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Natural and anthropogenic wave forcing in the Tallinn Bay, Baltic Sea

T. Soomere[1], K. Rannat[1], J. Elken[1] & K. Myrberg[2]
[1]*Marine Systems Institute, Tallinn Technical University, Estonia*
[2]*Finnish Institute of Marine Research, Finland*

Abstract

The Tallinn Bay is a 10×20-km semi-enclosed area of the Gulf of Finland. Since tidal currents are negligible in this area, wind waves and local currents that both cause moderate near-bottom velocities off shoreline govern the beach processes. In recent years, high-speed ship traffic has increased considerably and amounts to 70 traverse per day. The ships frequently sail with speeds close to the critical velocity. Comparison of a long-term reconstruction of wind wave climate with the direct ship wave measurement shows that, in the coastal zone of the bay the mean energy of ship waves is 7-10% from the bulk wave energy and wave-induced power as high as 40% from the bulk wave power. The annual maximum of significant wind wave heights is frequently <1.5 m (periods 5-6 s) whereas fast ferries generate waves with the heights about 1 m. The highest component of ship wake has frequently periods 10-15 s and causes unusually high near-bottom velocities at the depths of 5-20 m. Thus, the wake of fast ferries is a new forcing component of vital impact on the local ecosystem that may cause considerable intensification of beach processes as well as enhanced vertical mixing in the water body and have significant influence on the aquatic wildlife.

1 Introduction

The waves from fast ferries have become an environmental problem of growing concern in the sheltered non-tidal sea areas during the last years. They do not produce only higher waves than conventional ships, but also fundamentally different wave systems when sailing at supercritical speeds (e.g. [1]). In inland channels, rivers and in shallow straits, fast ferries have also caused serious wake problems that can harm to the aquatic wildlife and severe shoreline erosion. It is generally believed that the wake is negligible in the open sea areas where the fast ship traffic is sparse and natural waves are frequently much higher than the wash. This assumption is indeed true for coasts exposed to high tidal waves or in places where wind wave loads exceed those of anthropogenic origin many times.

However, in many basins like the Black Sea or the Baltic Sea the tidal waves are small and near-bottom velocities in shallow areas are governed by the waves and local currents. Since the sea winds in elongated basins are frequently adjusted along the basin axis (e.g. [2]), semi-open bays may have a mild wave regime. In such bays, both coastal ecosystem and the structure of bottom sediments suit to small near-bottom velocities. These areas are particularly vulnerable with respect to the abrupt increase of wave activity caused by the fast ship traffic.

The Tallinn Bay is an example of a relatively well-sheltered sea region (ca 10×20 km) in the central part of the Gulf of Finland, Baltic Sea (Fig. 1; for details concerning the Gulf of Finland see [3]). The area between the Estonian and Finnish capitals, Tallinn and Helsinki, apparently has the heaviest fast ferry traffic among the open sea areas of the Baltic Sea. Nearly 70 crossings of the gulf take place daily during the high season. A variety of different types of high-speed ships operate there, including 100 m long monohulls, wave-piercing catamarans and hydrofoils. The resulting high anthropogenic wave load may affect the intensity of coastal processes essentially in the calm parts of the bay. It may also be of major danger to a part of the local ecosystem because the wind wave climate of the bay is particularly mild and its brackish-water ecosystem is the most vulnerable.

This paper describes the results of a recent study of the impact of ship waves on the coastal areas of the Tallinn Bay. The goal was to distinguish whether the ship waves can play a key role in the coastal erosion or be dangerous to the ecosystem of the bay. First, the wind wave climate of the bay was estimated on

