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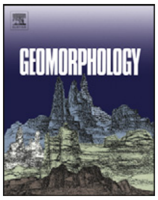

Investigation of medium-term barred beach behavior using 28-year beach profile data and Rotated Empirical Orthogonal Function analysis

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A R T I C L E I N F O

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A B S T R A C T

A 28-year beach profile dataset for a stretch of the Hasaki coast in Japan was examined using Rotated Empirical Orthogonal Function (REOF) analysis to investigate the cross-shore variation in the characteristics of beach profile change. The data were obtained weekly, on a micro-tidal wave-dominated intermediate beach, along a survey line extending from the backshore to a water depth of approximately 5 m. REOF analysis using the first eight empirical orthogonal functions led to the study area being divided into five unique zones based on beach profile change patterns, namely the backshore, the foreshore, the inner and outer transition zones and the bar-trough zone. Although these zones were notably distinct from one another, the profiles in foreshore and the shoreward part of the inner transition zone changed in the same way over periods of 6 and 12 months.

1. Introduction

The nearshore bathymetry of a sandy beach changes at various temporal scales corresponding to waves, water levels and nearshore currents. From a morphological perspective, the nearshore area is divided into several zones such as the foreshore or the bar-trough zone. The morphological changes within a zone are sometimes strongly and sometimes negligibly correlated with those in other zones. Shepard (1950) and Winant et al. (1975) reported that an inner bar is formed when a foreshore is eroded, but the bar disappears when the foreshore recovers. On the other hand, Birkemeier (1984); Lippmann et al. (1993); Larson and Kraus (1994); Guillén et al. (1999); Kuriyama (2002); Ruessink et al. (2007) and Price and Ruessink (2011) showed that the shoreline movement, which represents the bathymetric change in the foreshore, or the inner bar movement is not strongly linked with the outer bar movement.

Bathymetric changes on sandy beaches under various wave conditions, including cross-shore movements and plan configuration changes of bar and shoreline, were conceptually modeled by Wright and Short (1984) on the basis of filed data for micro-tidal wave-dominated sandy beaches. According to the model, under severe wave conditions, a beach will shift toward a state where the outer bar is located offshore and the bathymetry is relatively uniform alongshore, whilst under mild wave conditions it will shift toward a state where the outer bar is located near to or attached to the shore and the bathymetry varies rhythmically alongshore.

The beach states predicted by the Wright and Short model and the transitions between the states were confirmed through the analysis of video and survey data collected in the field. The results of these analyses validated the model and were used to modify and expand it, making it applicable to beaches under a wide range of wave, tide and sediment conditions (e.g., Wright et al., 1987; Sunamura, 1988; Lippmann and Holman, 1990; Masselink and Short, 1993; Short and Aagaard, 1993; Ranasinghe et al., 2004; Castelle et al., 2007; Ortega-Sánchez et al., 2008; Sénéchal et al., 2009; Price and Ruessink, 2011; Scott et al., 2011). However, the Dean's parameter (Dean, 1973), which is a parameter for predicting the beach state and consists of the sediment fall velocity and the wave height and period, does not necessarily perform well (e.g., Anthony, 1998; Levoy et al., 2000; Masselink and Pattiaratchi, 2001; Jackson et al., 2005). The beach state is also influenced by other factors including the cross-shore variation of grain size and geological control.

The model essentially assumes that the bathymetries in the bar-trough zone and near to the shoreline co-vary. Bar and shoreline movements are often strongly linked. However, in the field, the timescale of outer bar deformation is not necessarily the same as that of foreshore bathymetry change as mentioned before (e.g., Birkemeier, 1984; Lippmann et al., 1993; Larson and Kraus, 1994; Guillén et al., 1999; Kuriyama, 2002; Ruessink et al., 2007; Price and Ruessink, 2011). One reason for the difference is the cross-shore variation of the ratio of broken waves. Only large waves break on an outer bar. However, the ratio of broken waves increases with the decrease in water depth and eventually all of the waves break near the shore. As a result, even when waves are relatively low and an outer bar does not move, the shoreline or the inner bar can still change with respect to the cross-shore position and plan configuration.

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The field observations shown above suggest that the temporal characteristics of bathymetry change are not constant in the cross-shore direction. However, the profile changes in various morphological zones in medium term (over a decade), in particular between the foreshore and bar-trough zone, and the linkages of the changes are not well understood although they are vital in terms of sediment budget, wave energy dissipation due to wave breaking (which can reduce the risk of coastal flooding), marine ecology and environment, and the effects of climate change.

In the investigations of morphological change in the nearshore, Empirical Orthogonal Function (EOF) analysis and Complex Empirical Orthogonal Function (CEOF) analysis are commonly used. Winant et al. (1975) showed that the second mode in EOF analysis represents a profile change in which a berm is eroded and a bar is formed in winter, and the converse occurs in summer. On beaches where at least one bar always exists, EOF and CEOF analyses successfully reveal the characteristics of bar movement (e.g., Wijnberg and Terwindt, 1995; Kuriyama, 2002; Ruessink et al., 2000; Kuriyama et al., 2008, Karunarathna et al., 2012). Bar movements are generally well represented by the first one to two modes (when EOF and CEOF analyses are applied to the elevation values with the means removed). However, other profile changes shoreward of the bar-trough zone are represented by several minor modes in EOF and CEOF analyses and hence, beach behaviors in that area are not clearly revealed in those analyses.

Rotated Empirical Orthogonal Function (REOF) analysis, which is widely used in climate research, is a method in which EOFs are transformed to a non-orthogonal linear basis (e.g., von Storch and Zwiers, 1999; Hannachi et al., 2007). REOF analysis is considered to be useful to detect localized behaviors, whereas EOF analysis tends to detect behaviors spanning the whole domain, which are sometimes difficult to interpret.

