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Linkages between sediment composition, wave climate and beach profile variability at multiple timescales

Harshinie Karunarathna [a,*], Jose Horrillo-Caraballo [a], Yoshiaki Kuriyama [c], Hajime Mase [b], Roshanka Ranasinghe [d,e,f], Dominic E. Reeve [a]

[a] College of Engineering, Bay Campus, Swansea University, Fabian Way, Swansea SA1 8EN, UK
[b] Disaster Prevention Research Institute, Kyoto University, Uji 611-0011, Japan
[c] Port and Airport Research Institute, 3-1-1 Nagase, Yokosuka 239-0826, Japan
[d] UNESCO-IHE, PO Box 3015, 2601, DA, Delft, The Netherlands
[e] Harbour, Coastal and Ocean Engineering, Deltares, PO Box 177, 2600, MH, Delft, The Netherlands
[f] School of Civil Engineering, The University of Queensland, Brisbane, QLD 4072, Australia

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ABSTRACT

The paper analyses, compares and contrasts cross-shore morphodynamic behaviour of four diverse beaches that have very different regional settings, wave climates and sediment characteristics, with the aid of rarely available long term measurements of beach profiles and incident waves. The beaches investigated are Narrabeen Beach, New South Wales, Australia; Milford-on-Sea Beach, Christchurch Bay, UK; Hasaki Coast, Ibaraki Prefecture, Japan; and Joetsu-Ogata Coast, Niigata Prefecture, Japan. A statistical analysis, equilibrium beach profile analysis and Empirical Orthogonal Function analysis are used to investigate, compare and contrast spatial and temporal variability of cross shore beach profiles of the selected beaches at short-, medium- and long-term timescales. All beaches show evidence of multi-timescale morphodynamic change. Narrabeen Beach profile has the highest sensitivity to local weather patterns. Milford-on-Sea, Joetsu-Ogata and Hasaki profiles are sensitive to seasonal variation of the wave climate however, they also show some correlations with regional climate variabilities. The nature of sediment exchange across the profile, which contributes to profile shape change with time, is found to be related to sediment characteristics across the profile. At Milford-on-Sea and Joetsu-Ogata, both of which have composite profiles, sediment exchange between the upper beach and the inter-tidal zone dominates profile change, irrespective of the distinct differences in sediment composition found in the two beaches. On the other hand in Narrabeen and Hasaki where beach sediment comprises medium to find sand, sediment exchange and hence profile change occur mainly in intertidal and subtidal zones.

1. Introduction

Temporal variability of beach morphology is driven by sediment transport in cross-shore and/or longshore directions. Longshore beach change is mainly characterised by long term variability of shoreline position, beach rotation and development of rhythmic features. On the other hand, cross-shore change is characterised by changes in the shape of cross-shore profile and the area of beach cross section in time. While longshore beach changes have significant impacts on the medium to long term beach position and orientation, cross-shore change occurs over a wide range of timescales and can have detrimental impacts on the stability of natural and man-made sea defences, coastal eco-systems, infrastructure and safety. In this study we specifically focus on morphodynamic change in the cross-shore direction as cross-shore beach profile change spread over a range of time scales and is crucial to short-medium term beach stability and storm response, stability of coastal defences, wave overtopping and coastal inundation.

Beach profile morphology changes over a range of time and space scales. Here we define short term variability as that which occurs over a period of days to a month as a result of episodic events (storms); medium-term variability as that which over several months (e.g. winter-summer wave change) to several years (e.g. due to regional climate variability, engineering intervention and prevailing sedimentary processes; and long term variability as that which occurs over a period of a decade to a century, associated mainly with climate change impacts; and very long term millennial scale evolution as a result of quaternary sea level changes. Cross-shore beach change is widely thought to be controlled by the incident wave climate, water level variability, nearshore currents, sediment characteristics and sediment distribution across the profile (Niodoroda et al., 1995; Stive and de Vriend, 1995; Pedrozo-Acuna et al., 2006; and many others). The cross-shore variability of sandy beaches is distinctly different to that of coarse grain beaches and/or composite sand-gravel beaches in terms of profile shape and profile

* Corresponding author.
E-mail address: H.U.Karunarathna@swansea.ac.uk (H. Karunarathna).

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response to hydrodynamic forcing (Larson and Kraus, 1994; Pontee et al., 2004; Karunarathna et al., 2012).

Relationships between beach change and drivers that govern the change have been extensively studied in the past, using field measurements, experimental investigations and numerical models, covering a range of time scales spanning from short-term to long-term. For example, Lee et al. (1998) studied storm driven beach change using beach profiles measured at Duck, North Carolina. Ferreira (2005) investigated beach response to storms using a set of measured data from a Portuguese coast. More recently, Coco et al. (2014) investigated beach response to storm sequences using beach profiles measured at Truc Vert Beach, France. McCall et al. (2015) modelled storm response of gravel beaches and barriers. Karunarathna et al. (2014) investigated storm scale morphodynamic beach profile response using historically measured beach profiles of Narrabeen Beach Australia. They found that single storms or storm clusters predominantly change the supra tidal and inter-tidal part of the beach profile and that beach erosion volumes are strongly correlated to the power of the storm. In addition, many research results have been published on numerical modelling studies of storm scale beach change (e.g. Larson and Kraus, 1989; Roelvink et al., 2009; Ruiz de Algeria-Arzaburu et al., 2011; Williams et al., 2012; Callaghan et al., 2013; Pender and Karunarathna, 2013; McCall et al., 2015).

