VARIABILITY IN WAKE PROPERTIES GENERATED BY HIGH -SPEED FERRIES IN TALLINN BAY

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The main anthropogenic impact on the coasts of small islands in semi-sheltered urban areas hosting intense ship traffic is frequently caused by the highest and longest components of transcritical waves generated by high-speed ferries. The high variability of such waves and their infrequent occurrence make it difficult to collect a reliable statistics. Tallinn Bay is one of the few places where high-speed ferries frequently (with up to 50 sailings per day in the summer period) operate close to the shoreline at transcritical speeds. Experimental data of waves, induced by high-speed ferries (~500 recorded ship wakes), are processed and analyzed. This data set is used to construct empirical distribution functions of wave parameters, such as wave height, wake energy, wake power and wave asymmetry, for waves with different properties with an acceptable accuracy.

ИЗМЕНЧИВОСТЬ СВОЙСТВ ВОЛН, ВЫЗВАННЫХ ВЫСОКОСКОРОСТНЫМИ СУДАМИ В ТАЛЛИННСКОМ ЗАЛИВЕ

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Основное воздействие на берега, в том числе и небольших островов, в мелководных зонах оказывают высокие и длинные компоненты волн, вызванных прохождением быстроходных судов. Большая изменчивость таких волн и их нечастое появление вызывают определенные сложности при сборе данных для построения надежной статистики. Таллиннский залив является одним из немногих мест в мире, где высокоскоростные суда ходят на больших скоростях часто (до 50 в день, в летний период) и довольно близко к береговой линии. В данной работе мы опишем результаты обработки экспериментальных данных, включающих около 500 измерений судовых волн (сигналов). На основе этих данных, с приемлемой точностью, были построены функции распределения основных волновых параметров, таких как высота волны, энергия и мощность волнения, а также распределение асимметрии судовых волн.

INTRODUCTION

At present time, man-made islands are very important for a human life, industrial and infrastructure. A lot of places in the world are the potential objects for the building sites. For example, the UAE – is the place with the biggest construction of man-made islands. In Saint-Petersburg, the Vasilievskiy Island has been extended for constructing the biggest sea passenger terminal in Europe. There are plans to construct a man-made island in the Black Sea, which would follow the contours of the shape of Russian Federation on the world map. This plan may be fulfilled as soon as by 2014.

The construction of a large artificial island, in particular, in areas affected by large waves, is a very expensive and complex task. The largest problem is how to make the entire new structure stable against various marine hazards so that it would be safe and usable for a long time. The central question, with many aspects of scientific interest, is the determination of main properties of surface wave field at the location of the planned artificial islands.

Recently it has been established that intense ship traffic may, under certain circumstances, influence significantly the local wave climate regime. Such a situation is observed since about the year 2000 in Tallinn Bay which hosts the one of the most frequent fast vessel traffic in the world [4, 6, 7, 14].

The contribution of ship waves to the total energy of the local wave field is usually negligible on the beaches, which are open to the high energy ocean waves. Indeed, many medium- and high-energy shorelines have been affected by vessel wakes for many years whereas the effects of ship wakes have either been negligible or accepted as reasonable. However, following the introduction of high-speed passenger ferries in the 1980s, most of which are large and fast high-speed craft (HSC), able to carry passengers and vehicles, with service speeds ~50 knots, new and significant adverse effects were observed in numerous locations [7, 10].

High vessel wakes may seriously damage the coastal environment [7, 8, 10]. For example, in the low-energy environment of the Marlborough Sounds, New Zealand, the sudden change in the wave regime caused by introduction of HSC caused initial rapid and significant accretion, which continued in many places for the duration of HSC operation [6]. The changes have been irreversible: there has not been a return to pre-HSC beach morphology following their slowing in late 2000 [8].

Several different criteria for the properties of wake waves have been introduced in different countries to properly manage the coastal zone. Wash Rule employed in Denmark since 1997 and a modified version of it employed in New Zealand limits the maximum height of wake components at the depth of 3 m [7]. Washington State Ferries compares wave height and energy in deep water at a distance of 300 m from the ship track [1].

