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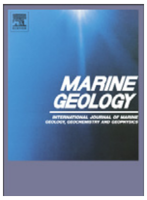

Formation of two-section cross-shore profile under joint influence of random short waves and groups of long waves

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ABSTRACT

We show that beach profiles may develop a two-section almost-equilibrium structure under joint impact of short wind waves and groups of long waves with duration of a few minutes and properties that are independent of wind waves. The upper section of the profile is convex and follows the power law $h \sim x^{4/3}$ at small depths and in the swash zone. Wind waves may cause either erosion or accretion of this section but groups of long waves effectively redistribute the sediment over the convex section and practically do not alter the sediment volume. The ability of short groups of highly energetic waves to regularly build up such profiles from those created by random sea waves is a principally new feature of wave-coastal interaction that may have extensive consequences on the estimates of the wave-induced coastal hazards.

1. Introduction

The cross-shore beach profile is one of the most important characteristics of natural sea coasts for a variety of aspects, starting from its use as a tool to indicate whether or not the beach is accreting or eroding (Healy, 1996) and ending with the predictions of the vulnerability of the particular region with respect to anomalous "nonreflecting" wave behavior (Didenkulova et al., 2009b; Didenkulova and Pelinovsky, 2010). The search for a universal equilibrium shape of beaches (eventually reached only as a long-term average) was initially based on empirical data (Dean, 1977, 1991). The assumption of the uniform volumetric wave energy dissipation in the surf zone leads to the simple power law $h = Ax^{2/3}$ for the increase in the water depth h with the distance x from the waterline (Dean, 1991).

A variety of profiles following the power law $h = Ax^b$ with different values of exponent b may reflect different balances of constructive and destructive forces (Bowen, 1980; Dean and Dalrymple, 2002). Such profiles are universal (at least for certain seasons (Larson and Kraus, 1994; Karunarathna et al., 2009)) for a variety of wave conditions (Wang and Kraus, 2005; Grasso et al., 2009). For Dutch dune profiles $b = 0.78$ provides a better fit (Steetzel, 1993). Kit and Pelinovsky (1998) found a range of $b = 0.73$–1.1 for Israeli beaches. Various power-law approximations for beach profiles are also used in theoretical models (Kobayashi, 1987; Kit and Pelinovsky, 1998). Other, for example, exponential and logarithmic approximations of the beach profile (Romańczyk et al., 2005; Dai et al., 2007) can also be approximated by the power law in the vicinity of the shoreline.

Although the unique power law for the entire beach profile is a widely used model even in extreme conditions (Romańczyk et al., 2005; Are and Reimnitz, 2008), realistic beach profiles frequently have a much more complex structure. Some profiles consist of two concave sections, each of which follows the 2/3 power law: a surf profile with a milder slope in the vicinity of the waterline and a shoaling profile with a steeper slope further offshore (Inman et al., 1993; Bernabeu et al., 2003). A more general family of two-section profiles involves both convex (usually close to the shoreline) and concave sections (usually further offshore; e.g. terrace-like or step-like profiles in macrotidal environments hosting substantial wave loads (Wright and Short, 1984)). Such situations could be interpreted as a limiting case of bimodal wave systems where the periods of long (tidal or seiche) waves exceed those of wind waves by several orders of magnitude.

More generally, the joint impact of wave systems with different internal properties (such as short random waves, wave groups, single long waves, etc.) apparently has a major role in the formation of realistic beach profiles (although the contribution of short groups of long waves may become explicitly evident during limited time intervals (Baldock et al., 2011) and averaging over relatively long intervals may easily smooth out their impact). The influence of a superposition of wind waves and long waves (from swells to infragravity waves, incl. effects of wave groupiness) on the cross-shore sediment transport is quite well understood. In deeper areas, offshore from the surf zone and in the outer surf zone, bound long waves usually favor offshore transport (Shi and Larsen, 1984; Ruessink et al., 1998). The situation is far more complicated in the vicinity of sand

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bars (Osborne and Greenwood, 1992; Aagaard and Greenwood, 2008) where the transport directions may largely diverge. Near the waterline regular long waves tend to promote onshore transport and a beach accretion.

The influence of wave groupiness on sediment transport is also extremely complicated (Sato, 1992; Ting and Kirby, 1995; Ting, 2002). Long waves tend to promote shoreward transport and accretion (Baldock et al., 2011), whereas random waves and especially series of bichromatic wave groups increase offshore transport and promote erosion compared to the impact of the background monochromatic short-wave conditions only (Baldock et al., 2010). Therefore, particularly large change in the beach response may be expected when groups of long waves are systematically superposed with a mostly random wave field.

In this paper we address beach profiles that develop a specific two-section structure under the impact of two wave fields with clearly different properties. In contrast to the earlier research, we consider a situation in which the properties of short groups of long waves are not correlated with those of the background wave system. The key development is the observational demonstration of the existence of a convex section of the beach profile following the power law $h \sim x^{4/3}$ at small depths and in the swash zone. This section is developed and maintained under joint impact of wind waves with periods of 2–3 s and groups of ship-induced waves with typical periods of 8–10 s and duration of a few minutes in a situation where the average energy and energy flux of both wave systems are approximately equal and where ship waves arrive several times a day after irregular intervals.