The objective of this study was to investigate localized medium-term features of the beach profile change from the bar-trough zone to the backshore on a barred beach to understand the profile changes in various zones, which may have different time scales, and their correlations. For this purpose, we applied REOF analysis to the beach profile data that were weekly obtained at the Hasaki coast in Japan over a period of 28 years.

2. Study site and data description

The Hasaki coast is located in eastern Japan facing the Pacific Ocean (Fig. 1). At Hasaki, there is a 427 m-long field observation pier of Hazaki Oceanographical Research Station (HORS). Along the pier, the profiles were measured at 5 m intervals using a rope with graduated depth-marking and a 5 kg lead from the pier and a level and a staff landward of the pier every workday from March 12, 1986 to March 31, 2011, and once a week, mostly on Mondays, since April 5, 2011.

The dataset used in this study consists of the Monday profile readings taken from March 17, 1986 to November 3, 2014. Where readings were not taken, data were inferred by linear interpolation of adjacent measured values.

The mean beach slope was approximately 1/25 at $z = 0$ m (z is the elevation) and 1/120 at the tip of the pier (Fig. 2). The elevation was based on the datum level at Hasaki, and defined to be positive in the upward direction.

The bathymetry around HORS is nearly uniform alongshore, and the influence of the pilings of the pier on the bathymetry is relatively small (Kuriyama, 2002). The medium sediment size is 0.2 mm (Katoh and Yanagishima, 1995). The high, mean, and low water levels are 1.25 m, 0.65 m, and −0.20 m, respectively.

Offshore waves were measured at a water depth of about 24 m with an ultrasonic wave gauge for 20 min every 2 h (see location in Fig. 1). The mean offshore significant wave height and period are 1.34 m and 8.00 s, respectively (Banno and Kuriyama, 2012). Waves are large from January to April owing to extratropical cyclones and from September to October owing to typhoons (tropical cyclones) (Kuriyama et al., 2012). The offshore wave energy flux E_f ($=\rho g H_s^2 C_g / 16$, ρ is the seawater density, g is the gravitational acceleration, H_s is the significant wave height and C_g is the group velocity corresponding to the significant wave period) has peaks at 6 and 12 months (Fig. 3). The data used in the spectral analysis is the same as those used in Kuriyama et al. (2012), from October 1986 to January 2009, because of missing data after the 2011 off the Pacific coast of Tohoku Earthquake. The data were tapered using the Boxcar window. The spectral densities

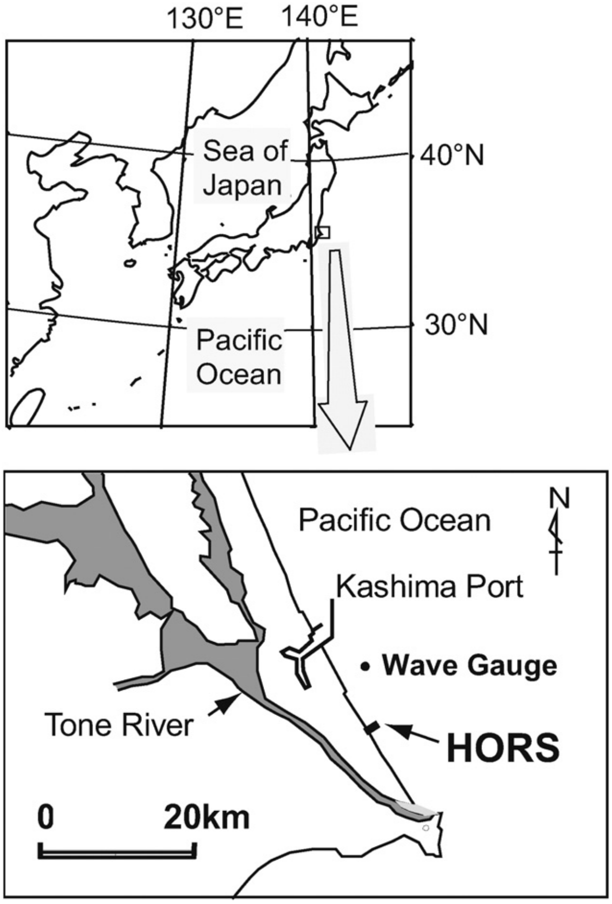

Fig. 1. Study site.

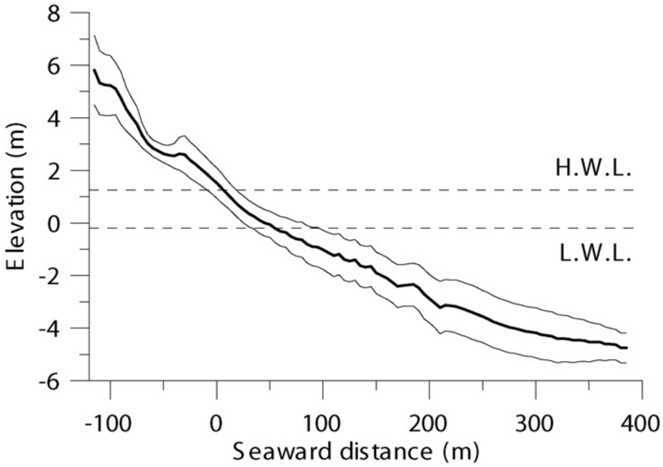

Fig. 2. Mean beach profile (thick solid line) and the mean plus and minus one standard deviation (thin solid lines).