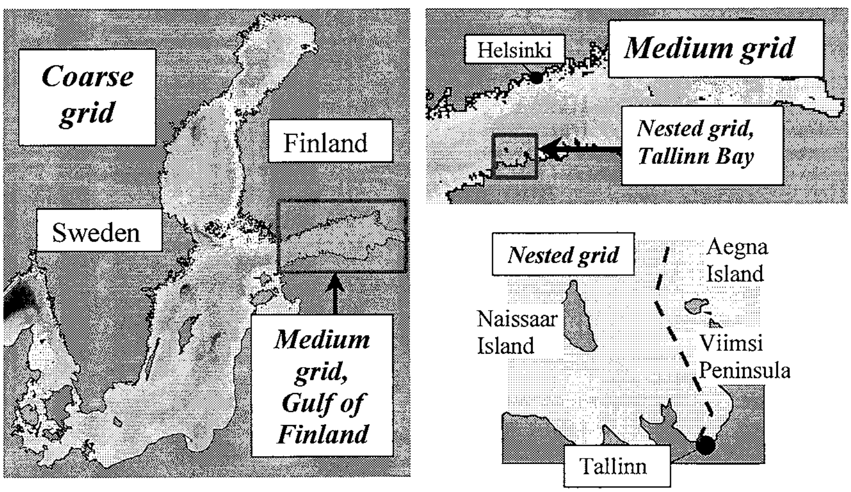

Figure 1: Coastal, medium and nested wave model grids. Dashed line shows the Tallinn-Helsinki ship lane.

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the basis of long-term calculations of wave fields with the use of a high-resolution wave model. An extensive field study of ship wave properties in different parts of the coast was performed. The impact and the relative role of ship waves was estimated based on the comparison of (1) the occurrence probability of the waves of different origin, (2) basic properties of the waves and wave-induced processes, (3) energy density and (4) wave-induced energy flux in the coastal zone owing to wind and ship waves.

2 Long-term calculations of the wind wave regime

A third-generation model WAM [4] was used to estimate the wave climate in the Tallinn Bay. This model computes the full wave spectrum, systematically including the main effects affecting the wave generation and dissipation as well as non-linear interactions between the wave harmonics. A three-step model hierarchy with one-way coupling was used (Fig. 1). First, a coarse model was run for the whole Baltic Sea on a regular grid with a step about 3 miles. Further, a medium-resolution model was run for the Gulf of Finland with the grid step about 1 mile. The bathymetry of these models was based on the data from [5].

The medium-resolution model fails to describe the impact of major topographic features of the Tallinn Bay as well as transformation of wave patterns near the coastal line. For that reason, a high-resolution model was run for the Tallinn Bay and its neighbourhood (the grid step about 1/4 mile). The wave field properties predicted by the nested model were tested against *in situ* measurements and were found to be reliable as close to the coast as 200-300 m.

In long-term calculations, pre-computed wave fields corresponding to the steady wind conditions were used. This approach is based on an evidence that the winds of a large part of the Baltic Sea and the Gulf of Finland (in particular, the winds that are capable of creating substantive wave heights) are highly homogeneous in large sea areas [2,6]. The meteorological data have the time step of 3 hours and have to be interpreted as mean wind conditions during ±1.5 hours from the measurement instant. Changes in the wind direction exceeding 25° lead to a fast decrease of wave amplitudes and the changes in wind speed exceeding ±2 m/s cause fast adjustment of wave fields [4,7]. Moreover, both the Tallinn Bay and the Gulf of Finland are so small that, within 3 hours by changing wind conditions the waves generated by the wind from the 'previous' direction either have reached the coast or have left the area of interest. Thus, to the first approximation, the instant wave field in the Tallinn Bay is primarily a function of the wind speed and direction. This guess fails only for the swell originating from other parts of the Baltic Sea. However, the considerable remote swell in the Tallinn Bay coexists usually together with the locally generated wind waves.

If steady wind blows during a longer time interval, the wave field in the Baltic Proper becomes saturated within 6-8 hours [8] whereas the saturation in the Gulf of Finland may last for 10-11 hours. Thus, it is sufficient to consider steady wind events with the maximum duration of 12 hours. It was assumed that in changing wind conditions, during ±1.5 hours from a wind measurement, the wave field properties equal to those of a wave system excited by steady wind lasting 3 hours. Linear interpolation of wave properties was used in case of need. If wind conditions were stable within 3, 6 or ≥9 hours, wave field properties corresponding to steady winds blowing for 6, 9 or 12 hours, respectively, were used. The wave height was set to zero for wind speeds less than 4 m/s according to [9].

In this way, the fast saturation of wind waves allows to use the approach of precomputed wave patterns to estimate the long-term wave climate depending on the variable open-sea wind data. Such a simplified approach does overestimate heights and periods of waves generated by short storms. It underestimates only those in short calm intervals between gales and thus gives an estimate of the upper bounds of parameters of the long-term wind wave climate.

