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Shoaling and Runup of Long Waves Induced By High-Speed Ferries in Tallinn Bay

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ABSTRACT

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High-amplitude water waves induced by high-speed ferries are regularly observed in Tallinn Bay, the Baltic Sea, where, during the high season, high-speed ferries service the Tallinn-Helsinki route up to 50 times per day. Long-wave runup is examined theoretically and experimentally, focusing on the dependence of runup height on the incident wave properties. Experimental data include measurements of wave parameters 100 m from the coast and measurements of wave runup on a beach. Data from 212 ship wake events in Tallinn Bay demonstrate that ship wakes in the nearshore have large heights (up to 1.6 m) and periods (10–15 s), whereas wind waves have typical heights of <0.5 m and periods of 3–6 s. The largest ship generated waves approaching the coast break (plunging or spilling breaking) in the nearshore (with a typical breaking parameter $Br > 13$) and have only weak wave amplification at the beach. On average the runup height of ship wakes exceeds the wave height offshore at the depth of 2.7 m by a factor of 1.3, and this amplification factor decreases with an increase in wave amplitude. This effect is explained by wave breaking and dissipation in the turbulent bottom boundary layer. Estimates of the amplification factor given in the framework of shallow water theory are in agreement with the observed data.

ADDITIONAL INDEX WORDS: *long wave runup, shallow water wave theory ,wave breaking*

INTRODUCTION

High-speed ships induce significant waves at the sea surface (LYDEN *et al.*, 1988; WYATT and HALL, 1988; REED and MILGRAM, 2002; TELLO *et al.*, 2005). Nonlinear theory of ship waves has been developed over the last few decades (PEREGRINE, 1971; BROWN *et al.*, 1989; CHEN and SHARMA, 1995; REED and MILGRAM, 2002; TORSVIK *et al*., 2006; SOOMERE, 2007; TORSVIK and SOOMERE, 2008). In the coastal zone, ship waves are amplified due to effects of wave shoaling, refraction and diffraction. Under certain conditions these waves can form rogue waves, which can be hazardous in the coastal environment (SOOMERE, 2006). Large-amplitude ship waves, result in significant near-bottom velocities in shallow water and induce bed sediment transport (SCHOELLHAMER 1996; OSBORNE and BOAK; 1999; ERM and SOOMERE, 2006; OSBORNE *et al*., 2007) and can also cause significant geomorphic change to the beach and nearshore (PARNELL *et al*., 2007).

Significant ship generated waves occur in Tallinn Bay, the Baltic Sea, where during the high (summer) season, the number of ferry crossings servicing the Tallinn-Helsinki route can reach 50 per day (PARNELL *et al*., 2008). Vessels departing from Tallinn towards Helsinki frequently sail in the near-critical regime (depth Froude number ~0.9) and may induce waves up to 1.7 m. By comparison the wind wave background is commonly about 0.3–0.4 m. Ship wakes comprise wakes of different characteristics, with the leading groups being effectively long waves (wavelengths up to 250 m), and at depths to 10–20 m can be analyzed in the framework of shallow water theory. These waves typically break approaching the coast and an adequate theory should take into account the wave shoaling and breaking processes, the theory for which is not well developed. Because of this, experimental studies are very important.

In this paper, we present the results of an experiment study of the shoaling and runup of long breaking waves. The characteristics of the ship wakes in the nearshore and on the beach are presented. Data is analyzed using simplified shallow-water theory with linear damping, which parameterizes the wave breaking and bottom friction.

SHIP WAKES OFFSHORE AND IN THE VICINITY OF THE SHORELINE

The experiment was undertaken on the SW shore of the island of Aegna in Tallinn Bay, the Baltic Sea (Figure 1), in summer 2008 and focused on long wave shoaling and runup. It is described in detail in PARNELL *et al*. (2008). Waves were recorded about 100 m from the shoreline, at a water depth of about 2.7 m, using an ultrasonic echosounder (LOG_aLevel® from General Acoustics) (Figures 2 and 3). The measurement range of the sensor was 0.5–10 m to the water surface with an accuracy of ±1 mm. The surface water elevation data were collected almost continuously over 30 days (21 June – 20 July 2008) at a recording frequency of 5 Hz. Ship wakes, approaching the coast, are shown in Figures 2 and 3.

