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Effects of storm clustering on beach/dune evolution

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ABSTRACT

Impacts of storm clustering on beach/dune morphodynamics were investigated by applying the state-of-the-art numerical model XBeach to Formby Point (Sefton coast, UK). The adopted storm cluster was established by analysing the observed winter storms from December 2013 to January 2014 using a storm threshold wave height. The first storm that occurred during this period is regarded as exceptionally intense, and the occurrence of such a cluster of events is very unusual. A 1D model was setup for the highly dynamic cross-shore at Formby Point. After initial calibration of the model parameters against available post-storm profile data, the model was used for the simulation of the storm cluster. It was assumed that no beach recovery occurred between adjacent storms due to the very short time intervals between storms. As a result, the final predicted post-storm profile of the previous storm was used as the pre-storm profile of the subsequent storm. The predicted evolution during each storm was influenced by the previous storms in the cluster. Due to the clustering effect, the bed level change is not proportional to the storm power of events within the cluster, as it would be in an individual storm case. Initially, the large storm events interact with the multi-bared foreshore enabling the subsequent weaker storms to influence the upper beach and lower dune system. This results in greater change at the dune toe level also during less severe subsequent storms. It is also shown that the usual water level threshold used to define dune erosion is over predicted by about 1 m for extreme storm conditions. The predicted profile evolution provides useful insights into the morphodynamic processes of beach/dune systems during a storm cluster (using Formby Point as an example), which is very useful for quantifying the clustering effects to develop tools for coastal management.

1. Introduction

Beach/dune systems which play the role of a natural barrier against coastal inundation are often under threat due to storm-induced erosion (Hanley et al., 2014; Tătui et al., 2014; Harley and Ciavola, 2013; Gómez-Pina et al., 2002; Hanson et al., 2002 and references therein). This poses major concerns for coastal safety and sustainable development in the areas where frontal dune systems are present. Damages to beach/dune systems from storm impacts depend on a number of factors. Large storm events with higher wave heights and extreme water levels cause great damage while storm duration, direction and peak wave period also significantly contribute to the extent of the damage (Karunarathna et al., 2014; Cox and Pirrello, 2001). Moreover, occurrence of a series of storms could result in a major impact compared with a single storm with the same characteristics (Coco et al., 2014, Dolan and Davies, 1994). Examples of storm impact on dunes and on coastal systems for series of events can be found in Karunarathna et al. (2014); Ferreira (2005); Callaghan et al. (2008); Vousdoukas et al. (2012), Houser (2013), Van Enckevort and Ruessink (2003) and Lee et al. (1998). Karunarathna et al. (2014) showed that clusters of small storms occurred at close intervals can be more damaging than isolated large single storms at Narrabeen Beach Australia. Ferreira (2005) compared erosion due to storm clusters and single events using a long-term wave record from the northwest Portuguese coast and found that storm clusters with small return levels induce average erosion volumes similar to that of a single storm with a larger return period. Callaghan et al. (2008) showed the impact of closely spaced storm events on the erosion volumes using a probabilistic approach. Beach erosion and recovery processes due to consecutive storms were investigated by Vousdoukas et al. (2012). Impacts of foredune morphology on the barrier island response to extreme events at Texas were investigated by Houser (2013). Van Enckevort and Ruessink (2003) showed that the temporal scale of bar position fluctuations is related to the storm sequence. Lee et al. (1998) found that storm groups of close succession can have a large impact on morphology.

An intense storm can cause episodic erosion of a beach/dune system, however, the system generally recovers by onshore sediment transport process (Vousdoukas et al., 2012). The time required for the system to recover to its' pre-storm state is termed the '*recovery period*'

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(Dissanayake et al., 2015b). If a second storm event which has less erosion potential compared with that of the first, attacks before the recovery period of the first event, more damages are expected to be experienced on beach/dune due to the fact that the system becomes more susceptible to erosion after the first storm event. This is due to reduced wave dissipation across the shoreface following erosion and feature flattening (Dissanayake et al., 2015b). However, the localized impact at the dune toe will depend on the extent to which the frontage has recovered. If it is still set far enough back, the secondary storm may not be able to cause continued retreat as this will be limited by the water elevation relative to the dune toe location enabling the waves to act on the dunes. Therefore, a cluster of storm events tends to worsen storm induced erosion of beach/dune systems compared with that of the single occurrence of a more intense storm (Dissanayake et al., 2015a).

Numerical models which are dedicated to investigate the storm driven evolution, have rapidly advanced over the last years with increased physical processes embedded to predict more accurate and reliable beach/dune evolution (Stive and Wind, 1986; Larson and Kraus, 1989; Roelvink and Stive, 1989; Bosboom et al., 2000; Larson et al., 2004; Roelvink et al., 2009). The XBeach model (Roelvink et al., 2009) is one of the latest developments and an open-source model which is being continually improved by applications in different coastal environments around the world. This model has proven to be capable of predicting storm impacts on morphodynamics of beach/dune systems in numerous case studies (Dissanayake et al., 2014, 2015a, 2015b; Souza et al., 2013; Harley and Ciavola, 2013; Splinter and Palmsten, 2012; Harley et al., 2011; Williams et al., 2011; McCall et al., 2010; Lindemer et al., 2010). These previous applications motivated us to use XBeach in the present study in order to investigate storm driven beach/dune evolution during an extreme storm cluster, using Formby Point, Liverpool Bay (Sefton coast, UK) as a case study. The hypertidal conditions at this site extend previous research in storm cluster impact to regions where the tidal regime at the time of the storm is also an important factor. The mean spring tidal range is 8.2 m (Brown et al., 2010a), storms that occur during neap or mean tides are therefore unlikely to impact the dune toe unless the surge at high water is large enough to increase water levels to at least similar elevations as those during spring tides (Pye and Blott, 2008). Such storms will however change the beach profile modifying the beach-dune system resilience to later storms. This research therefore enables an assessment of the robustness of typical water level thresholds used to determine likely dune erosion events under extreme wave conditions.