3 Distributions of wind wave heights

The wind wave regime in the Tallinn Bay is mild due to a sheltered basin. Outside the coastal surf zone, with the probability of 50% the wave height does not exceed 0.25 m. In the central area of the bay, the wave heights are less than 1.25-1.5 m with the probability of 99% (Fig. 2). In the adjacent open part of the Gulf of Finland this threshold for waves is 2.0-2.5 m. In other words, annually only during 70-80 hours the wave heights exceed 1.5 m in the open part of the bay but may be as high as 2.5 m in the central part of the Gulf of Finland. In the eastern coastal region of the bay the wave heights are 20-30% lower than in therest of the bay. This feature is somewhat unexpected, because high waves in the bay generally occur during western winds, but such areas do not exist in the eastern part of the bay.

There are several reasons for such a low natural wave activity. The bay itself is a semi-enclosed basin, sheltered from the rest of the Gulf of Finland by the islands of Naissaar and Aegna, and Viimsi Peninsula. The wind regime in this

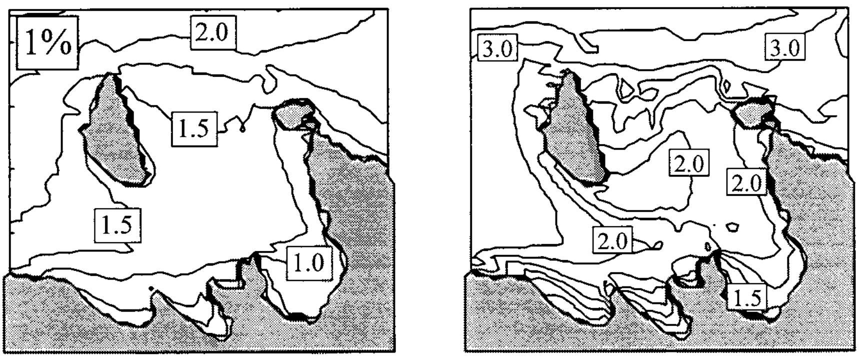

Figure 2: Probability for wave heights in the Tallinn Bay (left panel) and the 1-year return values of maximum wave heights (right panel) based on the Helsinki wind statistics.

area is strongly anisotropic [10]. The highest waves in the neighbouring sea areas are mainly generated by western and northeastern winds; these waves do not penetrate into the bay. The waves are additionally damped by numerous shallow areas (with a depth of 1.5-6 m) located at the entrances of the bay.

Another important measure of the wave regime is the distribution of 1-year return values of wave heights (maxima of wave heights expected to occur once a year, Fig. 2). The highest waves occurring in the bay are formed during the NW storms and enter the bay from the north. The wave heights once a year do not exceed 2.1-2.2 m in the center of the bay whereas in the adjacent central area of the Gulf of Finland the wave heights as high as 3.5 m are expected to occur once a year. An extensive area with relatively low waves is present off the south-eastern coast of the island of Naissaar. Another area with a low natural wave intensity (where the wave heights do not exceed 1.6-1.8 m) can be found along the western coast of the bay.

An analysis of long-term wind statistics shows that the mean wind speed in extreme storms occurring in the Baltic Proper once in 50 years and lasting several hours does not exceed 27 m/s (Soomere, 2001). In the Gulf of Finland the wind speed is 10-15% lower [2,11] and the mean wind speed should not exceed 22-23 m/s. Indeed, the 6-hour mean wind speed during an extreme storm (November, 2001) did not exceed 23 m/s (although the 10-minute mean wind speed at times exceeded 27 m/s; T. Tomson, personal communication).

Figure 3 shows the distribution of maximum wave heights, calculated on the basis of wind data of this storm from the entrance of the Gulf of Finland. The wave heights may be interpreted as maximums occurring once a century. They may be as high as 4 m in the central area of the bay (whereas the peak periods are6-7 s) and 4.7-4.9 m in the open area of the Gulf of Finland. In fact, the wave heights near Helsinki during this storm were about 20-25% higher than the 1-year return values and exceeded 5 m for a short period [12].