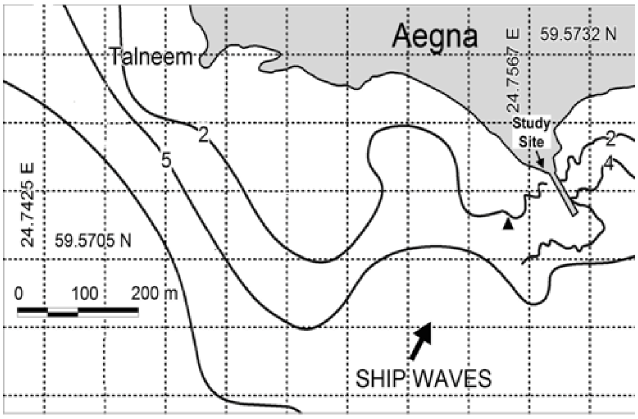

Figure 1. The study site on the SW coast of Aegna, Tallinn Bay, The Baltic Sea. The triangle is the position of the echosounder.

Around much of the Aegna coast, a belt of boulders at depths of 0.5–2 m occurs (which effectively damps wave energy so that at times ship waves are almost invisible at the shoreline). The belt of boulders is not present at the runup measurement site which is located adjacent to a small jetty. In the vicinity of the jetty, seaward from the site, water depths increase over a short distance to approximately 2 m, beyond which there is a slight, more or less linear slope to the position of the tripod. The isobaths beyond the tripod are predominantly oriented perpendicular to the ship wave rays (PARNELL *et al*., 2008). To the east of the measurement site, wave components reflected from the coast fast decrease due to diffraction and damping in the boulder belt. The jetty to the west is protected by tetrapods which effectively damp wave energy so that there is no visible reflection of wave energy from the jetty back to the study beach (Figure 1). Ship wakes arrive at the study site slightly obliquely so that the tripod is sheltered from waves reflected directly from the beach (PARNELL *et al*., 2008).

The runup of individual ship-induced waves on the beach was measured using two 5-meter survey poles joined together (Figure 4) and a video recorder. The water surface level varied significantly over the experiment (from –7 cm to +30 cm), with this being taken into account in the analysis of runup.

The runup of 212 ship wake events were analysed, including 59 wakes of Nordic Jet and Baltic Jet vessels, 11 wakes of SuperFast, 45 wakes of SuperSeaCat, 47 wakes of Star and SuperStar, 13 wakes of Viking and 37 superimposed wakes from 2 or more ships. The characteristics of ships analysed in the experiment are given in the Table 1.

The largest ship wakes were frequently preceded by relatively small amplitude non-breaking waves (typically below 5 cm) with very long periods (20–30 s). This part of the wake may be associated with the precursor solitons that are customary for near-critical speeds but which may be produced for as low depth Froude numbers as 0.2 (ERTEKIN *et al*., 1986; BROWN *et al*., 1989). At least one disturbance of this type was normally (in about 70% of cases) present in the wakes.

Typically, the highest and longest ship waves are breaking waves. Some were breaking relatively close to the echosounder, 100 m from the shore (Figures 2, 3). The breaker type varied with different weather conditions and different vessels. Figures 2 and 3 show plunging and spilling breakers respectively. The heights of the ship-waves were up to 1.5 m, with periods of 10–15 s. The typical daily highest ship wave was approximately 1.2–1.3 m. Combined, wind and vessel generated waves resulted in waves of ~1.7 m (PARNELL *et al*., 2008). The periods of leading vessel waves was up to 15 s, which is much larger than characteristic wind wave periods of 3–6 s, typically found for wind-generated waves in the relatively sheltered Tallinn Bay. A typical time-series of a ship wake is presented in Figure 5. The ship wakes are clearly evident above the background of wind waves. During the experiment ship wakes were always visible even in storm conditions (wind speed up to 12 m/s). PARNELL *et al*. (2008) presents a detailed description of wake characteristics at the study site, and Kurennoy et al. (2009) discusses the methods used for wind- and ship- generated wave separation.

