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Beach profile change caused by vessel wakes and wind waves in Tallinn Bay, the Baltic Sea

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ABSTRACT

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Beach dynamics resulting from the interplay of vessel wakes and background wind waves are studied experimentally using data obtained in 2008 in Tallinn Bay. The beach profile *h* is presented schematically as a power function of the coordinate *x* (distance from the coast) with an exponent *b* ($h \sim x^b$). On the basis of field measurements, the parameter *b* has been presented as a function of time and studied as a beach characteristic with respect to changes in wave properties. The number of ship crossings does not change significantly from one day to another and the properties of ship induced waves are quite stable. Therefore we are able to focus our analysis on the changes in wind wave background. Special attention is given to the dependence on wave periods. It is shown that wind waves of longer period are more energetic and are able to accrete the beach which generally loses sediment due to ship wakes.

ADDITIONAL INDEX WORDS: *beach dynamics, power approximation of beach profile, influence of wave period*

INTRODUCTION

Beach profile change is an important consideration in coastal geomorphology and coastal engineering. It usually depends on many factors, such as wave climate, coastal currents, and the properties of the sediment. Possible changes in the wave climate may influence beach processes dramatically and may result in a total beach changing from accretive to erosional state and *vica versa*.

This study represents a detailed analysis of beach profile changes resulting from the interplay of two wave systems: intense vessel wake waves with a duration of a few minutes and background wind waves. Beach changes were studied experimentally in a field study carried out in Tallinn Bay, Baltic Sea in 2008, and analysed with respect to changes in wave systems.

TWO SYSTEMS OF WAVES

Tallinn Bay, the Baltic Sea (Figure 1), experiences very intense ship traffic, with up to 70 ferry crossings each day during the high season on the Tallinn-Helsinki route (Parnell *et al.*, 2008; Torsvik *et al.*, 2009). Ships frequently sail at near-critical speeds and generate packets of large, highly nonlinear, at times solitonic, very long and long-crested waves, the heights of which match the typical wind wave heights but which differ from the natural waves in the bay in terms of wave length, propagation direction and group structure. Tallinn Bay is one of a few places in the world where high-speed ferries frequently operate at their cruise speeds close to the shoreline and where wake-waves may have a significant effect on the morphology and the sediment dynamics on medium-energy beaches. The proportion of ship-wave energy is about 10% of the total energy of the wave field, however during the relatively calm spring and summer season, ship waves may dominate on some sections of the coast (Soomere, 2005).

The specific contribution of long ship-waves to the wave field in semi-sheltered areas is frequently equivalent to an increase to the typical wave lengths in the affected area. Conceptually, such a change in the local wave regime is similar to a case where open ocean swell reaches coastlines not previously affected, and can be interpreted as a model case of a major shift in the wave climate towards longer periods.

It has been shown in Osborne and Greenwood (1992) that significant change in wave period may also change the direction of sediment transport. The short-wave components produce strong onshore transport at wind wave frequencies ($0.1 < f < 0.5$ Hz), whereas long-wave components produce offshore transport at frequencies lower than the wind wave band.

In this paper, we focus on the result of the interplay of two wave systems with considerably different periods. Such a situation occurs in Tallinn Bay. The characteristic periods of vessel waves are in the range of 10–15 s and significantly longer than the natural wind wave background in the bay (Kurennoy *et al.*, 2009). According to Osborne and Greenwood (1992) vessel waves should cause offshore sediment transport. The peak periods of wind waves are usually well below 3 s, reaching 4–6 s in strong storms and only in exceptional cases do they exceed 7–8 s. Thus, they normally are in the frequency range which should produce onshore sediment transport (Osborne and Greenwood, 1992).

Thus, both wave systems exist simultaneously and cause cross-shore sediment transport in opposite directions. The properties of ship waves do not change very much and vary little from averages,

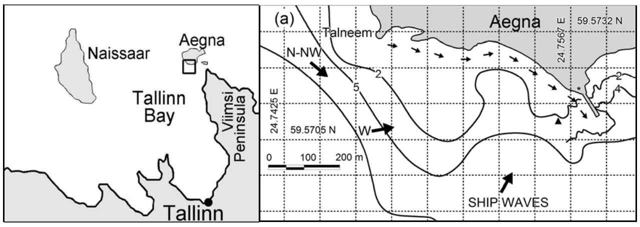

Figure 1. Location of the study site: Tallinn Bay and the island of Aegna. The large arrows show the approach directions of the predominant wave systems (wind waves from the west and N-NW; ship waves from S-SW) and small arrows indicate the direction of the wind-wave-induced littoral drift.

while the properties of wind waves depend on weather conditions and may change significantly with respect to both wave amplitude and period.