From the coastal engineering viewpoint, the primary properties of surface waves are the wave height, period, propagation direction, energy, energy flux (wave power) and wave shape. The total impact of a wave system essentially depends on the combination of these parameters. The existing studies [6, 12] are mostly concentrated on determination of their maximum values. For the purposes of coastal management, frequently more important and general information can be inferred from the probability distribution functions of the relevant parameters. The construction of such functions for ship wakes has been difficult in cases when fast ferries sail infrequently. This task became feasibly only recently after massive high-resolution measurements of wake properties, during which the parameters of a few tens of wakes of each ship were filed in the same environment [6].

The goal of this paper is to quantify the variability of the main parameters (maximum height, energy, energy flux and wave symmetry) of high-speed vessel wakes in Tallinn Bay based on long-term, high-resolution recordings of wave parameters.

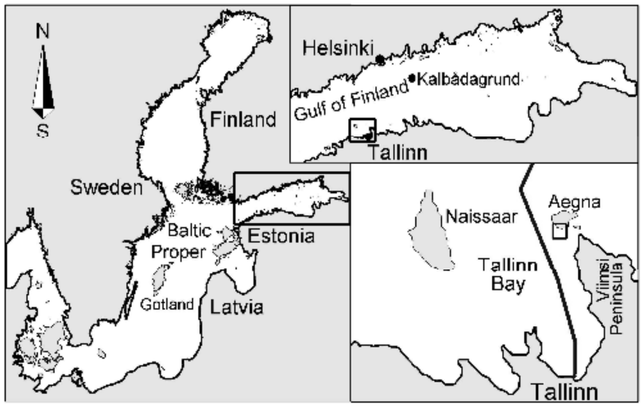


Fig. 1. The Baltic Sea, Tallinn Bay, the study site on the SW coast of Aegna (right lower panel), and approximate sailing line of ferries from Tallinn to Helsinki.

STUDY SITE AND MEASURMENTS

The sea area between Tallinn (Estonia) and Helsinki (Finland, Fig. 1) is one of the most intense fast-ferries traffic regions in the world. Tallinn Bay is one of the few places in the world where these vessels continue to operate at service speeds close to the shoreline and create high, dangerous waves.

The fast-ferries fleet, operated in Tallinn Bay in summer period 2008, consisted of a range of vessel types. There are two sister monohulls (*SuperSeaCat*), and two twin hull sister vessels (*Nordic Jet* and *Baltic Jet*). Among high-powered conventional ferries there are sister ships *Star* and *Superstar*, *Superfast*, and *Viking XPRS*. The total number of departures of HSC ships from Tallinn to Helsinki was 22–25 per day [6]. The characteristics of these vessels are presented in Table 1.

Table 1

Ships operating the Tallinn-Helsinki ferry link in summer 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

The properties of waves were established from a high resolution (sampling frequency 5 Hz, resolution of single measurements ±1 mm) time series of water surface elevations collected almost continuously over the period from 21 June to 20 July using an ultrasonic echosounder (General Acoustics LOG_aLevel®). The device was mounted on a heavy tripod in about 2.7 m water depth, ~100 m offshore from the shore. The site was about 2700 m from the sailing line of outgoing vessels, at the closest point [6]. The isobaths in the vicinity of the tripod and in the sea area between the tripod and the coast were largely perpendicular to the crests of vessel waves. Therefore, there were almost perfect wave propagation conditions towards the coast. A belt of boulders in the natural nearshore, down to the depths of about 2 meters, and a jetty protected by energy-absorbing tetrapods in the vicinity of the measurement site effectively damped ship wave energy and avoided wave refraction and reflection back to the tripod area. This allowed for recording of incoming waves only. This area of the coast was, therefore, a suitable place for measurements of vessel wave parameters and has also been the subject of several previous studies [2, 4–6, 12, 13]. The total record contains more that 650 wake events from fast ferries sailing from Tallinn to Helsinki.

WAVE HEIGHT

After filtering and computation procedures, records of 418 wakes were taken for the further wave properties analysis. Among them, there are 21 “double” wakes of ships that arrived almost simultaneously at the study site and were indistinguishable from each other, and 157 wakes of unidentified origin (UW). All other waves were attributed to particular ships.

