

# Fast-ferry Generated Waves in South-West Tallinn Bay

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## ABSTRACT

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Waves generated by high-speed ferries sailing at near-critical speeds (depth Froude number  $\sim 1$ ) may substantially affect the coastal zone. As typical for large-amplitude waves in shallow water, waves from fast ferries frequently have a substantially nonlinear nature and are often able to seriously damage the coastal environment. We report wake characteristics of fast-ferries sailing in Tallinn Bay in June 2009. Waves were measured using an echosounder in the nearshore at Pikakari Beach at a depth of 2.7 m, 2.4 km from the sailing line. The record contains  $\sim 150$  wake events for which primary wake parameters as the maximum wave height, wake energy and its flux were estimated. The shape of the highest vessel waves was analyzed in terms of crest-trough asymmetry. Maximum wave heights (up to 0.7 m) occurred exclusively for the longest waves with periods  $\sim 10$  s. These waves are substantially nonlinear with wave crests exceeding wave troughs typically by a factor of 1.3. Incoming ferries generally excited smaller waves compared to a previous study of outgoing ferry wakes in north-west Tallinn Bay. This apparently reflects the high spatial variability of wake waves along the impacted coastal sections and is not an evidence of an overall decrease in the ship wave intensity.

**ADDITIONAL INDEX WORDS:** *coastal zone management, wave measurements, ship wakes, Baltic Sea*

## INTRODUCTION

Intense vessel traffic may significantly affect the wave climate in locations with naturally low and medium wave energy. It is well known that semi-sheltered coastal areas in the vicinity of large harbors and fairways can be substantially impacted by vessel waves, particularly by the highest and longest components of waves generated by high-speed ferries sailing at near-critical speeds (depth Froude number  $\sim 1$ ) (Soomere, 2007). As typical for large-amplitude waves in shallow water, waves from fast ferries frequently have a substantially nonlinear nature. These waves generated and propagating at moderate depths can result in energy concentration not only in the vicinity of the fairways but also in remote sea areas (Soomere, 2005b).

Tallinn Bay in the Gulf of Finland, the Baltic Sea, hosts some of the most intense fast ferry traffic in the world, with fairways located close to the shoreline and vessels operating at cruise speeds up to 55 km/h (30 knots) (Parnell *et al.*, 2008). The favorable wind wave climate in this basin (that contains extensive periods with very low waves in spring and summer seasons) makes this bay a suitable laboratory for studies into the properties and impact of vessel wakes.

An extensive experiment focusing on the properties of high-speed vessels in the north-eastern part of Tallinn Bay at Aegna Island (Parnell *et al.*, 2008; Kurennoy *et al.*, 2009a) was undertaken during the high traffic period in June and July 2008. The study examined waves excited by vessels sailing from Tallinn to Helsinki, with 418 wake events from different high-speed vessels identified and analyzed. The results first showed high variability in the principal wake parameters. The maximum vessel wave height was 1.5 m, significantly higher than the typical wind

wave heights and comparable to the top 1% of the annual highest wind waves which occur in Tallinn Bay.

Numerical simulations of vessel wakes (Torsvik *et al.*, 2009), however, demonstrated that the properties of the largest wake waves have extensive spatial variability and that the affected areas also substantially depend on the sailing direction.

This study undertaken in June 2009 examines the wakes generated by vessels sailing into the Port of Tallinn, with a particular goal to estimate the potential differences of the largest wake waves for different sailing directions. We concentrate here on the analysis of the primary parameters of the vessel wakes (the maximum wave height, wake energy and its flux) and on certain characteristics reflecting potential nonlinearity of the wave field such as the asymmetry of the shape of the largest vessel waves (Kurennoy *et al.*, 2009b).

## STUDY SITE AND DATA

At the end of 2008 the number of high-speed vessels that operated in Tallinn Bay decreased considerably. The classic high-speed vessels (high-speed craft) sailing at 35–40 knots (Parnell *et al.*, 2008; Kurennoy *et al.*, 2009a) were removed from service and since then the high-speed fleet consisted of three strongly powered but otherwise conventional vessels (*Star*, *SuperStar* and *Viking XPRS*) with a length of about 200 m and a cruise speed up to 30 knots (for detailed parameters see Kurennoy *et al.*, 2009a). The total number of daily crossing of the bay by fast vessels decreased significantly. The daily number of arrivals of the fast ferries from Helsinki to Tallinn in 2009 was 14–16 (including hydrofoils), compared to 22–25 arrivals in 2008.