The ship waves are relatively high, with the typical height of the highest components ~1 m, while the significant wave height of wind waves exceeds 0.5–0.75 m in the bay with a probability of 10% and 1.0–1.5 m with a probability of 1% (Soomere, 2005).

The runup characteristics of ship and wind wave systems also differ. Very frequently, the largest waves reach over 1 m above still water level with some (evidenced by overwash deposits) going over a small berm crest, over 1.5 m above still water level. Wind waves with the typical height of <0.5 m produced runup up to 20–30 cm above still water level (Didenkulova *et al.*, 2009).

BEACH PROFILE CHANGE

In summer 2008 the properties of ship waves were measured continuously over four weeks ~100 m offshore from a semi-sheltered beach on the island of Aegna, located at the northern entrance to Tallinn Bay, ~2700 m from the sailing line. The site was located close to a jetty, which restricts sediment transport from the east and creates favorable conditions for studies of cross-shore sediment transport (Figures 1 and 2). Beach profiles were measured up to several times a day for more than 20 days. The first analysis of beach profile data (Soomere *et al.*, 2009) shows that overnight and during medium-energy wave conditions (significant wave heights ~0.7 m), wind generated waves build the beach adjacent to the jetty. During calm periods, when there is no wind-wave generated sediment transport, the beach is not replenished and significant loss of sediment across the beach profile is evident due to the effects of the vessel-generated waves. The beach again builds when wind waves return. It has been supposed that in the longer-term, in the absence of vessel-generated waves, the beach on the updrift side of the jetty would be expected to accrete to a point of equilibrium where the beach shape would provide some protection to the coast to the west, thereby reducing shoreline erosion and also protecting the jetty. Currently, wind waves bring sediment from the sediment-depleted beach to the west, and vessel-generated waves take those sediments offshore into deeper water adjacent to the jetty, and the shoreline to the west of the jetty remains unprotected. The beach, therefore, never reaches an equilibrium shape, as might normally be expected on the updrift side of a groin with a unidirectional sediment transport system. Instead, the area offshore, adjacent to the jetty, serves as a sink for the beach sediment (Soomere *et al.*, 2009).

Although properties of single wakes may vary considerably (Kurennoy *et al.*, 2009), the daily average values of vessel wave energy, its flux and the properties of the largest waves (over 22–25 crossings per day) show quite limited variations (Soomere, 2005; Parnell *et al.*, 2008). The properties of wind waves, however, are rather changeable and the daily average wind wave energy and its flux changed by several orders of magnitude during the study period. Therefore, it is reasonable to assume the daily average impact of ship waves to be constant and to analyze beach changes with respect to the changing wind wave background. In the result we can see how the beach is developing under the low wind wave background (when ship waves prevail) and in storm conditions (when wind waves prevail).

Figure 2. The study site.

To the first approximation, we quantify the beach profile changes in terms of the match of particular profiles with the power law for the increase in the water depth h with the distance x from the shoreline:

$$h = kx^b \,. \tag{1}$$

The power asymptotic of the beach profile is widely used (Romańczyk *et al.*, 2005; Are and Reimnitz, 2008). The most common is the famous Dean's Equilibrium Profile with $b = 2/3$, see, for example, Dean and Dalrymple (2002). 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 asymptotic approximations for beach profiles in terms of power laws 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 Eq. (1) in the vicinity of the shoreline. This type of approximation is particularly suitable at sites where the profile does not contain pronounced berms (cf. Figure 2).

For quantitative analysis of beach shape changes, the beach profile has been presented schematically as a power function of the coordinate with an exponent b. On the basis of field observations and measurements the parameter b has been presented as a function of time. Specifically, we studied its reaction to the changes in wind waves, while ship waves are assumed to be constant. Note that the dimension of coefficient k in Eq. (1) varies depending on the exponent b. This coefficient has a similar behavior to b (negative correlation to b).