Figure 2. Plunging waves from ship wakes approaching the coast of Aegna on 27 June, 20:00 (*Baltic Jet:* see Table 1).

Figure 3. Spilling waves from ship wakes approaching the coast of Aegna on 14 July, 11:24 (*Star:* see Table 1). The tripod on which the echosounder was mounted is also shown.

Table 1: Ships operating the Tallinn-Helsinki ferry link in summer 2008 (PARNELL *et al*., 2008).

Ship	Type	Length, m	Width, m	Operating speed, knots
	High-speed ferries			
SuperSeaCat	monohull	100.3	17.1	35
Baltic Jet, Nordic Jet	catamaran	60	16.5	36
	Conventional ferries with increased cruise speed			
Star	monohull	186.1	27.7	27.5
Superstar	monohull	176.9	27.6	27.5
Viking XPRS	monohull	185	27.7	25
Superfast	monohull	203.3	25	25.5–27.1

As an example, the wave runup heights (above still water level) of the waves from the *Star* at 11:24 on 14 July (Figure 5) on the adjacent beach are shown in Figure 6. Very frequently, the largest wave heights were 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.

ANALYSIS

For analysis of the shoaling effect of waves induced by high-speed ferries, the maximum wave height at the echosounder (100 m from the coastline) and the maximum runup height above still water level were found for each ship event. The analysis was undertaken for different types of high-speed ferries (Table 1) and for superimposed ship wake events (Figure 7). Wave amplification (expressed as the ratio R/H of the maximum runup height and the measured wave height 100 m offshore) decreases with increasing wave height. Waves of smaller height have high amplification, whereas the runup from high waves is damped due to the effects of wave breaking and bottom friction, and is more pronounced for high waves. The data presented in Figure 7 can be fitted by the curve

$$\frac{R}{H} = 2.08 - 0.94H \, , \qquad (1)$$

Figure 4. Runup of ship wakes on 14 July, 10:40 (*Nordic Jet:* see Table 1).

where H is the wave height and R is the maximum runup height in meters, with coefficient of correlation of 0.6.

The runup height, on average, is higher than the wave height at the echosounder demonstrating wave amplification at the runup stage. The mean value of the amplification factor is 1.3.

Taking into account the wavelength of the wake at the echosounder, determined by the linear dispersion relation (40–80 m) at a water depth of 2.7 m, shallow-water wave theory can be applied to describe the processes of wave shoaling and runup. In the case of wind waves, which are significantly shorter than ship wakes in Tallinn Bay, the Iribarren number is frequently used for describing waves in the coastal zone. It is determined from wave characteristics in deep waters (STOCKDON *et al*., 2006). For ship waves, which are much longer than wind waves, the concept of the Iribarren number is not directly applicable, and the analytical theory of long wave runup on a beach (MAZOVA *et al*., 1990; DIDENKULOVA *et al*., 2006; DIDENKULOVA *et al*., 2007) is needed to explain the relationship between maximum wave height offshore and runup height on the beach. If an incident wave can be approximated by a sine wave, and the wave approaches the coast without breaking, the maximum runup height is determined by

$$\frac{R}{H} = \pi \sqrt{\frac{2L}{\lambda_0}} \, , \qquad (2)$$

where L is a distance from the measurement point to the shoreline and λ_0 is the wavelength of the incident wave (in papers, cited above, wave amplitude A is used instead of the wave height H, for a sine wave $H = 2A$).

