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Analysis of the Properties of Fast Ferry Wakes in the Context of Coastal Management

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Declaration:
Hereby I declare that this doctoral thesis, my original investigation and achievement, submitted for the doctoral degree at Tallinn University of Technology has not been submitted for any academic degree.

/Dmitry Kurennoy/

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Contents

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Introduction

Waves from high-speed vessels

The importance of the contribution of ship traffic to the local hydrodynamic activity in confined waters has been recognized for a long time. Ship traffic has the potential for causing environmental damage in narrow channels and the vicinity of vulnerable areas such as islands, artificial islands, wetlands or low-energy coasts (Schoellhamer, 1996; Bourne, 2000; Parnell and Kofoed-Hansen, 2001).

The hydrodynamic influence of ship traffic on the marine and coastal environment is usually negligible in areas receiving significant natural wave energy (Lindholm et al., 2001) but becomes evident in small, micro-tidal lagoons and bays, straits and inner waters of archipelagos. Examples of effects are the enhancement of vertical mixing along the fairway that may intensify eutrophication effects (Lindholm et al., 2001), resuspension of fine sediments and changes to the coastal processes in areas affected by ship wakes (Schoellhamer, 1996; Parnell and Kofoed-Hansen, 2001; Erm and Soomere, 2006; Osborne et al., 2007; Velegrakis et al., 2007) and the direct impact on sea life (Wolter and Arlinghaus, 2003; Boyd, 2008). Several aspects of the impact of ship traffic have been extensively studied in the Åland archipelago, the Baltic Sea, over several decades (Rönnberg, 1981; Rönnberg et al., 1991; Madekivi, 1993).

The increase in the number, speed and size of ships over the last few decades has led to the situation where ship wakes may be a significant driver of hydrodynamics on some coasts that are exposed to relatively high natural hydrodynamic loads. Such a situation was identified a few years ago for several sections of Tallinn Bay (Soomere and Rannat, 2003; Soomere et al., 2003). This area is characterized by an overall mild wave regime with the annual mean significant wave height H_S well below 0.5 m. At the same time, rough seas with H_S exceeding 3–4 m occasionally occur in the inner sections of the bay (Soomere, 2005a). Studies of ship wave properties in 2001–2003 established that the daily highest ship waves (with a typical height of slightly over 1 m) were equivalent to the annual highest 1–5% of wind-generated waves. Ship traffic was so intense that ship-generated waves contributed at least 5–8% of the total wave energy, and about 18–35% of the energy flux (the transport rate of the wave energy, frequently called wave power in the coastal engineering literature) even in those coastal areas of Tallinn Bay that were exposed to dominant winds (Soomere, 2005b).

A large part of such an unusual energy concentration in vessel wakes stems from the extremely frequent traffic of high-speed vessels in Tallinn Bay (Soomere et al., 2005). High-speed vessels (called also fast ferries) are interpreted here as the vessels the regular sailing regime of which contains extensive sections with the depth Froude number $F_h = V\big/\sqrt{gh} > 0.6$, where V is the ship's speed, g is the gravity acceleration, and h is the local water depth. When this threshold is exceeded, the classical, linear Kelvin wave system is modified and specific, nonlinear components of wakes frequently exist (Sorensen, 1973; Soomere, 2007). The speed at which the Froude number is equal to 1 is called critical speed.

Vessel waves as a challenge for coastal management

High vessel wakes may seriously damage the coastal environment and are able to jeopardize the safety of people and their property (Parnell and Kofoed-Hansen, 2001; Parnell et al., 2007; Soomere, 2007). For example, in the low-energy environment of the Marlborough Sounds, New Zealand, the sudden change in the wave regime caused by introduction of high-speed craft (denoted as HSC below) caused initial rapid and significant accretion, which continued in many places for the duration of HSC operation (Parnell and Kofoed-Hansen, 2001).

The apparent reason behind these changes is that the HSC may add a qualitatively new key forcing factor—relatively high and very long waves—to the local marine system (Soomere, 2005b). For example, the highest ship waves detected in Tallinn Bay in 2001–2003 were only about 1 m in height, but had generally periods of over 10 s (Soomere and Rannat, 2003). Such waves very seldom exist in the Baltic Proper where the typical wave periods are 4–6 s (Broman et al., 2006) and are even more infrequent in Tallinn Bay under natural conditions.