The maximum wave height of vessels’ wakes varies significantly within each day (Fig. 2), and frequently is substantially different for different departures of the same ship. The highest waves in wakes in questions all are significantly higher than wind wave background. The maximum height of waves within a single wake normally was close to or exceeded 1 m. The largest ship wave heights in more or less calm conditions were 1.5 m. The combined ship and wind wave heights reached 1.7 m on a few days, with the significant height of the background about 0.3–0.4 m.

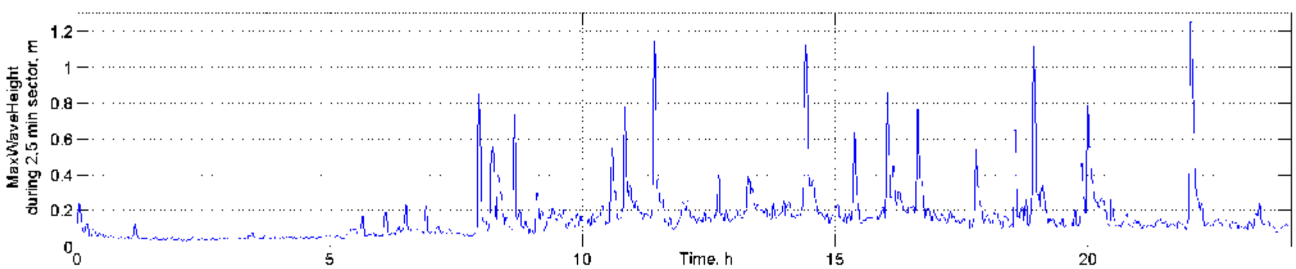


Fig. 2. Maximum wave height within 2.5-minute sections on 05 July 2008. Almost all spikes higher than 15 cm correspond to ship wakes.

Fig. 3 shows the distribution of the maximum wave height in single wakes for different vessels. The double wakes were typically the highest. On average, the highest waves of a single ship were generated by *Superstar* with the overall mean of the highest waves being 98 cm. Also, her sister ship, *Star* produced waves of comparable height. The average of maximum wave heights from the *SuperSeaCats* was 85 cm. The typical values of the highest waves from other ships were clearly smaller, about 60 cm (Fig. 3).

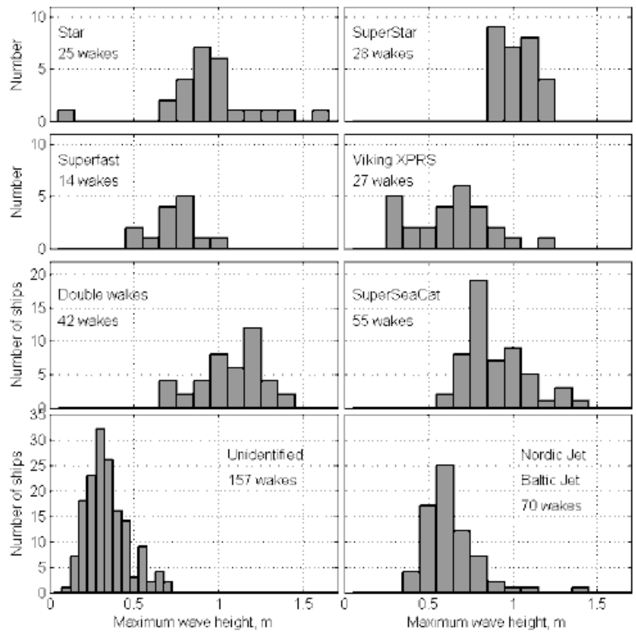


Fig. 3. Frequency of occurrence of maximum wave heights in wakes from di fferent ships.

The histograms of the frequency of occurrence of different maximum wave heights, equivalently, the empirical probability distribution functions of the maximum wave height in single waves, shown in Fig. 3, present some interesting features. First, it is clearly distinguishable that the width of these distributions substantially varies for different ships. The maximum height of wakes from *Superstar* lies in quite a narrow range, from 81 to 117 cm. The range for *Superfast* is somewhat wider, but still concentrated between 41 and 97 cm. Both distributions are almost symmetric and contain no outliers. The distribution for unidentified wakes (UW) is somewhat wider and skewed, but it also contains no clear outliers.

