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Morphological response of a sandy barrier island with a buried seawall during Hurricane Sandy

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ABSTRACT

Coastal populations continue to increase globally, causing potential damage costs of coastal hazards to rise and community resiliency to become a worldwide priority. Recently, Hurricane Sandy (2012) devastated areas of New York and New Jersey and caused overwash and breaching of several urbanized barrier islands along the U.S. eastern seaboard. This study focuses on the morphological response of Bay Head, NJ, a township on a barrier island fronted with a buried seawall. The hydrodynamics and morphology of Bay Head during Hurricane Sandy are simulated with XBeach, a numerical model designed to study these processes during storm events. From the simulations, the seawall protected Bay Head by effectively dissipating wave energy during the peak of the storm and from rapidly increasing bay water levels that flood the backbarrier region of the island. When the seawall is removed from the simulation, dune heights are lowered, allowing bay side flooding to cause a devastating erosive event that completely destroys the remaining dune system. XBeach indicates severe erosion seaward of oceanfront buildings in the absence of a seawall (vertical erosion under the dune peak about 15 m more than in the presence of the seawall), and wave energy propagates further inland even after the storm has passed. However, with the seawall present, wave attack is reduced on the island by a factor of 1.7 and prevents bay side flooding from causing significant morphological change on the island. Therefore, the seawall increased resiliency of the Bay Head community during and after peak Hurricane Sandy forcing by preserving the dune system.

1. Introduction

Globally, coastal populations continue to grow, further increasing the need to develop sustainable communities resilient to coastal hazards (Hinrichsen, 1999; Neumann et al., 2015; Small and Nicholls, 2003). In 2000, an estimated 10% of the world's population lived in coastal zones with elevations of less than 10 m above sea level, which are highly vulnerable to damage from waves and flooding (McGranahan et al., 2007). Because of the concentration of urban development in these areas, coastal populations are expected to continue to increase, leading to new infrastructure and higher potential costs due to coastal storm events. These costs include tangible and intangible losses, such as physical damage to infrastructure, ecosystem loss and degradation, business and social disruptions and loss of life (Donnelly et al., 2006; Escudero et al., 2014; Kraus and Wamsley, 2003; Smith et al., 2015) have shown that, in the U.S. from 1980 to 2014, 50% of the direct economic damage caused by natural disasters were due to tropical cyclones. In other words, costs of coastal hazards are nearly equal to the combined costs of all other major natural disasters, placing a significant burden on the U.S. economy.

By accurately predicting the behavior of developed coastal areas during storm conditions and coupling the results with appropriate risk analyses (Escudero et al., 2012), city planners can make better-informed decisions on sustainable infrastructure development and protection measures. However, the precise extent of storm-induced beach erosion, especially along barrier islands, is currently difficult to predict. Barrier islands, which make up 6.5% of the world's open ocean coastlines (Stutz and Pilkey, 2001), are the mainland coasts' first line of defense against storms, but they are susceptible to severe damage by overwash and breaching.

Overwash deposits are the landward transport of sediment from its originating dune, which lowers dune heights and increases vulnerability to damage from subsequent storms. However, overwash fans can also create new habitat, including those for endangered or threatened species (Dennison et al., 2012). In extreme cases, breaching can occur, which is the formation of a channel across a barrier island. Breaching occurs most commonly on narrow islands with low frontal dune heights. It can destroy infrastructure as the channel is formed (Donnelly et al., 2006; Sallenger, 2000), but it can also reduce flooding from storm surge by equilibrating water levels on the ocean and bay sides (Kraus and Wamsley, 2003). Although both processes can have positive

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environmental and ecological impacts, they are often detrimental to urbanized coasts.

To reduce storm damage along sandy beaches, combinations of nature-based and hard structures, such as armored dunes, have been implemented in several locations globally because they are more cost-effective and environmentally sustainable with respect to the use of hard structures alone (Basco, 1998). Examples in the U.S. include Virginia Beach, VA (Basco, 1998; Basco, 2000; U.S. Army Corps of Engineers [USACE], 2008), Galveston, TX (Gibeaut et al., 2003), and Jekyll Island, GA (Yang et al., 2010; Yang et al., 2012). However, the force-reducing effects of these combinations of nature-based and hard protection designs have not been quantitatively assessed in the field, since it is not possible to remove the structure, recreate the same storm conditions at that location, and compare island responses with and without a structure present. Some laboratory studies, as summarized by Kraus and McDougal (1996), indicated seawalls, which were exposed in most of the experiments, can cause localized increases in erosion, but the net volume of sediment transported was generally less or about the same for cases with a hard structure compared to cases without a hard structure. Morton (1976) qualitatively described erosion around a seawall near Panama City Beach, FL during Hurricane Eloise (1975), but the seawall's effectiveness as a protective structure was not assessed. Irish et al. (2013) described a buried seawall in Bay Head, NJ, which was exposed during the peak of Hurricane Sandy (2012). In their study, the seawall's effectiveness at reducing wave forces was assessed during the peak of the storm using a Boussinesq-type wave model, where the dune shape was static and the seawall was presumed to be exposed throughout the numerical simulations. This approach yielded a factor of two wave force reduction with respect to a “no seawall” case.