2. Wave properties and experiment setup

The reaction of the beach profile to the joint impact of random wind waves and groups of long waves (with periods matching typical periods of open ocean swells) was performed in Tallinn Bay in the Gulf of Finland, the Baltic Sea. This area hosts regular fast ferry traffic, with fairways located close to the shoreline and vessels operating at cruise speeds up to 30 knots (Parnell et al., 2008; Soomere et al., 2011). During spring and summer seasons the periods of the highest vessel wake waves considerably exceed those of wind waves (Soomere, 2005). Wake waves are concentrated into 10–20 minutes usually separated by longer time intervals. The experiment was performed in overall low natural wave conditions in June 2009. The properties of the waves and the reaction of the beach were measured continuously during 18 days at Pikakari Beach (Tallinn Bay, Baltic Sea) (Kurennoy et al., 2011). The evolution of this relatively sheltered site is almost entirely dominated by wave action in this almost tideless area. The sandy beach, formed to the north of a jetty (that was constructed about 100 years ago) has evolved to an almost equilibrium state, with very limited longshore drift, a well-defined shallow section of the profile down to the closure depth (Fig. 1a) and a relatively steep slope further offshore, at depths >3 m.

Waves approaching the study site were recorded using a downward-looking ultrasonic echosounder (resolution 1 mm, sampling frequency 5 Hz) mounted on a stable tripod approximately 100 m from the shoreline, 2.4 km from the sailing line at a water depth of about 2.7 m. The record contains more than 150 clearly identifiable wake events (Kurennoy et al., 2011). Maximum wave heights (up to 0.7 m, comparable to the highest wind waves during the study period) occurred exclusively for the longest wake waves with periods ~10 s. The typical periods of wind waves were 2–3 s. The details of the experimental setup and devices, the type of environment and primary parameters of the vessel wakes can be found in (Kurennoy et al., 2011).

Although only 14–16 appreciable wakes reached the site each day, their contribution to the total wave energy and its flux was significant. In five typical summer days with the average significant wave height of $H_S = 17$ cm ship wakes formed ~14% of the total wave energy and ~23% of the energy flux. During moderate wind conditions ($H_S = 28$ cm, equivalent to the long-term average H_S in the interior of Tallinn Bay (Soomere, 2005)), ship wakes contributed about ~6% (~13%) to the total wave energy (energy flux) (Kurennoy et al., 2011).

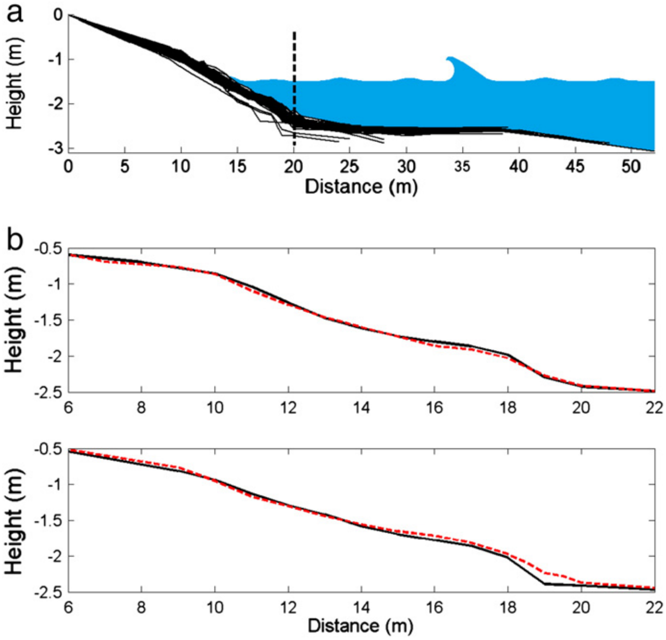

Fig. 1. Coastal profiles of Pikakari Beach in summer 2009 (a): the dashed line corresponds to the approximate position of closure depth for summer wind waves. Examples of ship wave action on the beach on 17 (top) and 22 (bottom) June 2009 (b): solid lines correspond to the early morning beach profile and dashed lines – to its change by the effect of the first ship wake.

3. Convex beach profile

Measurements of the beach profile (138 recordings altogether) were performed 10–15 times a day on 12 June – 01 July 2009 using an electronic level and range finder, and standard measurement staff with a resolution of 1 cm. The profile usually covered at least a 30 m long section from a fixed reference point (located approximately 5 m onshore from the reach of the swash during the extreme runup events of vessel wakes and about 15 m from the undisturbed waterline) down to about 1.3 m water depth, with a typical step of about 1 m on dry beach. The seaward end of the profiles varied to some extent depending on the water level and wave conditions (Fig. 1a). The first profile of each day was filed in the early morning and represented the shape created by overnight wind waves (solid lines in Fig. 1b). The separation between subsequent wakes was usually 1–2 hours that allowed for accurate beach profiling twice in connection with each strong vessel wake: this was just before the wake arrived and immediately after the end of the wake (see Fig. 1b). During some days a late-evening profile was also surveyed.

During the experiments wind waves effectively shaped only a short section of the profile covering the swash zone (ca 12 m from the reference point) and extending down to a depth of about 1 m (ca 5 m offshore from the waterline, ca 20 m from the reference point). Long and high vessel waves were usually shore normally incident and thus did not favor longshore transport. They started to break at a distance of 20–25 m from the undisturbed waterline (35–40 m from the reference point). This situation favors the generation of an offshore section of the profile, similar to the shoaling profile of (Inman et al., 1993; Bernabeu et al., 2003) and a surf profile onshore