Medium term beach profile change and its relationship with changes in wave climate have also been well studied and modelled my numerous researchers. For example, Vellinga (1983, 1984) developed a relationship between cross-shore distance and profile depth for erosive beach profiles, as a function of grain size. Inman et al. (1993) investigated winter/summer seasonal variability of beach profile shape. Kuriyama (2002) and Kuriyama et al. (2012, 2008) investigated the medium term cross-shore profile behaviour including shoreline position change, inter-tidal bar movement and profile shape variability using a set of regularly measured beach profiles over a few decades at Hasaki Coast, Japan. Their studies were able to form linkages between seasonal to inter-annual change in wave climate and profile behaviour. Relationships between incident wave conditions and medium term profile variability have also been examined and established using various techniques and field observations by, among others, Larson et al. (2000), Kroon et al. (2008), Horrillo-Caraballo and Reeve (2008, 2010), Karunarathna et al. (2012), using numerous field observations.

Long term adjustments of beach profiles associated with sea level changes have also received the attention of many researchers. Bruun (1954) investigated cross-shore profile change and developed the concept of equilibrium beach profile shape on sandy beaches. Using this concept as a basis, a simple empirical relationship between long term sea level change and profile shape (Bruun Rule) was developed by Bruun (1962). Dean (1977) provided the physical argument for the shape of this profile shape and developed Dean's equilibrium profile. Later, Dean (1991) included gravity effects to the Dean (1977) profile to get the linear upper beach retain the dependence on grain size. Bodge (1992) proposed an exponential beach profile model. Larson et al. (1999) provided physical reasoning for a linearly sloping upper beach but this result was independent of grain size. Long term adjustments of beach profiles to Quaternary sea level changes have also been studied by Carter (1986) and Carter and Orford (1993).

Even though numerous studies have been reported on change of cross-shore morphodynamics of different beach types under different wave and hydrodynamic conditions in isolation, studies on inter-comparison of sites with different characteristics are sparse. For example, two different sites with different site characteristics may behave very differently under the same wave and hydrodynamic condition. Also, there are still substantial gaps in our knowledge on how beach morphodynamics vary over the full range of timescales. For instance, profile variability of coarse sediment and mixed sediment beaches is largely unknown. In addition, studies on the effects of medium term climatic variability on profile shape changes are scarce. This study focuses on comparing and contrasting cross-shore morphological change of four very different beaches using historic measurements of beach profiles. The aim of this study is to identify commonalities and divergences in beach profile behaviour among the case study sites. Section 2 of the paper describes the four field study sites. In Section 3, general variability of beach profiles at the four sites is analysed. In Section 4, beach profiles are compared with Dean (1991)'s equilibrium profile. Section 5 analyses profiles using Empirical Orthogonal Functions (EOFs). In Section 6, a discussion of the results presented in Sections 3, 4, and 5 are given and those results are related to incident wave climate. Chapter 7 concludes the paper.

2. Study sites

The field sites used in the present study are Narrabeen Beach, New South Wales (NSW), Australia; Milford-on-Sea Beach, Christchurch Bay, UK; Hasaki Coast, Ibaraki Prefecture, Japan; and Joetsu-Ogata Coast, Niigata Prefecture, Japan. These sites have distinctly different characteristics in terms of exposure, sediment characteristics, tidal regime and incident wave climate. Historical beach profile surveys and wave measurements spanning a few decades are available at all 4 sites making them ideal candidates for this multi-time scale analysis and inter-comparison. The selected cross-shore transects selected from these sites reported to have the least impact from longshore sediment transport.

2.1. Narrabeen Beach, New South Wales, Australia

Narrabeen Beach is a wave-dominated embayed beach located 20 km north of Sydney, in New South Wales (NSW), Australia. The beach is 3.6 km long and bounded by two headlands, Narrabeen Head to the north and Long Reef Point to the south and is composed of medium to fine quartz and carbonate sands with $D_{50} = 0.3–0.4$ mm (see Fig. 1a).

The beach is exposed to a highly variable, moderate-to-high energy wind waves superimposed on long period, moderate-to-high energy south-easterly swell waves (Short and Wright, 1981). Waves are derived from three cyclonic sources: Mid-latitude cyclones pass across the southern Tasman Sea all-year-round, generating south-easterly swell; extra-tropical cyclones off NSW coast generating east and south-easterly waves peaking between May and August; tropical cyclones that generate moderate to high north-easterly and easterly swell during February and March. In addition, summer (December to March) sea breezes generate low to moderate north-easterly seas. On average, Narrabeen Beach is subjected to 12 storms per year (based on the local definition that $H_s > 3$ m lasting more than 1 h represents a storm (Callaghan et al., 2008)). Fig. 1b shows typical offshore wave climate measured at the wave buoy near Long-Reef Point located in around 80 m water depth offshore of Narrabeen Beach. The beach experiences micro-tidal, semi-diurnal tides with mean spring tidal range of 1.6 m and neap tidal range of 1.2 m. MHWS and MLWS are 0.9 m and −0.7 m above Australian Height Datum (AHD) respectively. The effect of tides on the morphology of Narrabeen Beach is considerably less than that of waves (Short, 1985; Short and Trembanis, 2004).

Cross-shore beach profiles at five alongshore locations along the Narrabeen Beach have been regularly measured first at bi-weekly intervals and then, at monthly intervals since 1977, by the Coastal Studies Unit, University of Sydney. Surveys were undertaken at low tide and profiles were recorded at 10 m cross-shore intervals from a fixed bench mark at the landward limit of the active beach at 10 m elevation. Beach profiles measured at monthly intervals from 1977 until 1992 were used in this study. Hourly non-directional (1976–1992) and directional (1992–2005) wave data were also measured at an offshore wave buoy located at the Long Reef Point, at a depth of 80 m. Cross-shore beach profile surveys carried out at Profile 4, situated in the central part of the Narrabeen Beach (Fig. 1a), which is the least likely location