An important consequence for coastal management is that the changes at the coasts caused by wakes from HSC may be irreversible. For example, in the Marlborough Sounds there has not been a return to pre-HSC beach morphology following their slowing in late 2000 (Parnell et al., 2007). The reason is that natural energy levels in this environment are not sufficient to move gravel-sized sediment in supra-tidal berms that were created by the first HSC wakes. These features are now essentially relict (and quite stable), and will take a long time, or increased wave energy, to become active again.

Many authors emphasize that, in line with the definition of pollution in the United Nation Convention of the Law on Sea (UNCLOS), vessel waves should be considered as a specific type of (energy) pollution (Stumbo et al., 1999; Soomere, 2005b; Kelpšaite et al., 2009). The field of vessel waves, therefore, forms a generic component of environmental impact, and should be taken into account in the analysis of environmental impacts of harbours and associated ship traffic in the neighbourhood of vulnerable areas.

After wide recognition of the effects of vessel wakes, efforts have been made to reduce their impact in areas of intense ship traffic. In some places fast ferries have ceased operation (for example, in Denmark (Parnell and Kofoed-Hansen, 2001) and Washington State, USA), or significant speed limits have been introduced for sensitive sections of the vessel routes (for example, in New Zealand (Croad and Parnell, 2002), Finland and Sweden). In other places, attempts have been made to optimize vessel operation or encourage operation in water depths (normally deeper water) that avoid critical speeds (PIANC, 2003). New generations of vessels with hulls carefully optimized to reduce the wave resistance (and therefore the height of ship-induced waves) at specific speeds have entered into service.

There exists a large pool of studies into properties of linear and nonlinear ship waves over many decades (Peregrine, 1971; Wyatt and Hall, 1988; Brown et al., 1989; Chen and Sharma, 1995; Reed and Milgram, 2002; Torsvik et al., 2006; Torsvik and Soomere, 2008; see also overviews Sorensen, 1973; Soomere, 2007). Contemporary satellite imagery enables detection of many ship wake properties from space (Lyden et al., 1988; Reed and Milgram, 2002; Tello et al., 2005).

While the basic properties of ship waves in deep waters offshore and the local influence of intense ship traffic on the water column and sediments are understood to some extent, the potential for remote impacts is largely unknown. The basic concern is that the waves excited by strongly powered ships sailing at high speeds at moderate depths can result in a significant energy increase not only in the vicinity of the sailing line, but also in the far-field, many kilometres from the vessel track (Soomere and Rannat, 2003; Soomere, 2005b; Parnell et al., 2007). The amount of the wake wave energy that reaches fairly remote areas may be comparable with the wave energy in the vicinity of the ship lane. The reason is that certain groups of waves excited by high-speed ships under certain conditions are practically non-dispersive compact entities carrying massive amounts of energy. The wave energy may become active in the form of violent plunging breakers far from the ship lane (e.g., Hamer, 1999). The remote influence of wakes may be responsible for drastic thermal changes several kilometres away from the fairway (Fagerholm et al., 1991). The impact of vessel wakes may be comparable with that of quite large wind waves (Soomere and Kask, 2003). This feature shows that, under certain conditions, vessel wakes should be interpreted as a specific type of marine hazards affecting selected coastal areas, in particular, if long-living compact wave groups form a part of the wake. The level of danger caused by such waves essentially depends on the typical natural wave conditions at each site.

The Baltic Sea is a unique water body, the dynamics of which combines features of large lake, large estuary and small ocean (BACC, 2008). The intricacy of its internal dynamics extends far beyond the typical features of basins of comparable size (Alenius et al., 1998; Soomere et al., 2008). The International Maritime Organization recognized the Baltic Sea as a particularly sensitive sea area at the end of 2005. The combination of the relatively small size and the vulnerability of its ecosystem and its relatively young coasts makes this region extremely susceptible with respect to any increase in the anthropogenic pressure. For this reason, it is important to understand the potential role of ship wakes in its dynamics and development.

Many earlier studies have indicated or hypothesized that ship wakes may serve as a major driver of sediment transport at certain depths (Erm and Soomere, 2006) and directly or indirectly impact coastal processes near the waterline (Soomere and Kask, 2003; Soomere, 2005b; Osborne et al., 2007; Parnell et al., 2007). However, almost no unambiguous, *in situ* experimentally verified evidence exists about the behaviour and impact of ship wakes on medium- or high-energy coasts.