The wakes of vessels sailing into Tallinn were measured at Pikakari beach (Figure 1), located on the south-western coast of Tallinn Bay and formed during the last century at the northern side of a small jetty. This location has relatively low natural wave activity as it is sheltered from the largest wind generated waves (that enter the bay from the western or N-NW directions; Soomere, 2005a). The coast and nearshore slope of the study site are sandy. Experimental conditions, the type of environment and the location and depth of the devices were similar to the previous studies (see Parnell *et al.*, 2008 for a detailed description of the setup for wave measurements). The approaching waves were measured using an ultrasonic echosounder mounted on a stable tripod approximately 100 m from the shoreline, 2.4 kilometers from the sailing line at a water depth of about 2.7 m. The properties of the waves were measured continuously during 15 days. The total record contains more than 150 clearly identifiable wake events from fast ferries sailing from Helsinki to Tallinn.

### DATA PROCESSING

Single vessel wakes were firstly separated from the wind wave background based on a detailed analysis and visualization of the water surface elevation data (Parnell *et al.* 2008; Kurennoy *et al.* 2009a). It was straightforward on relatively calm days (Figure 2a) when both the leading group of high and long vessel waves and the final, short group of almost monochromatic waves (Soomere, 2007) were easily identifiable in the record. On days with substantial wind-wave activity (Figure 2b), spectral filters (elliptical filters in Matlab) were applied to the raw record sections in order to suppress wind waves, to locate the components of vessel wakes and to adequately define the beginning and the end of wake event.

To determine the properties of the wind wave field, sections of about 15–20 min preceding each wake were considered. This data was also used for the adjustment of the record to a mean zero water level. During several stormy days but the highest waves in a wake record were almost totally masked. As a result, only 52 wake events were attributed to particular vessels and analyzed.

As expected, vessel wakes usually have a group structure with

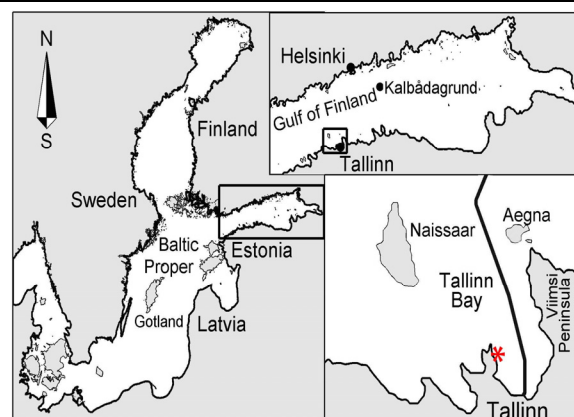


Figure 1. The Baltic Sea, Tallinn Bay, the study site on the western coast (star on right lower panel), and approximate sailing line of ferries from Helsinki to Tallinn.

at least 3 distinct wave groups (Figure 3). The longest, highest and most asymmetric waves are in the first group. These waves were used to determine the maximum wave height and wave asymmetry. The subsequent groups are smaller in their height, but sometimes of longer duration and at times contribute substantially to the integral wake parameters (such as the total energy and energy flux).

For the estimation of vessel wave height each wake event was separated into single waves using both zero-upcrossing and zero-downcrossing methods. The maximum vessel wave height was defined as the maximum of wave heights obtained by these methods. While the maximum wave height is a good indicator of the overall characteristics of the wave field (Parnell *et al.*, 2008; Kurennoy *et al.*, 2009a), integral characteristics like the total wake energy and its flux are more useful for the coastal development. The total energy of each vessel wake was directly calculated from the surface elevation record using the expression