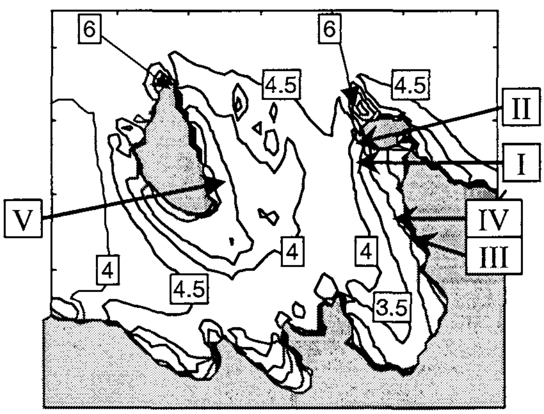

Figure 3: Maximum wave heights in an extreme storm. The contour interval is 0.5 m. Large arrows show the ship wake measurement sites I-V.

4 Energy density and flux of wind waves

The impact of waves can be quantified in terms of wave energy and its flux. Traditionally, the wave energy is interpreted as integral energy density in the whole water column (e.g. J/m^2) that is proportional to the wave height squared. The wave energy propagates with the group speed. The product of the wave energy density and group speed equals to the density of energy flux (that is equivalent to the density of bulk power carried by the wave per unit of length of wave crests, e.g. W/m). Since only non-directional wave measurement techniques were used, it was assumed that the energy of all components propagates with the group velocity of the wave with maximum energy.

Both the distributions of annual mean energy density and density of energy flux of wind wave fields are qualitatively similar to the distributions of probabilities for wave heights and 1-year return values of wave heights. Annual mean wave energy flux is 250-400 W/m in the central area of the bay. During the summer season it is less than 250 W/m and during the winter season up to 500 W/m. In specific coastal areas both wave energy and its flux are up to two times less than in the centre of the bay.

Thus, the Tallinn Bay has a relatively mild local wave regime. The wave climate has significant annual variation, with relatively stormy autumn and winter period, and calm spring and summer. Several coastal regions (mainly a large part of the western coast) are particularly favourably sheltered from high waves.

5 Parameters of ship waves

The ship wash properties were measured in the coastal zone in the vicinity of 5 m isobath of the Tallinn Bay at a distance 2-8 km from the ship lane using pressure sensor based wave recorder SBE26 (Sea-Bird Electronic). Several witnesses claimed that the ship waves could be as high as 4 m high at specific sites. The visual estimates of wash patterns by experienced personnel together with preliminary experiments suggested that they are less than 2 m high. Consequently, the sensor was mostly positioned at the depth of about 2 m that allowed to record the wave components with the periods >1.5 s.

A fast ferry generally excites a wave packet lasting about ten minutes and consisting of several tens of waves. The height of individual waves is typically moderate and in most cases reaches 60-80 cm in the coastal areas that lie about 2 km from the ship lane (Fig. 4). In a more remote coastal zone of the island of Naissaar (about 8 km from the ship lane) it is about 20-40 cm.

The highest wash components produced by a single ship had heights up to 1.1 m and typical periods 8-15 s. The reason why such high waves occur at large distances from the ship lane is that the ships sailed occasionally with speeds close to the critical velocity (the latter is 25-50 knots in different parts of the ship lane). The resulting wave system disperses slowly and remains more or less coherent up to the coast.

