Coastal Engineering 115 (2016) 58–66

Contents lists available at ScienceDirect

Coastal Engineering

journal homepage: www.elsevier.com/locate/coastaleng

Observations and simulations of wave runup during a laboratory dune erosion experiment

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ARTICLE INFO

Article history:
Received 23 April 2015
Received in revised form 21 December 2015
Accepted 8 January 2016

Keywords:
Runup
Swash
XBeach
Dune erosion

ABSTRACT

XBeach, a process-based numerical model designed to simulate morphologic change during extreme storm events, was calibrated and compared to observations from a large-scale laboratory dune erosion experiment. Wave conditions along the tan, wave runup at the beach, and 3-dimensional position of the dune were measured throughout the experiment. Seiching modes in the tank were simulated and matched the observations once the model was calibrated. Simulated waves were sensitive to γ, the ratio of wave height to water depth, and c_f, the coefficient of friction. Simulated runup explained 50–87% of the observed variance in observations. However, the magnitude of simulated wave runup was underestimated throughout the experiment. Errors in simulated runup were composed of a high bias and gain error in mean water level, low bias in the infragravity swash, and low bias and gain errors in incident swash. Observed probability density functions of swash were statistically consistent between times when swash was confined to the foreshore and times when swash interacted with the dune. However, simulated probability density functions of swash were statistically different during the collision regime. Despite the systematic underestimation of wave runup, modeled dune erosion compared well with observations after the sediment transport parameters were calibrated. Modeled dune erosion was sensitive to the critical slope parameters over the wet and dry regions of the beach, the depth of the interface between the wet and dry regions of the beach, and the threshold depth for sediment transport and return flow.

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1. Introduction

Much of the world's population live within the coastal zone and are vulnerable to the impacts of sea level rise and extreme storms. Along sandy coastlines, these storms potentially result in extreme erosion events and inundation of low-lying areas as storm surge, setup, and swash interact with the subaerial beach. However, the presence of sand dunes can provide soft protection for eco-systems and land-side development against these extreme water levels. There are worldwide examples of dunes being used for coastal protection. For example, during Hurricane Sandy in October, 2012, protective dunes in Keansburg, NJ, USA were attributed with minimizing damage to backing infrastructure (US Army Corps of Engineers, 2013). Similarly, artificial dunes built by beach scraping are used as a coastal engineering tool to protect infrastructure from winter wave and surge events along the Emilia-Romagna coastline in Italy (Harley and Ciavola, 2013). Dunes also protect infrastructure and buildings along the Gold Coast of Australia from waves associated with East Coast Lows (Splinter and Palmsten, 2012).

Improving forecasts of dune erosion is essential because sand dunes are so widely used as the last line of defense against storm surge and large waves generated by extreme events. As a first step toward forecasting failure of dunes, the conceptual Storm Impact Model (Sallenger, 2000), is widely used to the compare storm total water levels and dune elevation (Stockdon and Sallenger, 2010). However, this simplified model can only categorize the expected storm response into four finite regimes termed swash, collision, overwash, and inundation. Long et al. (2014) and Stockdon et al. (2007) combined elements of the storm regime model with the estimates of wave runup to demonstrate that the conceptual regimes of the Storm Impact Model can be related to a characteristic magnitude and direction of sediment transport. The Storm Impact Model was extended to a probabilistic model (Plant and Stockdon, 2012) for estimating dune crest elevation change. This probabilistic approach was also extended to include beach and dune widths and was used to estimate dune elevation change and dune crest and shoreline position change and its uncertainty on Santa Rosa Island, FL (Plant and Stockdon, 2012) and Gold Coast, Australia (Palmsten et al., 2014).

Under storm conditions, barrier dunes can erode rapidly under the direct impact of wave forcing due to elevated water levels and wave processes such as wave runup, setup, storm surge, and tides. Models such as those proposed by Vellinga (1986) and Harley et al. (2009)

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http://dx.doi.org/10.1016/j.coastaleng.2016.01.007
0378-3839/Published by Elsevier B.V.

provide an estimate of total beach erosion due to increased water levels and wave impacts. However, these models have no time dependence to allow for feedbacks between the dune and swash. Accounting for the feedback between dune and swash is key to estimating the time dependent change in beach morphology (Palmsten and Holman, 2012; Splinter et al., 2014).

Another modeling approach which includes the feedback between swash and dunes are the dune impact models derived from Overton et al. (1988) (e.g., Larson et al., 2004; Palmsten and Holman, 2012). The advantage of this approach is that the simplified relationships require no knowledge of the subaqueous beach profile and fairly little calibration. While this approach captures some of the feedback between dunes and wave runup during the collision regime, the foreshore dynamics are neglected, making it less useful for detailed hindcasting of the full beach profile.

All of the time dependent approaches for modeling dune erosion described above use the Stockdon et al. (2006) parameterization for wave runup or other similar parameterizations (e.g., Hunt, 1959). In Stockdon et al. (2006), extreme runup is defined as the 2% exceedance height of discrete water level maxima. The Stockdon et al. (2006) parameterization is based upon the nearly Gaussian distribution of wave runup maxima that was observed in data from 10 field experiments over a range of beach and wave conditions. In the Stockdon et al. (2006) approach, runup is decomposed into three components: mean water level, significant swash height in the incident band, S_{Inc}, and significant swash in the infragravity band, S_{IG}. The data used to develop the Stockdon equation were not collected during conditions where the swash was interacting with the dune. In many cases however, the Stockdon et al. (2006) parameterization has been applied to predict wave runup during storms when waves were interacting with dunes and when the Gaussian distribution of swash has not been verified (e.g., Almeida et al., 2012; Armaroli et al., 2012; Gervais et al., 2012; Hanson and Larson, 2008; Jiménez et al., 2009; Plant and Stockdon, 2012; Splinter and Palmsten, 2012; Stockdon et al., 2007; Villatoro et al., 2014; Vousdoukas et al., 2012b). The dataset presented here allowed us to determine whether the assumption of a nearly Gaussian distribution is valid for swash interacting with the dune.