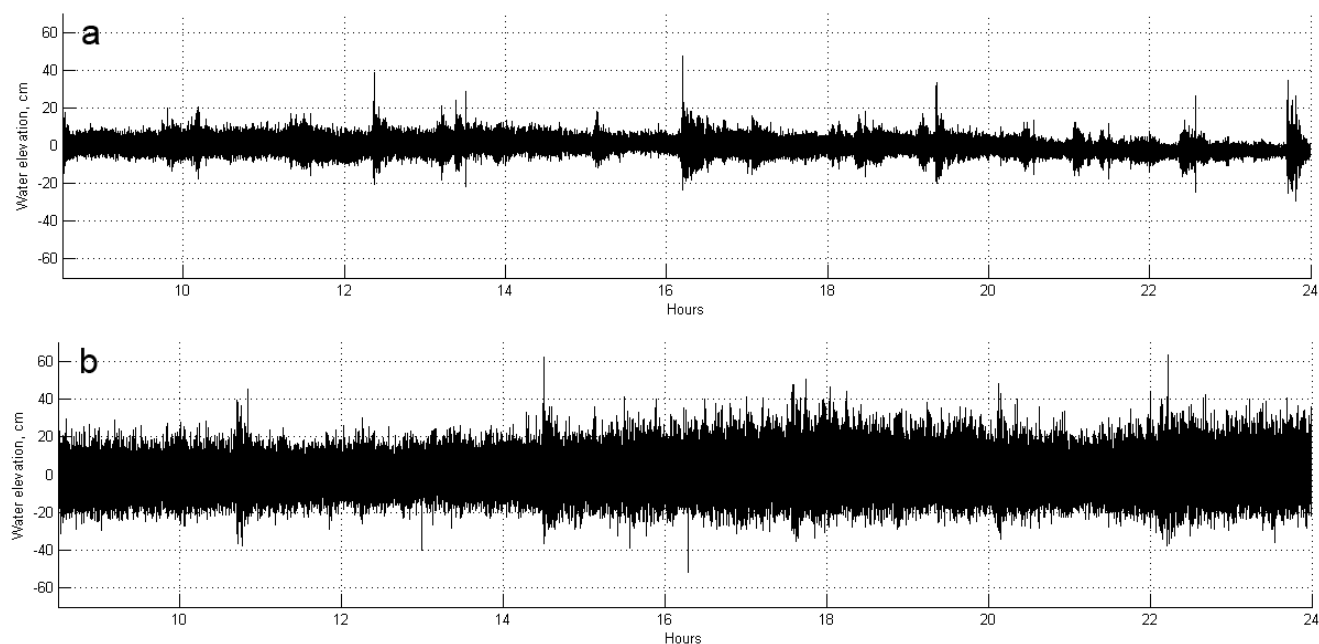


Figure 2. a) Record of water surface elevation on 27 June 2009, calm conditions; b) on 17 June 2009, stormy conditions.

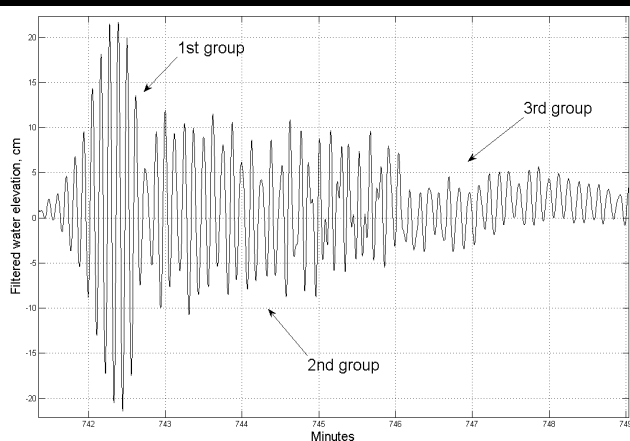


Figure 3. Group structure of the wake from the *Star* on 27 June 2009 at 12:15.

$$E = \rho g \int_{T_0}^{T_0+T_w} \eta^2(t) dt,$$

where  $T_0$  stands for the beginning of the wake,  $T_w$  is the duration of the wake,  $\rho$  is the water density,  $g$  is gravity acceleration and  $t$  is time.

The bulk energy flux  $P$  created by waves per unit of length of wave crests equals the product of the wave energy density and group speed. This implies that, generally, wave components with different lengths contribute differently to the total wave energy flux (Dean and Dalrymple, 1991).

The calculation of the wave energy flux presumes the knowledge of group speed of the contributing waves. This quantity can be adequately estimated from surface elevation time series when the water depth of the measurement site is known. Although there were certain variations in the water level at the measurement site, they normally did not exceed  $\pm 0.3$  m. Owing to such small magnitude of variations, in calculations of group speed we used the mean water depth 2.7 m on these days.