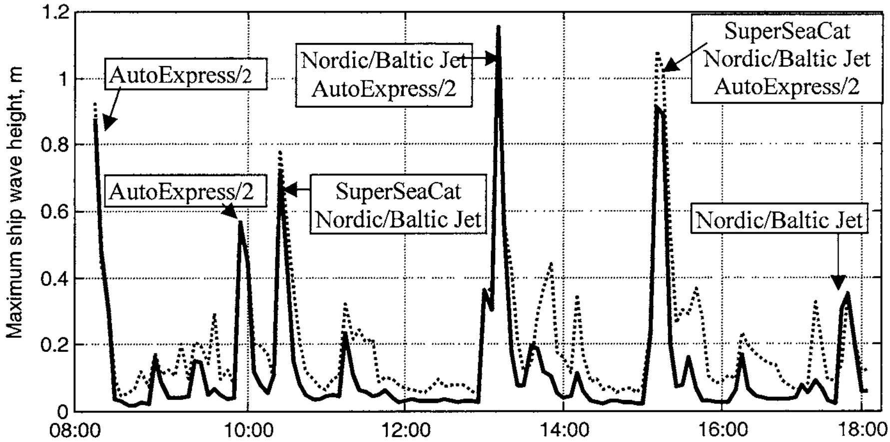

Figure 4: Heights of the long-wave components (periods >8 s; bold line) and the whole wash of fast ferries (dotted line) near the island of Aegna, 14.04.2002. Names of ships are indicated for several peaks.

Much higher waves occur either due to the superposition of waves excited by two or more ships or owing to the superposition of wind and ship waves. In suchcases wave heights up to 1.5 m have been recorded several times and once even as high as 2.3 m.

The major part (about 70-80%) of energy of fast ferries wash is concentrated in the wave components with the periods exceeding 5-6 s (Fig. 5) that is in accordance with other studies (e.g. [13]). Notice that conventional ships mainly produce waves with the periods of 3-5 s. Waves with periods of 3-4 s form another energy-containing part of certain types of fast ferries wash. In remote

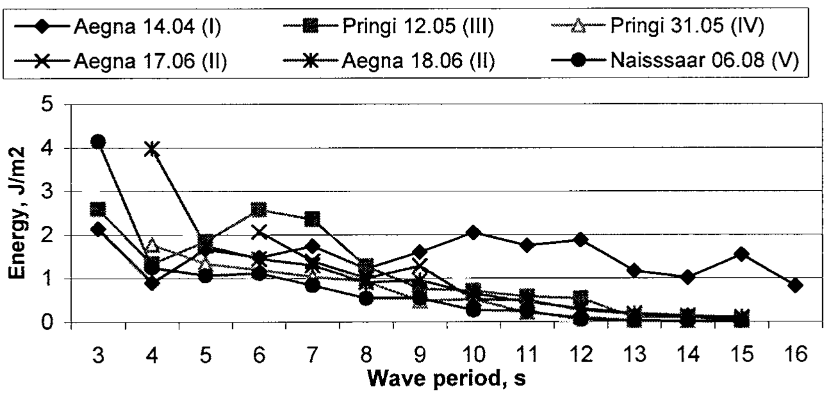

Figure 5: Energy of wash components with different periods.

areas, at times, this part reached 60-70 cm and was the highest. In these cases the short-wave component resembles an envelope soliton [14].

6 Comparison of ship wash with wind waves

The above has shown that the heights of fast ferries wash in the coastal zone of the Tallinn Bay indeed is moderate. The number of wave crests with the heights close to 1 m is frequently many tens per day in several parts of the coast. However, because of the mild natural wave regime, these waves belong actually to the highest 1-5% of wind waves (Fig. 6). The density of fast ferry traffic is so high that, as a matter of fact, ship waves do play a significant role in the bay.

The mean energy density of ship-generated waves in the coastal zone of the bay (at the 5 m isobath) is 6-10% from the total density of wave energy (Fig. 7). Notice that the direction of wave propagation was ignored in calculations of density of wind wave energy. Since wind waves propagate frequently towards theopen sea but ship waves do not, the relative role of ship wave energy in the total wave energy balance is more significant than indicated above.

While the wave energy is proportional to the wave height squared, the energy flux (wave power) takes implicitly into account the wave periods since longer waves generally show higher group velocities. The annual mean bulk power of ship waves in the coastal area of Tallinn Bay is about 100 W/m. It constitutes 25-40% from the total wave power at the western coast of the bay at a distance 2-3 km from the ship lane and about 15% at the eastern coast areas about 8-10 km from the ship lane. The reason for such a high portion is the above-discussed feature that a great part of ship wave energy is concentrated in long-period components. Since the propagation direction is not included in the calculations,