In this experiment [bottom slope $\alpha \sim 0.027$; $L \sim 100$ m; characteristic wave frequencies $\omega \sim 0.4 - 0.7$ rad/s (wave periods are $\sim 9 - 15$ s)], from Eq. (2) it follows that the amplification ratio R/H should be approximately 5, which is significantly larger than 1.3 as measured. The difference is likely to be due to Eq. (2) being for the runup of non-breaking waves, whereas the waves approaching the shore at the study site (Figures 2, 3) were frequently breaking. This can be confirmed by computing the breaking parameter (DIDENKULOVA *et al*., 2006; DIDENKULOVA *et al*., 2007)

$$Br = \frac{\omega^2 R}{g\alpha^2} \, , \qquad (3)$$

which is < 1, for non-breaking waves and > 1 for breaking waves (where g is gravity acceleration). Even for minimum values of the wave runup height (0.6 m), it follows from Eq. (3), that the breaking parameter $Br > 13$ significantly exceeds the critical value, $Br = 1$. Therefore wave breaking is important for reducing ship wave effects as it may reduce the runup height. A rigorous analytical theory of long wave runup in the case of breaking

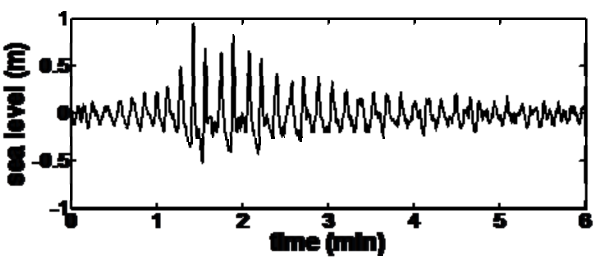

Figure 5. Ship wake record at the echosounder on 14 July, 2008, 11:24 (*Star:* see Table 1).

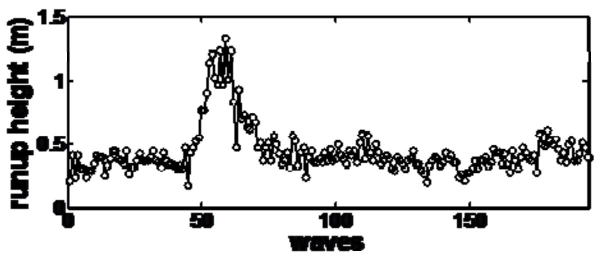

Figure 6. Distribution of runup heights of ship wakes on 14 July, 2008, 11:24 (*Star:* see Table 1).

waves is not yet well developed. However, some estimates can be made in the framework of linear theory for long wave runup on a sloping beach if wave breaking and bottom friction can be parameterized by the linear friction term in shallow water equations

$$\frac{\partial \eta}{\partial t} + \frac{\partial}{\partial x}\left[h(x)u\right] = 0 , \qquad \frac{\partial u}{\partial t} + g\frac{\partial \eta}{\partial x} = -\delta u , \qquad (4)$$

where η is water displacement, u is depth-averaged velocity and δ is a friction coefficient assumed to be constant. An analytical solution of Eqs. (4) is obtained by MAZOVA *et al*. (1990) and the runup height is described by

$$\frac{R}{H} = \pi\sqrt{\frac{2L}{\lambda_0}}\exp\left(-\delta\sqrt{\frac{L}{g\alpha}}\right) \qquad (5)$$

and differs from Eq. (2) with an exponential term. Various parameterizations of the dissipative processes can be used for estimation of the coefficient δ. Usually the wave damping in the turbulent bottom boundary layer is parameterized in Eq. (4) by the quadratic (Chezy) term $C_B u|u|/h$, where $C_B \sim 0.0025$. Such an approximation is used for modeling storm surges and tsunamis