As ship wakes are transient wave groups with varying spectral composition for different parts of a wake event (Didenkulova *et al.*, 2009), it is generally inappropriate to use standard spectral decomposition for the calculation of ship wave energy flux. Based on the high persistence of single wave crests in the nearshore (Kurennoy *et al.*, 2009b; Soomere *et al.*, 2009), we calculated the wake energy flux separately for every single wave crest from the surface elevation record:

$$P = \rho g \int_{T_0}^{T_0+T_w} \eta^2(t) c_{gr}(t) dt,$$

where  $c_{gr}$  is a group speed for each single wave crest in the wake extracted with the use of zero-upcrossing or zero-downcrossing method from the filtered signal. The group velocity is calculated from the linear wave theory using the mean water depth (2.7 m) and the period of the particular wave. The wave energy flux is calculated for each wake by means of summing the power carried by each single wave.

## RESULTS

### Vessel wave height

Figure 4 presents an example of the temporal course of the maximum wave height at the experiment site over 5-minute intervals during one measurement day. All spikes higher than 0.25 m correspond to vessel wakes. An expected feature is that that the maximum wave height in different wake waves varies significantly during the day and usually differs for different arrivals of the same vessel (cf. Parnell *et al.*, 2008). The daily maximum of wave heights is recorded for the highest waves from the leading (first) group of fast ferry wake with a period around 10 s. On average *SuperStar* produced the highest waves with a maximum of 0.66 m. *Viking XPRS* generated the lowest waves and whereas its wakes had the greatest variability among three fast ferries sailing in the bay.

Although the ferries operated at a similar speed and along the same sailing line, Table 1 indicates that the maximum wave height for the same vessel sailing into the Port of Tallinn varies by a factor of two or even more. This variation apparently stems from the difference in conditions of wave generation and once more confirms that properties of vessel wakes have high spatial variability.

### Vessel wake energy and its flux

In accordance with the analysis of the wave heights, *SuperStar* had the most energetic wakes (Table 1). The weakest wakes in terms of the total wake energy were produced by *Viking XPRS*, as it was in 2008. However, the average total energy of her wakes is close to the similar value for *Star*. Interestingly, the variability in the wake energy in 2009 is significantly higher than in 2008 as shown by large values of standard deviation for integral wake parameters.

The typical and maximum values of energy flux show similar patterns to the analogous values for total energy for different ferries: *SuperStar* has almost twice the energy flux of *Viking XPRS*. Values of integral vessel wake parameters are shown in Table 1.

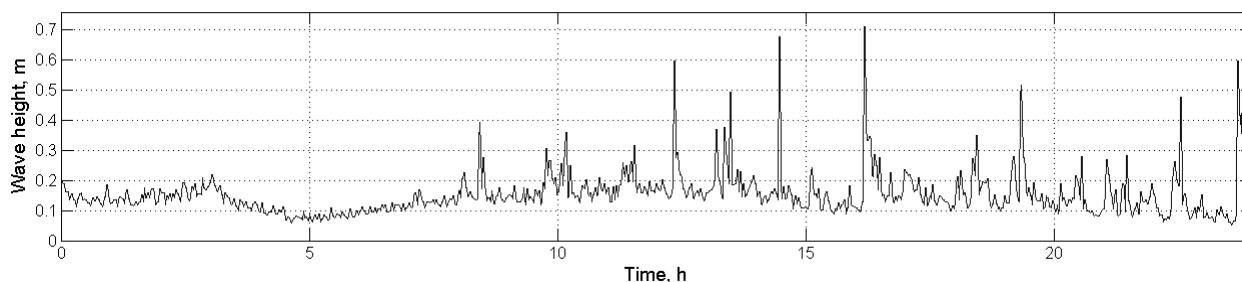


Figure 4. Maximum wave height within 5-minute sections on 28 June 2009.

Table 1. High speed ferries operating in Tallinn Bay in summer 2008 and 2009. Averages and standard deviations of maximum wave height, energy and energy flux.

Ferry	Number of wakes		Maximum wave height, cm				Wake energy, $10^4 \cdot \text{J} \cdot \text{s} / \text{m}^2$				Energy flux, $10^4 \cdot \text{W} \cdot \text{s} / \text{m}$			
	2008	2009	2008		2009		2008		2009		2008		2009	
			avr	std	avr	std	avr	std	avr	std	avr	std	avr	std
<i>Star</i>	25	22	89	26	44	13	5.0	1.8	2.00	0.99	24	9.5	9.00	4.48
<i>SuperStar</i>	28	19	98	11	52	14	6.6	1.2	3.27	1.53	30.7	6.4	14.7	7.00
<i>Viking XPRS</i>	27	11	58	23	33	20	2.0	1.0	1.80	1.76	8.9	4.7	7.93	7.93