In this study, we aim to evaluate the storm force-reducing effects of a dynamic sandy dune with a buried seawall when subject to storm conditions. Specifically, we use the numerical model, XBeach, to simulate hydrodynamics and morphology of Bay Head, NJ under Hurricane Sandy forcing. We then analyze the morphological response of the barrier island and the wave force reducing capabilities of the sandy dune and buried seawall as it becomes exposed during the storm. Expanding the work by Irish et al. (2013), the full duration of Hurricane Sandy and the resulting sediment transport are simulated here.

2. Methods

2.1. XBeach model description

To simulate hydrodynamics and morphology during Hurricane Sandy, we use the numerical model XBeach, version 4613 (Roelvink et al., 2009). The two-dimensional (2D) depth-averaged model resolves infragravity waves, which have been shown to be of importance in the dune erosion process (Roelvink et al., 2009; Van Thiel de Vries, 2009). XBeach is capable of seamlessly modeling all four dune impact regimes as defined by Sallenger (2000), and model skill has been demonstrated on barrier islands (Lindemer et al., 2010; McCall et al., 2010) and urbanized coasts (Nederhoff, 2014; van et al., 2015) among others. XBeach is chosen as the most appropriate numerical model to use, because it has been extensively validated for simulating morphological change over complex 2D bathymetry, and coastal structures can be represented as hard, non-erodable layers.

To calculate low frequency and mean flows, the nonlinear shallow-water wave equations are used. The radiation stress gradients, F, are determined by solving a wave action balance equation, which is coupled with a roller energy balance equation. Sediment transport is modeled using a depth-averaged advection diffusion Van Rijn–Van Thiel de Vries equation where sediment entrainment and deposition is determined by the difference between the depth-averaged and equilibrium sediment concentrations (Van Thiel de Vries, 2009).

Because XBeach does not resolve individual waves or full three-dimensional processes, some processes are parameterized using specifiable parameter values. In this study, most of these parameters are set to published default values; therefore, only parameters that were changed are discussed here. Since short wave runup can have a significant effect on morphology at the beach face (Van Thiel de Vries, 2012), this physical process is activated in all simulations, and the wave runup calibration coefficient, *facrun*, is specified to be 0.8 (default is 1.0, range is 0 to 2.0). Also, *jetfac*, an option used to mimic turbulence production near hard structures, is specified as 0.1 (default is 0, range is 0 to 1.0). Lastly, parameter *facua*, which governs onshore transport, is set to 0.25 (default is 0.1, range is 0 to 1.0) to account for wave skewness in the model. The reader is referred to Roelvink et al. (2009) for full details of the XBeach model.

2.2. Hurricane Sandy

On 29 October 2012, Hurricane Sandy made landfall near Atlantic City, NJ (Fig. 1) and devastated communities along the northeastern U.S. coastline. Hurricane Sandy originated from a tropical wave that entered the Caribbean Sea and intensified to a hurricane on 24 October. Prior to entering the Atlantic Ocean, the storm made direct landfall in Jamaica and Cuba. Then, on 29 October, the hurricane collided with a non-tropical weather system, locally known as a Nor'easter, which prevented Hurricane Sandy from moving offshore. Instead, the hybrid storm, often referred to as Superstorm Sandy, veered west making landfall in the U.S near Atlantic City, NJ at 23:30 GMT on 29 October (Blake et al., 2013).

The unusually large post-tropical storm had a radius of about 280 km, maximum sustained winds of 130 km/h, and a minimum pressure of 945 mb at landfall. Hurricane Sandy was also characterized by record storm surges and large waves lasting over several high tides (Blake et al., 2013; Irish et al., 2013). In total for the U.S., Hurricane Sandy caused 159 fatalities and damages are estimated as $67 billion (USD) (Smith et al., 2015), making it the second-costliest hurricane since 1900 (Blake et al., 2013). Other physical damages were severe dune erosion, overwash and breaching of several barrier islands, including Fire Island, NY, Assateague Island, VA and along New Jersey. Hurricane Sandy left over 8.5 million customers without electricity on the order of weeks to months after landfall, caused health concerns, such as upper respiratory symptoms and worsened chronic conditions, and psychological impacts, including anxiety, sleep disturbances and posttraumatic stress (Blake et al., 2013; Lowe et al., 2015; Subaiya et al., 2014). A total of 24 states were impacted by Hurricane Sandy, ranging from gusting winds over the eastern seaboard and the Great Lakes to heavy snowfall in West Virginia and North Carolina, causing severe disturbances to businesses, land and air transportation, and social aspects (Blake et al., 2013; Halverson and Rabenhorst, 2013).

2.3. Study area

This study focuses on Bay Head, a township located along a barrier island in New Jersey (Fig. 1). This island is a product of rapid post-glacial sea level rise and consists of Holocene beach and estuarine deposits, which are easily mobilized by waves and currents (Department of Environmental Protection, 1999; The Richard Stockton Coastal Research Center [RSCRC], 2015). Because the island is narrow, low-lying and mildly sloping, it is particularly vulnerable to storm surges (RSCRC, 2012; Williams, 2013). Although small patches of vegetation exist on the island, they are unable to protect Bay Head from large scale overwash during storm events, as has been observed in other locations (Feagin et al., 2015; RSCRC, 2012).

To help protect the island, over half of the shoreline is fronted with a rock seawall buried beneath a sand dune. The 1260-m long structure