The distinguishing feature of the distributions for some ships is the presence of a number of outliers – very high wakes. For *Nordic Jet* and *Baltic Jet* their number is comparatively small but still shows that these ships may potentially produce >130 cm high waves. The waves from *Viking XPRS* were usually reasonable (20–80 cm), but at times reached 120 cm. This large variability of the maximum wave heights *for Viking XPRS* stems from the use of different operating speed during the measurement period [5], whereas she also able to produce large waves. The largest number of outliers was recorded for *Star* and the *SuperSeaCats*. While the distribution of maximum wave heights is almost symmetric for *Star*, it is substantially skewed towards large values for *SuperSeaCat*. On the contrary, the distribution for double wakes is skewed towards smaller values, apparently because the synchronous arrival of the largest waves from two ships is improbable.

WAVE ENERGY AND POWER

The typical total energy and energy flux of wakes from different ships had a similar pattern to the one presented in Fig. 3. Unlike the maximum wave height of double wakes (which only slightly exceeded the wave heights of *SuperStar*), energy contained in double wakes was about twice as large as energy in the single wakes. The energy in wakes of unidentified origin was only a small fraction (a few per cent) of energy in wakes from fast vessels sailing to the North (Fig. 4).

The ratio of the standard deviation of wake energy and the average wake energy (also the ratio of the standard deviation of wake energy flux and the average wake energy flux) for different ships was very similar to the ratio of the standard deviation of maximum wave heights and the average of maximum wave heights. As the typical variation coefficients were the largest for the wave heights, the maximum wave height is an appropriate parameter to characterize the ship wakes and their variability.

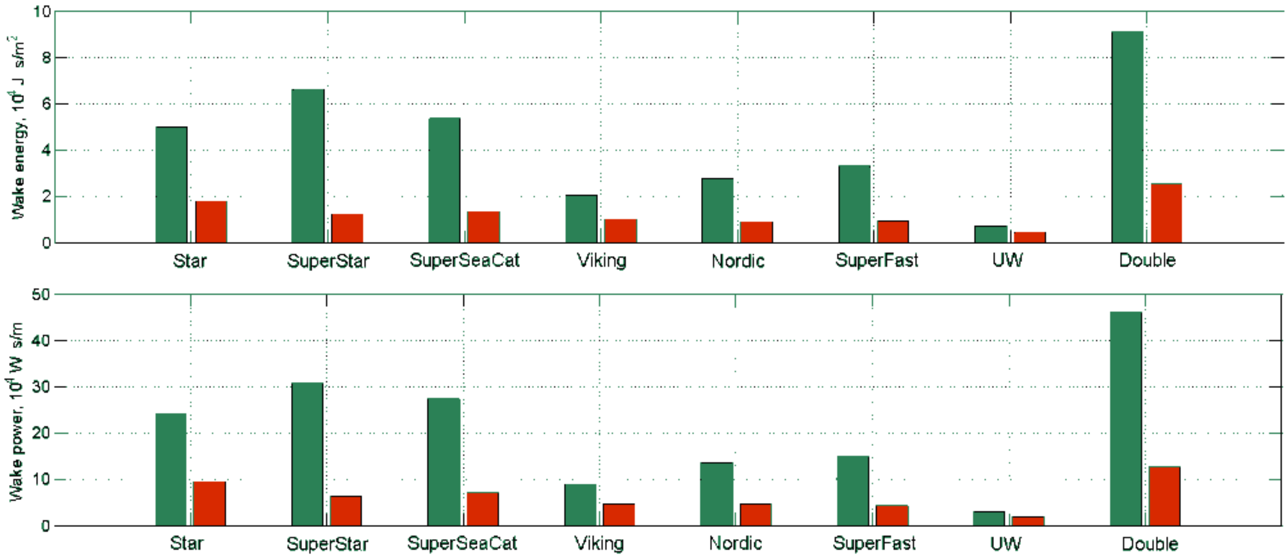


Fig. 4. Average values of wake energy and its standard deviation (top), average values of wake power and its standard deviation (bottom) for different ships.