Frequency of occurrence of the parameter b in June–July 2008 is presented in Figure 3. During the experiment the beach was changing its shape from convex ($b > 1$) to concave ($b < 1$). The

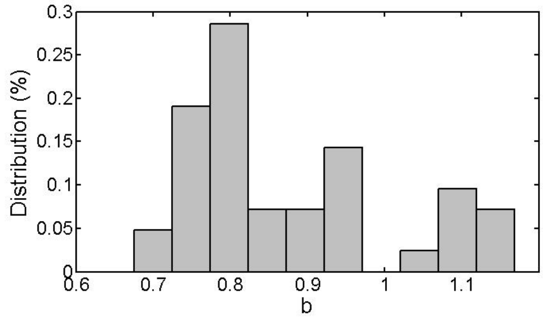

Figure 3. Frequency of occurrence of the parameter *b* in June-July 2008.

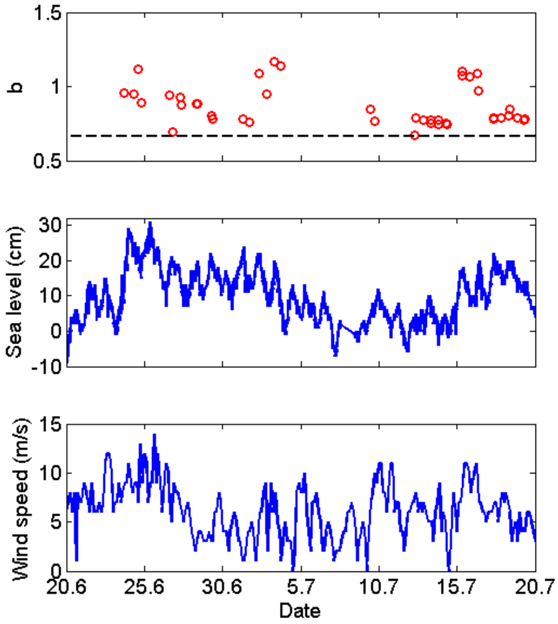

Figure 4. Variations in beach profile, sea level and wind speed in June–July 2008. The dashed line corresponds to the Dean's equilibrium profile; the date indicates day and month.

minimum value of *b* was 0.67 (this value also corresponds to Dean's equilibrium profile) and the maximum value was 1.2. The distribution of *b* has an asymmetric shape with a maximum at *b* = 0.8. The mean value is *b* = 0.87.

Figure 4 shows the variations in the parameter *b*. These variations reflect beach profile change owing to variations in sea level and wind speed in June–July 2008. The lowest value of the beach parameter *b* = 2/3 (dashed line in Figure 4) corresponding to the Dean's equilibrium profile, was achieved after a moderate storm had passed. The large variability in this parameter (Figure 4) is caused by rapid variations in sea level and wave properties. An insight into the rules governing this variability gives an analysis of the correlation between this parameter and the wave properties (Figure 5). Doing this is not straightforward: Figure 5 reveals that, formally, there is almost no correlation between the wind properties and the values of *b*. The reason is that the impact of vessel waves is unevenly distributed within each calendar day while relatively high wind waves, if present, are much more uniformly distributed. Note that this absence of correlation actually indicates an important fact: that ship waves are able to completely reshape the beach within a few hours from the beginning of the ship traffic early in the morning of each day (cf. Soomere *et al.*, 2009).

Although we have assumed that the overall vessel wave influence on the beach shape during each day is constant, the impact of wakes is not uniform during the day. For example, in the early morning before the first ferry passes the beach has a shape created by wind waves over night and in the evening after all ferries have passed the beach has been mostly shaped by vessel wakes. Therefore, for a sensible analysis of the influence of wind waves it is necessary to select those beach data, where the contribution of ship waves is equivalent, in other words, to select those beach profiles, which were measured at the same time of the day.

In our case it is natural to select the first beach profile measurements in the morning of each day because the profiles at later time instants are largely reshaped by vessel wakes. The first morning measurements usually reflect the state of the beach that has been formed under wind wave influence. This shape basically keeps the information on how wind waves have transformed the beach during the night.

It is interesting to notice that there was no correlation between beach changes and the sea level and between beach changes and wind speed for the first morning data, therefore the beach is mostly developing under a more complicated set of factors.