Although the number of vessels producing appreciable wakes at the study site is quite limited (14–16 ships sailing to Tallinn each day, that is, one ship per hour) and the duration of the high wave events in their wakes is only a few minutes (Figure 4), the contribution of vessel wakes to the total wave energy and energy flux is remarkable. A consistent estimate of this contribution is based on hourly averaged parameters of vessel wakes for each day. An approximation for the hourly average vessel-wake energy and energy flux for a particular day is found from the total amount of ship wake energy (flux) recorded for each day, divided by the duration of the recording interval for this day (cf. Soomere and Rannat, 2003). In summer conditions there is well-developed diurnal cycle of both breeze and wave conditions at the study site: most of the wind-wave energy reaching the beach is concentrated into the daytime when also ship traffic takes place. Moreover, during nights land breeze prevails and waves mostly propagate offshore. For this reason, we neglect the contribution of wind waves during nighttime.

In typical summer days and in relatively calm weather conditions (during 5 days with average significant wave height of 17 cm) ship wakes form ~14% of the total wave energy and ~23% of the energy flux. During moderate wind conditions with significant wave height of 28 cm (which is equal to the long-term average significant wave height in the interior of Tallinn Bay, Soomere, 2005a), ship wakes contribute about ~6% of the total wave energy and about 13% of the total energy flux.

### Wave shape

As typical for large-amplitude waves in shallow water, waves from fast ferries frequently have a substantially nonlinear nature. Nonlinearity of vessel wakes is important for coastal zone management because nonlinear wakes are considered as being able to seriously damage the coastal environment. Nonlinearity becomes first evident as a change in the linear wave shape: wave crests become steeper. This process is associated with an increase in the maximum near-bottom velocities compared to the orbital velocities in a linear wave (Parnell and Kofoed-Hansen, 2001; Soomere, 2005; Parnell *et al.*, 2007). In particular, it may lead to substantial asymmetry of the sediment transport patterns and to a large impact on bottom sediments in general. Changes to the front-back asymmetry of beaching waves may result in a drastic increase in their runup height (Didenkulova *et al.*, 2007). Another, principally new contribution to their impact is their ability to extremely rapidly reshape the beaches (Soomere *et al.*, 2009) and an ability to carry additional water mass to the shore (Soomere *et al.*, 2011).

A primary indicator of the appearance of nonlinearity in the generation and propagation of surface waves is the asymmetry of the wave shape. The highest waves at a distance of a few kilometers from the ship lane usually are the longest waves concentrated in the first group of the wakes (Soomere and Rannat, 2003; Kurennoy *et al.*, 2009b). These waves are also asymmetric with a clear prevalence of the crest height over the trough depth. Waves belonging to all other groups are mostly symmetric.

The shape of the 489 largest single vessel-generated waves from the first wave groups of the wakes (see Figure 3) were examined with respect to crest-trough asymmetry using the method described in (Kurennoy *et al.*, 2009b). All vessel-generated waves with periods varying between 6 and 12 s were clearly asymmetric at the study site. The most frequent values for the ratio of the crest height over the trough depth lie between 1.3 and 1.4 but in an extreme case reached 3.2 for *SuperStar*.

### CONCLUSIONS AND DISCUSSION

The main aim of this study was to experimentally establish the primary features of waves generated by fast ferries in the western part of Tallinn Bay. The conclusions are based on 52 single wakes of fast ferries sailing into the Port of Tallinn. The maximum vessel wave height reached 0.66 m with low wind wave background. The highest values correspond to the wakes from *SuperStar* as in the previous study at Aegna Island (Kurennoy *et al.*, 2009a). The combination of wind and vessel waves reached 1.1 m height under moderate wave conditions. The total wake energy and energy flux had a high variability for all studied vessels, as did the maximum vessel wave height. High variability in wake parameters is found in many studies of vessel wakes (Soomere and Rannat, 2003; Soomere, 2007; Parnell *et al.*, 2008; Kurennoy *et al.*, 2009a; Torsvik *et al.*, 2009).

The largest fast ferry waves are nonlinear. The degree of nonlinearity of the leading ship waves, with periods of 6–12 s, was estimated in terms of crest-trough asymmetry. In general, wave crests exceeded wave troughs by a factor of 1.3.

Incoming ferries generally excited smaller waves compared to the previous study. This difference may be explained by different conditions of wave generation along the sailing line. This feature may also reflect the high spatial variability of wake waves along the impacted coastal sections and cannot be taken as an evidence of an overall decrease in the ship wave intensity.

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