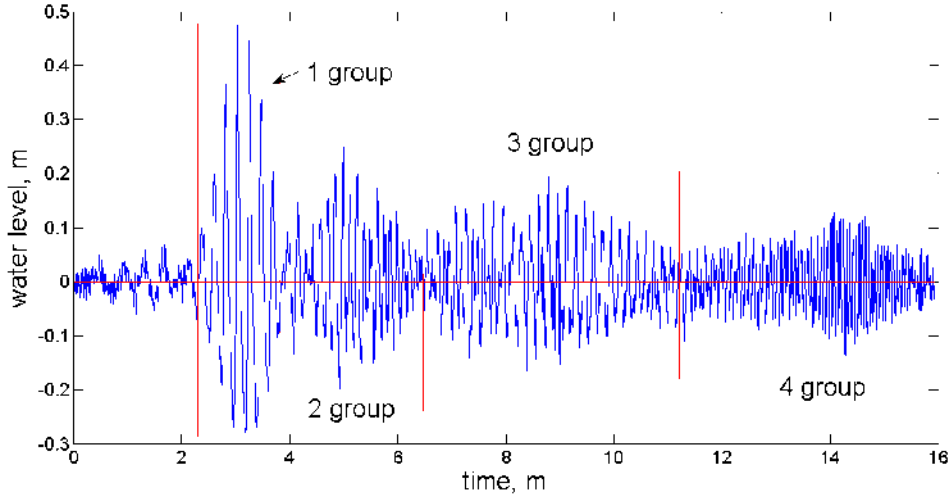
Wave asymmetry

The thorough analysis of the impact of the waves on the sediments in the nearshore and on wave runup and overtopping properties presumes detailed information about the shape of water surface in approaching waves, For example, wave-induced near-bottom orbital velocities directly follow the shape of the water surface and the maximum runup properties essentially depend on the asymmetry of the wave profile in terms of the difference of the mean slope of the front and the back of the wave [3].

It is relatively easy to estimate certain properties of the shape of the approaching waves in terms of the asymmetry of elevation under wave crests and dropdown under wave troughs. It is well known that long waves approaching the coast frequently become highly cnoidal, with much higher elevations at the crest compared with dropdown at the trough.

As this asymmetry is substantial for the longest and largest waves, in this analysis we used data sets of waves from the first group in each wake. More details on the group structure of ship wakes may be found in [5]. Total 1346 waves belonging to the first group of wakes from different ships of the selected 163 wakes from vessels are examined. For this analysis, only signals from vessels that did not contain waves created from other ships were selected. In particular, signals from superimposed wakes were eliminated from the analysis.

From Fig. 5 it can be seen that a typical wave record consists of, at least, three wave groups with varying wave parameters (amplitude, period, and symmetry). Previous analyses have shown that the most interesting of these are waves of the first group [13]. As a rule, (observe from Fig. 5) waves from the first group have higher amplitude and period in comparison to the following groups. They are frequently asymmetric, with an excess elevation compared to the dropdown, whereas waves in all other groups are more or less symmetric with respect to the calm water surface.