The most interesting was the dependence between beach changes and wind direction. The parameter *b* plotted against the wind direction for the first beach profile measurements in the

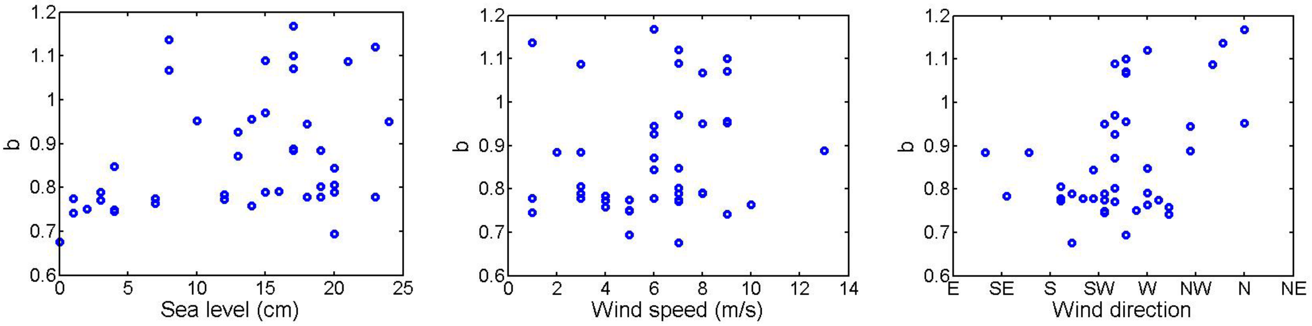

Figure 5. Beach changes with respect to the change in sea level, wind speed and wind direction.

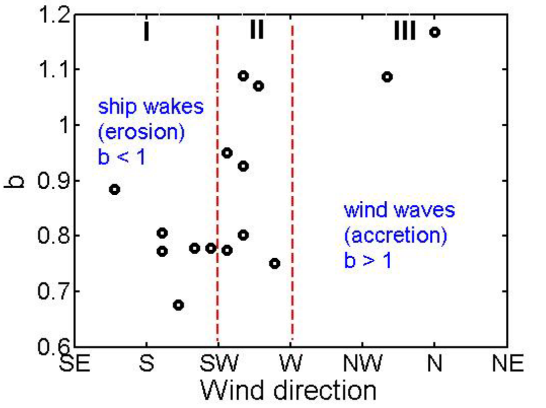

Figure 6. Parameter *b* plotted against wind direction for the first beach profile measurements in the morning.

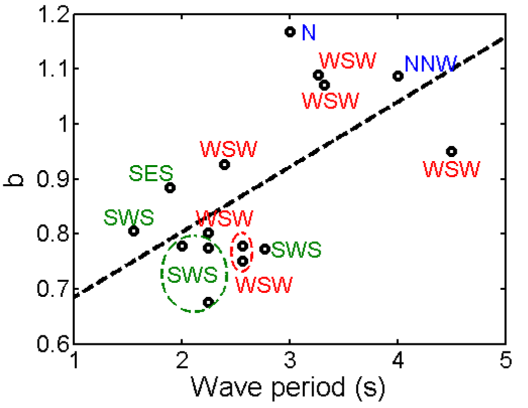

Figure 7. Parameter *b* plotted against typical wind wave period for the first beach profile measurements in the morning; the dashed line corresponds to the regression line (Eq. (2)).

morning is presented in Figure 6. This dependence becomes most evident and can be better understood if we analyze the location of the Aegna Island site and the wind wave climate there (see Parnell *et al*., 2008).

The measurement site is located on the SW coast of Aegna, at a small mixed gravel-sand beach immediately west of the jetty (59°34′50″N, 24°45′28″E). The island is located at the northern entrance of Tallinn Bay and is separated from the mainland (Viimsi Peninsula) by a shallow-water channel with two small islands. So, effectively, no wave energy enters Tallinn Bay from the east (Figure 1).