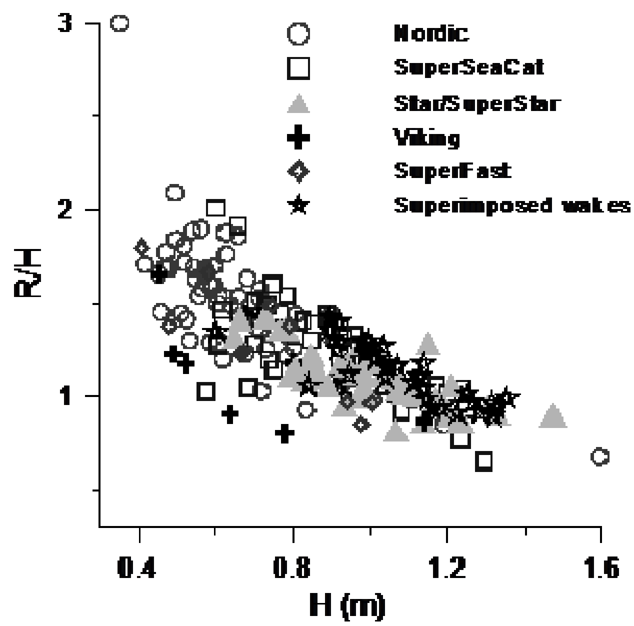

Figure 7. The ratio of maximum runup (R) plotted against maximum wave height (H).

(MURTY, 1984; LEVIN and NOSOV, 2008). It means that the linear friction coefficient is approximately

$$\delta \sim C_B u / h . \qquad (6)$$

Near the coast at the depth of 0.5 m for a wave of 1 m height, the depth averaged velocity, *u*, estimated from linear theory is ~ 2 m/s, and, therefore, δ is approximately 0.01 s^{-1}. If we assume that the wave breaking is described by the same term in Eq. (4), the value of the coefficient δ can be increased. If it is increased, for example, by a factor of 3, the amplification ratio R/H will be ~ 2.5, that is close to the observed value of 1.3. Since the friction coefficient is proportional to the wave height [it follows from Eq. (6)], this helps explain the decreasing amplification factor R/H with an increase in the wave height. As discussed above, the study site is a fairly narrowly confined section of shoreline, essentially non-reflecting, that should also reduce the wave amplification at the runup stage.

DISCUSSION

Understanding shoaling and runup of long waves on a beach is a classic problem in coastal engineering. The forecast of runup characteristics still remains a challenge. For wind waves, some empirical formulae are well established (STOCKDON *et al*., 2006). In the case of long waves (such as tsunami waves) which can lead to significant changes to the coastal morphology and the intensification of coastal processes, the major obstacle to better understanding is the uncertainty in the determination of the incident wave properties far from the shore, which may strongly influence the runup characteristics. For example, a wave with an asymmetric profile and a steep front penetrates a longer distance inland and with higher velocity than a symmetric wave (DIDENKULOVA *et al*., 2006; 2007). As observations of the characteristics of the potentially hazardous incident waves far from the shore are difficult, costly, and often dangerous to obtain, it is attractive to study such waves under controlled conditions. Waves dynamically similar to hazardous long waves are frequently generated by high-speed ferries. Such waves are regularly observed in Tallinn Bay, the Baltic Sea.

Data from 212 ship wake events in Tallinn Bay demonstrate that ship wakes in the nearshore have large heights (up to 1.6 m) and periods (10–15 s), whereas wind waves have typical heights of <0.5 m and periods of 3–6 s. The largest ship generated waves approaching the coast break (plunging or spilling breaking) in the nearshore (with a typical breaking parameter $Br > 13$) and have only weak wave amplification at the beach. On average the runup height of ship wakes exceeds the wave height offshore at the depth of 2.7 m by a factor of 1.3, and this amplification factor decreases with an increase in wave amplitude. This effect is explained by wave breaking and dissipation in the turbulent bottom boundary layer. Estimates of the amplification factor given in the framework of shallow water theory are in agreement with the observed data. The data demonstrate that ship wakes contribute significantly to the wave energy balance in the coastal zone.

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