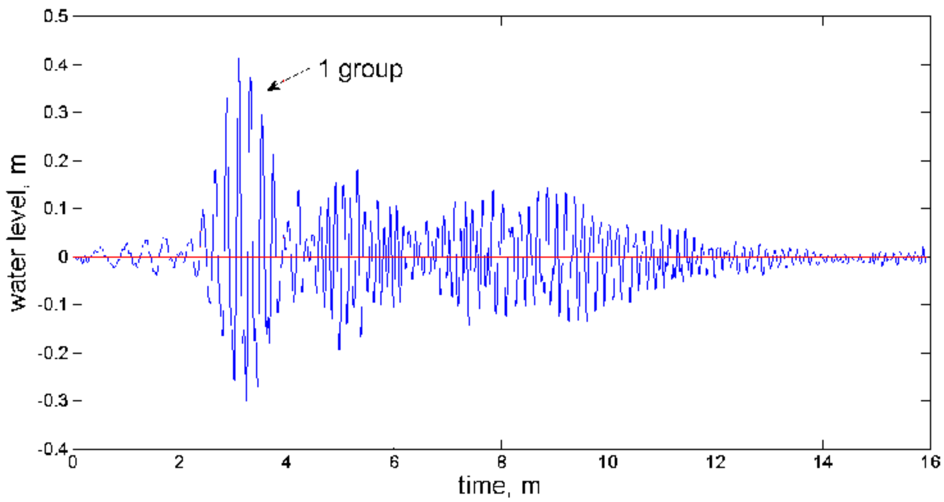


Fig. 5. Original (top) and filtered (bottom) record of the wake by SuperSeaCat 03 July 2008 at 21:40.

The analysis of the shape of the waves in terms of the potential difference between the elevation at the wave crest and the dropdown at the trough was performed for each wave in each of detected groups. The resulting ratio of the water elevations to the dropdown values is called asymmetry coefficient in what follows. The average values and the dispersion (standard deviation) of the values of this coefficient were calculated by means of using of the zero-upcrossing and zero-downcrossing methods for detection of single waves and the listed parameters of their shape. As expected, the two methods led to very similar results in terms of probability distribution functions. This indicates that the vessels' waves, by nature, are more akin to regular oscillations than to freak waves. Results of the asymmetry analysis of high-speed vessel waves are presented in Fig.s 6 and 7.

Fig. 6 shows the distribution of asymmetry coefficients for the different vessels. The crests of the most asymmetric waves are by 1.2–1.6 times higher than the water dropdown at the troughs. These distributions for *Star*, *SuperStar*, *SuperSeaCat*, *Nordic* and *Baltic Jet* are relatively narrow and have a shape generally close to a normal distribution. The distributions for *Viking XPRS* and *SuperFast* are relatively wide. This indicates that classical HSC vessels generate waves with approximately similar characteristics, while waves from relatively slow ferries show significantly higher variation. Note that highly asymmetric waves at times occur in wakes from all the vessels in question (Fig. 6).