The experimental site is fully open to the south. The maximum fetch length in this direction, however, is only some 10 km. Although the majority of storms blow from the SW, they produce no large waves at the study site. Moreover, these waves approach the shore perpendicularly and result in negligible longshore sediment transport. Owing to their small lengths, they only affect sediments at the coastline and in very shallow water. Significant wave energy enters Tallinn Bay from the North. The most significant waves at the study site come from the West, entering Tallinn Bay between the mainland and the island of Naissaar (Figure 1). Waves from the NW are effectively blocked but when they reach the study site owing to refraction, they impact the coast in a similar way to waves approaching from the West.

The described directional pattern of wave activity suggests that the strongest impact from the waves is expected to come from the West, NW and North and relatively weak influence on the beach change occurs for waves from the South and SW. This pattern is specifically reflected in Figure 6 for variations in parameter *b*. When the wind waves approach from the SE, South or SW (section I in Figure 6), the beach is mostly developed by ship waves which, as we may expect, cause beach erosion. This can also be seen from the values of the parameter $b < 1$ for waves from these directions (Figure 6), which correspond to the concave beach profile. On the other hand, strong waves coming from the West, NW and North (section III in Figure 6) build up the beach and lead to beach accretion. This is also reflected in the parameter $b > 1$, which corresponds to the convex beach profile. Section II in Figure 6 corresponds to waves from the West and SW and represents a kind of intermediate regime, where both beach accretion and erosion can occur.

Another interesting result can be obtained when we look at the dependence of the beach status on the wind wave period (Figure 7). The wave period here is calculated from the measurements of wind waves during the night, recorded by a downward-looking echosounder located ~100 m offshore from the study site (Parnell *et al*., 2008). The parameter *b* increases with an increase in the wind wave period. This means that wind waves of larger periods are more effective in building the beach. This dependence can be approximated by the linear line (dashed line in Figure 7):

$$b = 0.12 \cdot T + 0.57 , \tag{2}$$

where *T* is the wave period in seconds.

This result is in agreement with Osborne and Greenwood (1992) who say that short-wave components produce strong onshore transport at wind wave frequencies ($0.1 < f < 0.5$ Hz), whereas long-wave components produce offshore transport. In our case, the natural changes to the beach are substantially modified by the interplay of two wave systems and of corresponding processes of onshore and offshore sediment transport, induced by these systems. Long waves caused by high-speed ferries ($f \sim 0.07$ Hz) produce offshore sediment transport, which erodes the coast, while wind waves lead to beach accretion. When wind waves are insignificant as compared to ship waves, the beach is in an eroded state. As the wind wave periods are relatively small for low waves in the Baltic Sea (where long-period swell is almost missing, Räämet *et al*., 2010), the erosion events usually correspond to wind wave periods less than 3 s and very large separation of wind waves and vessel wakes in the frequency domain. When wind waves are more energetic (usually with periods larger than 3 s), they lead to faster beach accretion and can bring it to the accreted state over one night.

DISCUSSION

The beach profile is presented schematically as a power function $h = kx^b$ of the distance from the coast. The temporal pattern of the basic parameter – the exponent *b* – is determined on the basis of field measurements. It is presented as a function of time. Its changes are studied with respect to changes in wave properties.

It is not unexpected that with the varying intensity of wind waves and their approach direction the beach changes significantly during the period of measurements from eroded to accreted state, and parameter *b* varies from 0.67 to 1.2 with the mean value

$b = 0.87$. A much more interesting feature is that that vessel waves are systematically able to completely reshape the beach within a few hours from the beginning of the ship traffic early in the morning of each day even if their total energy is about 1/3 of that of the wind wave field (Kelpšaitė *et al.*, 2009). This conclusion is an important extension of the result of Soomere *et al.* (2009) who demonstrated that ship waves are able to rapidly reshape the beach under specific conditions.

The daily average energy and energy flux of vessel waves, as well as the properties of the largest waves, do not change significantly from one day to another as the ship schedule is the same with 22–25 crossings per day, and ship speed varies little on the section of the route where waves at the study site are generated. We can therefore assume them to be constant and focus on the changes in the wind wave background. It is natural that wind waves effectively create the sediment flux to the beach and lead to accretion of the beach under relatively large wind speeds. The key result is that this process substantially depends on the wind direction, although for almost all wind directions accretion of the beach by wind waves is expected. Winds from the West, NW and the North induce the most energetic waves. This dependence is also reflected in wave periods. Wind waves of larger periods are more energetic and are able to accrete the beach, which has been previously eroded by ship waves.

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