Liverpool Bay and more broadly the Irish Sea has been subjected to numerous research studies investigating the hydrodynamic and morphodynamic characteristics (Brown et al., 2010a, 2010b, 2010c, 2012; Wolf et al., 2011; Brown, 2010, Blott et al., 2006 and many others). Although not all of these results are directly applicable to the Sefton coast, they provide information on the tide and surge interactions, extreme wind and wave events, and also sediment transport and morphological changes which influence the local morphodynamics. Some studies have discussed morphological evolution along the Sefton coast itself (Souza et al., 2013; Esteves et al., 2009, 2011, 2012; Williams et al., 2011; Halcrow, 2009; Pye and Neal, 1994; Pye and Blott, 2008) and they have mainly focused on the historical data analysis implying the general patterns of morphological changes. Pye and Neal (1994) analysed the historical shoreline changes from 1845 to 1990 and concluded that centrally the Sefton coast (Formby Point) is eroding while northern and southern parts are accreting. Decadal variation in dune erosion and accretion from 1958 to 2008 was investigated by Pye and Blott (2008) using a series of beach and dune surveys. Only a few studies have focussed on applying numerical models to investigate beach/dune response to storm events (Dissanayake et al., 2014; Souza et al., 2013; Williams et al., 2011). Both Souza et al. (2013) and Williams et al. (2011) have focused on the storm driven dune erosion and potential hinterland flooding on the Sefton coast. They adopted the XBeach numerical model (1D) imposing event-scale wave boundary conditions (i.e. single event) over a few tidal cycles. Dissanayake et al. (2014) used a 2D XBeach model to investigate the Sefton beach/dune response to storm events. This research extends previous studies to look at clusters of storms rather than the previous event based researches.

During the 2013/2014 winter, the UK experienced an exceptional series of storms culminating in catastrophic coastal damages at many locations (e.g. Dawlish, Aberystwyth, see Wadey et al., 2014; Wadey et al., 2015) and widespread, persistent flooding at hinterland areas (e.g. Great Yarmouth, see Wadey et al., 2014). It should be noted that the first storm event that occurred during this period can be regarded as exceptionally severe, and the occurrence of a series of large storms at close intervals was also very unusual (Wadey et al., 2015) and appeared to be more damaging to coastal systems (see UK Met Office report online version, http://www.metoffice.gov.uk/media/pdf/n/i/Recent_Storms_Briefing_Final_07023.pdf).

The objective of the present study is to investigate the morphological changes of a beach/dune system (Formby Point) under the impact of clustered storm events, which occurred in the 2013/2014 winter period. The response of the Formby Point beach/dune system to the clustered storms was investigated through modelling cross-shore profile change and analysing cumulative impact of the storm cluster as opposed to individual storm events. We focus on wave impact over the full cross-shore profile to identify how changes in the lower beach profile (the multi-bared system) influence the vulnerability of the dunes in later storms with higher water elevation. The results found in this study will be very useful for the future management of this highly dynamic beach system as storm clustering during winter months is not unusual in the UK. Also, even though this study is focused on a selected beach, the research findings will be transferable to other sandy hypertidal coastal systems around worldwide.

The structure of this paper is as follows. Sections 2 and 3 describe the study area and the cluster of storms occurred in winter 2013/2014. Section 4 describes the modelling approach used to assess the morphodynamic impact of the storm cluster. A discussion of the model results is given in Section 5 while Section 6 provides the conclusions.

2. Study area

The Sefton coast is about 36 km long, convex in shape, and located between two estuaries, the Mersey (to the south) and the Ribble (to the north), in Liverpool Bay (Fig. 1a) (Williams et al., 2011). The Sefton coastal system consists of natural beaches/dunes of high recreational value, designated nature conservation sites, engineered beaches protected by seawalls, groynes and revetments and, rubble beaches covered with building material debris and rock armours (Fig. 1b). The dunes within the system extend about 4 km inland, reach about 30 m in height at some locations (Esteves et al., 2012) and represent 20% of the UK's dune population (Holden et al., 2011). These dunes form an effective natural coastal flood defence for the local urban areas, high grade agricultural lands and a significant number of conservation areas of national and international interest, which consist of an extremely high biodiversity, forming habitat for a number of rare animals and plants (Edmondson, 2010), e.g., priority habitats in the EU Habitats and Species Directive.

Several coastal management issues have been accelerated due to storm impacts on the Sefton beach/dune system; examples include exposing Nicotine waste that had been buried in the past, and coastal squeeze of land with different uses (conservation, agriculture, leisure and tourism) (Houston, 2010). Success of implementing solutions to these issues depends on the understanding how this complex beach/dune system interacts with coastal storm conditions.

The location also has challenging physical conditions, which management plans must consider. Liverpool Bay has an alongshore propagating semi-diurnal hyper-tide with a mean spring tidal range reaching about 8.2 m (Brown et al., 2010a; Palmer, 2010). Brown et al.