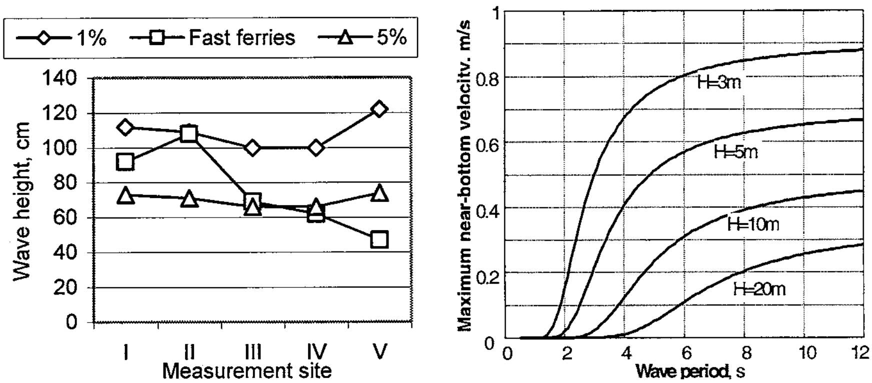

Figure 6: Comparison of the daily maximum height of the long-period component of fast ferries wash with the highest 1%-5% of wind waves at the measurement sites I-V (left) and the maximum wave-induced near-bottom velocity *versus* wave period for the wave height of 1 m and water depth of H=3-20 m (right).

the ship waves cause at least one-third of wave-induced energy flux near the western coast of the bay.

A seemingly insignificant contrast between the prevailing periods of natural waves (3-4 s during moderate winds, up to 7 s during extreme storms) and ship waves (mostly exceeding 8 s; frequently 10-15 s) causes highly diverse impact of the waves of different origin at medium depths (5-20 m). The reason is that for a fixed wave height, the wave-induced near-bottom velocity depends essentially on the wave period. For the mentioned depths, the highest variation of this velocity occurs when the wave period increases from 5 s to 8 s (Fig. 6). A typical ship wave with the height 1 m and period of 10 s induces the near-bottom velocity as high as about 45 cm/s at the depth of 10 m whereas the maximum velocity imposed by a wind wave with the period 4 s is only a few cm/s. Thus, the impact of a typical ship wake component on bottom sediments and aquatic wildlife is comparable with that of the waves occurring in extreme storms.

7 Conclusions

The bottom currents in the area in question are moderate and only in extreme cases exceed 20 cm/s. The above has shown that near-bottom velocities due to wind waves at the depths of 10-20 m are also lower than 20 cm/s even in extreme storms. Thus, in the deeper part of the coastal area the structure of bottom sediments and aquatic wildlife have been adjusted to low near-bottom velocities. Since typical periods of high-speed ship waves exceed these of wind waves, the ship wash causes unusually high near-bottom velocities at the depths of 5-20 m. In particular, this anthropogenic component of near-bottom velocity may dominate during the relatively calm high navigation season (April-September) when the biological productivity is at its seasonal maximum.

The fast ship waves appear as a new forcing component of the ecosystem of the bay that in addition to the direct effect upon fish and benthic plants may cause considerable intensification of beach processes. Indeed, at a depth of about 3 m in an area where the water depth is about 7 m, ship wave packets increase turbidity up to two times roughly during the double duration of the packet (T. Kõuts,

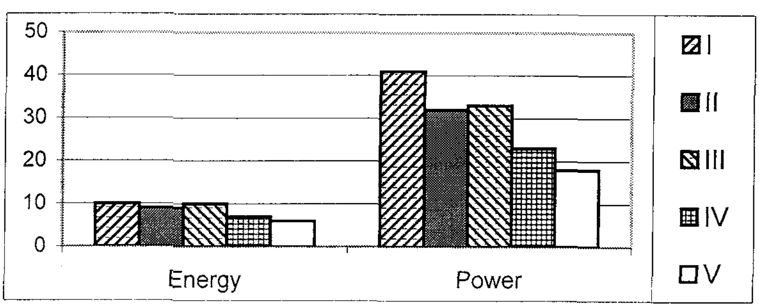

Figure 7: The role (%) of ship wash energy and energy flux (the wave power) in the total wave impact at the measurement sites I-V.

personal communication). The reduced water transparency, besides the effects of direct mechanical disturbances, may have a suppressing feedback to the bottom vegetation. Another potential mechanical effect of ship waves is enhancement of vertical mixing along the ship lane that may intensify the eutrophication effects due to the transport of nutrients into the euphotic layer.

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