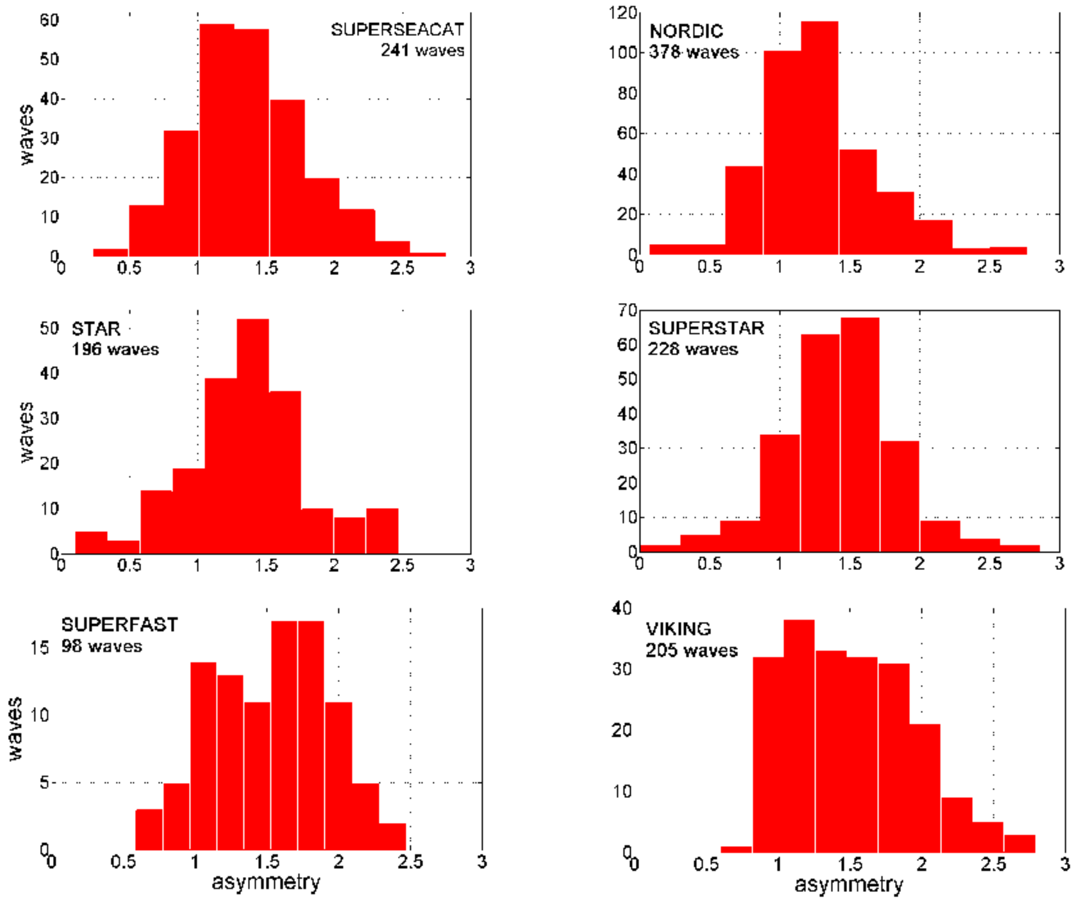


Fig. 6. Distribution of the asymmetry coefficient.

Fig. 6 shows that the maximum crest elevation, on average, is approximately 30–40% higher than the dropdown at the wave trough. The largest waves from fast ferries, therefore, are frequently essentially asymmetric and may create much larger near-bottom velocities and runup or overtopping than sinusoidal waves with the same basic parameters. This feature becomes also visible from Fig. 7, which presents a two-dimensional distribution of wave asymmetry as a scatter diagram of the frequency of occurrence of waves with different heights and asymmetry coefficients. The most frequent values of the coefficient of asymmetry are around 1.4 for the wave set in question. Fig. 7 also demonstrates that larger waves normally have higher asymmetry coefficient values.

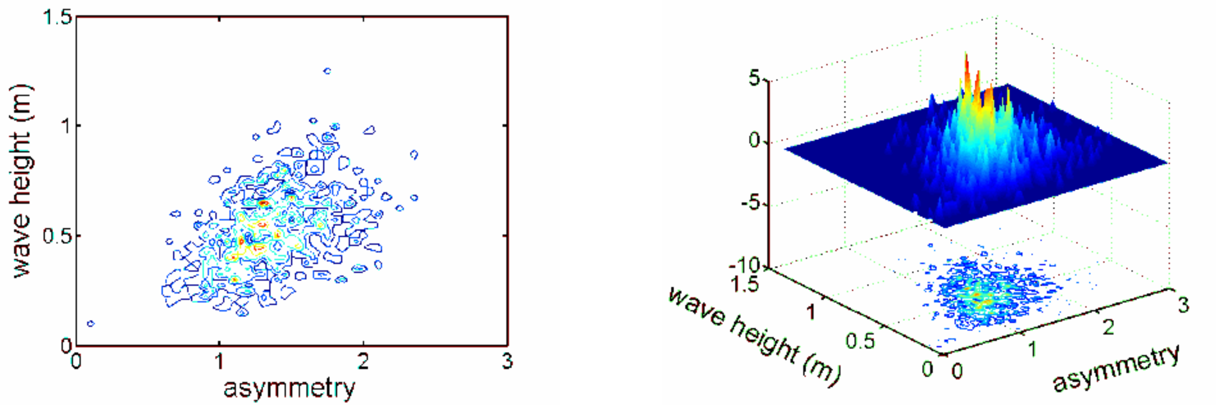


Fig. 7. Scatter diagram of the frequency of occurrence of waves with different asymmetry and wave height in terms of isolines (left) and the relevant surface (right). Shown are all large waves from the first group.

The presented results allow to conclude that the observed long and high ship waves, essentially all the waves from the first group of the wakes from fast ferries, have an overall shape that considerably differs from that of sine waves and therefore are highly nonlinear; apparently cnoidal (Fig. 8). This feature is important from the coastal engineering viewpoint, because, such waves not only create unexpectedly large near-bottom velocities [11], but are also able to effectively carry large water mass to the coastal zone [13].