Coupled hydrodynamic and sediment transport models, such as XBeach (Roelvink et al., 2009), a state of the art process-based coupled hydrodynamic and sediment transport model, can be used to simulate the temporal evolution of the full beach profile under storm conditions and gain a better understanding of the processes and feedbacks that govern the response. This process based approach to modeling dune erosion is the primary alternative to models relying on statistical parameterizations of runup and dune erosion described earlier in the Introduction. Like any model, XBeach contains a variety of assumptions and requires careful calibration with existing datasets before the model can be used with confidence (Vousdoukas et al., 2012a).

XBeach has been applied to hindcast a growing number of extreme erosion events. Roelvink et al. (2009) simulated a Nor'easter storm on Assateague Island assuming constant surge and wave period and observed a decrease in beach face slope, qualitatively reproducing the observations. Lindemer et al. (2010) simulated Hurricane Katrina on the Chandeleur Islands, LA, USA to test sensitivity to grid size, temporal resolution, and boundary and initial conditions on model results. They found that while their results were insensitive to grid size, temporal resolution and boundary conditions, results were sensitive to initial conditions. McCall et al. (2010) simulated Hurricane Ivan on Santa Rosa Island, FL, US testing the sensitivity of model results to variable surge and wave conditions. Their simulated results explained up to 70% of the observed variance in beach profile shape and elevation change. Splinter and Palmsten (2012) simulated an East Coast Low on the Gold Coast of Australia testing the sensitivity of a variety of model parameters. Resulting dune erosion was estimated with volume change errors of 11 to 30%, and the model was most sensitive to parameterizations for wave dissipation and skewness. XBeach simulations were relatively insensitive to the subaqueous beach profile. Vousdoukas et al. (2012a) performed an extensive sensitivity and validation study during storms at Faro Beach in Portugal. They found XBeach simulations were more sensitive to calibration for Irribaren numbers greater than 0.6 and parameters for wave skewness, choice of sediment transport equation, and slope of the wet beach. Harley and Ciavola (2013) used XBeach to simulate storms on the Emilia-Romagna coast of Northern Italy and successfully reproduced observed dune failure and stability. Harley and Ciavola (2013) found slope of the wet beach and time step between the hydrodynamic and sediment transport modules to be important calibration parameters for XBeach. Armaroli et al. (2013) also used XBeach to simulate storms on the Emilia-Romagna coastline. They also identified improvement in modeled results when wet beach slope was adjusted.

In all these examples, only the pre- and post-storm beach profiles were known. In some cases, the pre-storm profile was collected several years before the storm event. Wave conditions in the surf zone and at the dune were unknown, making detailed comparisons between observations and simulations challenging. Under conditions without dune erosion, runup from XBeach has been compared with observed runup (Stockdon et al., 2014; van Rooijen et al., 2012). In both comparisons, the swash component of runup was underestimated by XBeach. The present study, where we compared runup simulated by XBeach to laboratory observations of runup, allowed us to quantify XBeach performance under the swash regime, as well as the collision regime, which is rarely observed in real time in the field.

The objectives of this XBeach simulation of a laboratory dune erosion experiment are two-fold. First, to gain a better understanding of the sensitivity of XBeach parameters chosen under the time dependent variation of wave conditions. Second, to assess the capability of XBeach to accurately reproduce wave runup given the assumption that the incident component of energy in runup is negligible and the resulting dune erosion maybe estimated without interaction between incident band swash and dunes. Of particular interest within the context of the second objective was to determine the appropriate model calibration to minimize error in dune erosion associated with errors in wave runup. The experiment described here was unique for several reasons. 1) We observed the waves at high spatial resolution throughout the surf zone. 2) We reproduced a storm hydrograph and observed the time dependent dune erosion representative of the Nor'easter storm previously modeled in prototype by Roelvink et al. (2009). 3) We observed the wave runup impacting the dune.

2. Methods

2.1. Experiment

A large-scale dune erosion experiment was conducted at the Oregon State University O. H. Hinsdale Wave Research Lab Large Wave Flume. The flume has dimensions of 107 m × 3.7 m × 4.6 m (L × W × D) and was capable of generating waves up to 1.6 m in height with a 3.5 second period at the time of the experiment. Prototype wave conditions occurred during a Nor'easter storm off Assateague Island, MA/VA, USA from February 3–8, 1998. Over the course of the storm, the dunes retreated up to 30 m, depending upon alongshore location (Fauver, 2005). Prototype wave conditions were measured at NOAA Buoy 44004, (38.48° N, 70.43° W), 370 km east of Cape May, NJ. The maximum significant wave height, H_s (m), was 7.35 m, maximum peak wave period, T_p (s), was 12.5 s and maximum tidal residual, S (m), was 1.03 m. Conditions modeled in the laboratory were determined by Froude scaling (Dean and Dalrymple, 2002) with a model length scale 1/6 of prototype and resulting time factor of $1/\sqrt{6}$. The laboratory conditions required step-wise changes in wave height, period, and water levels, as opposed to smoothly increasing/decreasing functions during the prototype storm (Fig. 1). The experiment was run in 15-