A prerequisite for progress in this direction is comprehensive knowledge of the properties of vessel wakes. From the coastal engineering and management viewpoint, the primary properties of surface waves are the wave height, period, propagation direction, energy, energy flux and wave shape. The total impact of a wave system essentially depends on the combination of these parameters. The existing studies (e.g., Parnell et al., 2001; PIANC, 2003; Soomere and Rannat, 2003) are mostly concentrated on the determination of their maximum values. For the purposes of coastal management, the probability distribution functions of the relevant parameters are much more instructive as they include a significantly larger amount of information about the general properties of ship wakes. The construction of such distributions for ship wakes has been difficult in cases when fast ferries sail infrequently. Progress in this direction became feasible only recently after extensive high-resolution measurements of wake properties, during which the parameters of hundreds of ship wakes (a few tens of wakes of each type of ship) were filed in the same environment as described below.

The primary goal of this study is to quantify the variability of the main parameters (maximum wave height, energy, energy flux of wakes and the asymmetry of the wave shape, expressed in terms of crest–trough asymmetry) of high-speed vessel wakes in Tallinn Bay. A new development in this area consists in the construction of empirical probability distributions for the listed parameters.

Earlier experiments performed in 2002–2006 (Soomere, 2005b; Erm and Soomere, 2006) used sub-surface pressure sensors to detect the wave properties. This equipment is able to adequately distinguish the wave periods and average properties of wave fields, but, due to pressure attenuation with depth, single wave heights and the shape of the water surface during ship wake events could only be estimated approximately. In the present study, approaching waves were measured by means of high-resolution profiling of sea-surface elevations. Doing so allowed also adequate detecting of many properties of wave elements such as the crests and troughs, and the asymmetry of single waves.

Another focus of this study is analysis of ship wave runup on a beach. Runup properties to a large extent define the level of actual danger caused by ship wakes in the affected coastal areas (Didenkulova et al., 2007). The relevant studies are particularly important for connecting the measured properties of incoming waves with their potential impact. Such joint analysis of both wave heights and wave runup heights evidently provides a key to more adequate estimation of the impact of waves induced by high-speed ferries on coasts.

Outline of the thesis

The thesis is based on five academic publications in peer-reviewed international research journals, which are referred as Paper I – Paper V in what follows:

Papers indexed by the ISI Web of Science

I. Valdmann, A., Käärd, A., Kelpšaitė, L., **Kurennoy, D.** and Soomere, T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. Baltica 21/1-2, 3–12.

II. **Kurennoy, D.,** Soomere, T. and Parnell, K. E. 2009. Variability in the properties of wakes generated by high-speed ferries. Journal of Coastal Research, Special Issue 56/I, 519–523.

III. Didenkulova, I., Parnell, K. E., Soomere, T., Pelinovsky, E. and **Kurennoy, D.** 2009. Shoaling and runup of long waves induced by high-speed ferries in Tallinn Bay. Journal of Coastal Research, Special Issue 56/I, 491–495.

Peer-reviewed papers in other international research journals:

IV. Parnell, K. E., Delpeche, N., Didenkulova, I., Dolphin, T., Erm, A., Kask, A., Kelpšaitė, L., **Kurennoy, D.,** Quak, E., Räämet, A., Soomere, T., Terentjeva, A., Torsvik, T. and Zaitseva-Pärnaste, I. 2008. Far-field vessel wakes in Tallinn Bay. Estonian Journal of Engineering 14/4, 273–302.

V. **Kurennoy, D.,** Didenkulova, I. and Soomere, T. 2009. On the crest–trough asymmetry of waves generated by high-speed ferries. Estonian Journal of Engineering 15/3, 182–195.

The role of the applicant in these papers is as follows.

The applicant has the leading role in the collection of experimental data underlying analysis and writing of Papers II and V.

In case of Paper IV, the applicant actively participated in the field experiment. Further, the applicant performed separation of single ship wakes, calculated their basic properties and drafted the relevant parts of the paper.

For Paper I, the applicant collected historical data about coastal hazards in the Gulf of Finland region and prepared a draft of the relevant overview.

In case of Paper III, the applicant was responsible for part of the organization of the underlying field work (described in Paper IV), analysed the runup data and prepared the relevant figures and text sections.

The thesis starts with an overview of different marine-induced coastal hazards in the World Ocean and especially in the context of typical Baltic Sea conditions of almost non-tidal seas with relatively low wave activity. The importance of waves induced by high-speed ferries and their role in the marine-induced hazards in the context of the management of the coasts of the Baltic Sea is demonstrated in Chapter 1. This analysis is mostly reflected in Paper I.

The experimental study of ship waves in Tallinn Bay, including wave measurements in the nearshore, observations of their runup on the beach and the data processing are described in detail in Chapter 2, which mostly follows Paper IV. This experiment serves as the basis of the first focus of the thesis—a study of statistical properties of waves induced by high-speed ferries in Tallinn Bay.