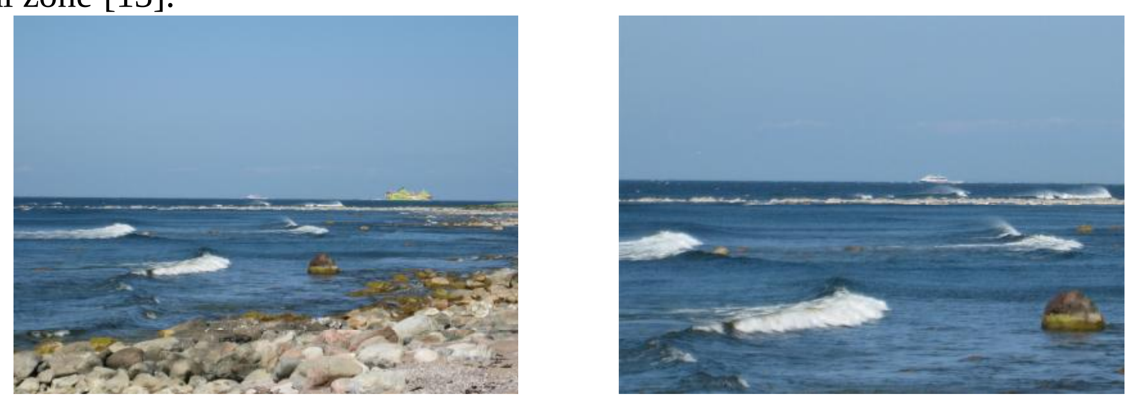


Fig. 8. Highly asymmetric ship waves created by *SuperStar* in Tallinn Bay.

CONCLUSIONS

The main goal of this study was to estimate the main properties (wave height, wake energy, energy flux and asymmetry) of waves from fast vessels' observed in the vicinity of a small island located in Tallinn Bay, Baltic Sea. The results give a good insight to wave conditions occurring at the coasts of artificial islands planned or located in the neighbourhood of ship lanes hosting intense traffic in otherwise sheltered sea areas.

The distributions functions for the listed properties of wakes were calculated for different classes of fast ferries. The largest ship wave heights in more or less calm conditions were 1.5 m. The combined ship and wind wave heights reached 1.7 m on a few days, with the significant height of the wind wave background about 0.3–0.4 m. Waves with such parameters may cause substantial damage to coasts of artificial islands designed for otherwise low wave conditions. The largest waves are usually produced by the classical high-speed craft whereas waves from conventional ferries (that are operating at relatively low speeds) normally are acceptable.

The total energy and energy flux were also calculated for each kind of vessels. The maximum wake energy is produced by classical high-speed vessels. They also create the largest values of the observed energy flux. The average energy and energy flux of superimposed wakes are, as expected, about 1.6 times larger than those for single wakes. The empirical distributions of the total wake energy and energy flux are very similar to the corresponding distributions for the maximum wave height.

As a new development, statistical analysis of the asymmetry of waves from the first group of wakes, caused by fast ferries has been performed. The average asymmetry coefficient, to some extent characterising the excess elevation of wave crests, for ship waves in the Baltic Sea is approximately 1.4, which indicates a high level of nonlinearity of the wave process and the necessity of using appropriate nonlinear approaches to adequately describe the impact of such waves. The values of the asymmetry coefficient, calculated using zero-upcrossing and zero-downcrossing methods, almost conincide. This feature suggests that ship waves, by nature, are more similar to regular, albeit transient, waves than to freak waves.

Asymmetry coefficients were also calculated separately for the different ferries. The resulting distributions were in accordance with the results of previously performed analysis of the maximum wave heights and the energy of the entire ship wakes [5].

The main outcome of the performed analysis is that the maximum wave height can be used as a basic parameter for estimating and characterizing the ship wakes and their variability.

The obtained empirical distributions of wakes' parameters allow to more adequately estimate the influence of ship wakes on the coastal zone, under present sailing conditions. Also, the appearance of these distributions can be used in deriving criteria for necessary adjustments of the wake parameters by changing either the sailing speed or line.

ACKNOWLEDGEMENTS

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