsdorp et al. [30]). Generally, in wave modeling, wave breaking is the key process for an accurate reproduction of energy dissipation in the nearshore area, and therefore most of the nearshore dissipation process. With SWASH, the use of 1 to 3 layers is sufficient to describe wave physics outside the surf zone. In regions were waves approach breaking, the model requires a high vertical resolution to accurately capture the bore dynamic, as wave steepening introduces strong vertical gradients in the flow variables. An accurate representation of energy dissipation due to wave breaking usually requires 10 to 20 layers (Smit et al. [35]).

However, for 2D applications, this number of layers is not efficient in terms of computational effort and simulation time. An alternative approach was developed in SWASH based on the HFA (Hydrostatic Front Approximation) (e.g., Kennedy et al. [36]; Tonnelli and Petti [37]). This method requires a few additional parameters in order to control the onset and cessation of wave dissipation: α to determine the maximum range of steepness (breaking initiation); β to indicate the limit of persistence of wave breaking and; μ an additional viscosity parameter to prevent the generation of high frequency noise due to activation of the HFA (for all details see Smit et al. [35]). The threshold value, α, at which the HFA is initiated, depends on how the model can represent the wave shape for highly non-linear waves and the wave dynamics leading up to breaking, and thus depends on the number of layers used in the model. The persistence parameter β was found to be much less sensitive to the number of layers used (Smit et al. [35]). The efficiency of the HFA approach was demonstrated in 1D and 2D by Smit et al. [35], comparing experimental data and results derived from multilayer model set-ups (more than 15 layers). They found that using α=0.6 and β=0.3 and μ=1 as default parameters allow reproducing well observed wave heights and wave periods in 1D or in 2D, and also wave-driven circulations and dissipation due to wave breaking. Nevertheless, since the bathymetric and wave conditions are very different in our study to those studied by Smit et al. [35], we are conducting several tests in 1D and 2D configurations to evaluate the influence of breaking parameters on setup and runup results.

The applicability of the SWASH model was assessed for several configurations. Two different simulation modes were used to reproduce wave setup and runup: in 2 vertical layers 1D mode with 6 cross-shore profiles (Fig. 1) to describe the bar and rip bathymetry at the center of the domain and at the sensor location, and in 2 vertical layers 2D mode covering the entire domain. For each mode (1D and 2D), the model was forced with spectral and estimated parametric wave data from the offshore buoy. The spectra (1D and 2D) comprise 32 frequencies from 0.7 to 0.04 Hz, and 24 directions for the 2D spectra. Parametric and 1D spectral characteristics were computed every 30 min and 2D spectra only every 3 h. In the present case, parametric forcing was integrated as a default TMA spectrum computed by SWASH (shallow water spectrum derived from the JONSWAP spectrum). Each simulation was computed from the initial stationary water level conditions. The simulation time was set at 20 min, with a 5 min spin-up and results output every 1 s, equivalent to post-processing characteristics for wave setup measurements and the acquisition time for the video observations used to calculate runup values. The simulation time step was set at 0.01 s, the minimum depth for computation at 0.01 m, bottom friction was integrated with a homogeneous Manning coefficient of 0.019 (default)