Statistical properties of waves are analysed in Chapter 3. This analysis is presented in more detail in Papers II and III. The data from 418 wakes on 15 days allows the construction of distribution functions of different wake properties (maximum height, wake energy and energy flux) with an acceptable accuracy. The periods of the highest waves vary insignificantly and are closely related to the cruise speed of the vessels. It is shown that the maximum wave height is an appropriate measure of the basic properties of wakes (such as the total energy and its flux in a wake) and their variability. Interestingly, wakes from 'classic' HSC are very variable, while wakes from large, basically conventional, but strongly powered ferries show quite limited variability. This feature suggests that both the average and extreme wake properties of such conventional ships can be more easily adjusted by changing their sailing regime.

Further analysis reveals that the crest–trough asymmetry of the largest ship waves from the first group is not necessarily well represented by the maximum wave height. This aspect is discussed in Chapter 4 with the use of certain elements of the cnoidal theory following the presentation in Paper V. On average, wave crests are about 1.4 times higher than the dropdown of water at wave troughs. In extreme cases, the crest height exceeds the trough depth up to three times. The results for the ratio of the crest height over the trough depth coincide with estimates made with the use of the classical cnoidal wave theory. The distribution functions of the wave asymmetry for vessels operating in Tallinn Bay are also constructed and discussed in Chapter 4.

The properties of ship wave runup on a beach, based on Paper III, are analysed in Chapter 5. The largest ship-generated waves approaching the coast usually break (both plunging and spilling breaking may occur) in the nearshore and have only weak wave amplification at the beach. On average, the runup height of ship wakes exceeds the wave height offshore at a depth of 2.7 m by a factor of 1.3. This amplification factor decreases with an increase in wave amplitude. This effect is explained by more intense wave breaking and dissipation in the turbulent bottom boundary layer for relatively high waves of the same length.

Approbation of the results

The main results described in this thesis have been presented at the following international conferences, symposiums and workshops:

Conferences:

SEAMOCS meeting, 22–25 October, 2008, Oslo, Norway, oral presentation: "Variability in wake properties generated by high-speed ferries".

International Conference Control Processes and Stability (CPS'09), 6–9 April, 2009, St. Petersburg, Russia, oral presentation: "Изучение свойств судовых волн в Таллинском заливе" (On the properties of vessel waves in Tallinn Bay, in Russian).

X International Coastal Symposium (ICS09), 13–18 April, 2009, Lisbon, Portugal, oral presentation: "Variability in the properties of wakes generated by high-speed ferries" (in cooperation with T. Soomere and K. E. Parnell).

European Geosciences Union (EGU) General Assembly, 19–24 April, 2009, Vienna, Austria, poster presentation: “Freak waves in Tallinn Bay, the Baltic Sea” (in cooperation with I. Didenkulova and T. Soomere).

International Conference “Construction of the artificial lands in the coastal and offshore areas”, 19–25 July, 2009, Novosibirsk, Russia, oral presentation: “Variability in wake properties generated by high-speed ferries in Tallinn Bay” (in cooperation with T. Soomere).

VII Baltic Sea Science Congress (BSSC 2009), 17–21 August, 2009, Tallinn, Estonia, poster presentation: “Variability in the properties of long waves generated by high-speed ferries in Tallinn Bay” (in cooperation with T. Soomere and K. E. Parnell).

At the time of writing the thesis, the following paper was accepted for presentation:

International Conference “Lithodynamics of bottom contact zone of ocean”, 14–17 September, 2009, Moscow, Russia, poster presentation: “Ship-wake measurements in Tallinn Bay” (in cooperation with T. Soomere).

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Because this thesis is based on published papers, I would like to declare my warm gratitude to all of the co-authors.

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1. Ship waves as a potential coastal hazard

1.1. Large-scale marine coastal hazards

Low-lying coastal areas are frequently under substantial pressure by different impact factors stemming from various processes on the sea. Part of these factors such as underwater earthquakes and landslides or hurricane winds may cause extremely dangerous hazards that could result in enormous losses of life and property in densely populated and economically developed coastal lowlands and estuaries. Coastal flooding and tsunami are usually recognized as having one of the largest damaging potential among natural hazards of various kind[1]. Some other phenomena such as currents, wind waves or gradual sea level changes usually do not cause direct, large-scale disasters but their long-term impact may result in even larger losses, for example, through intense coastal erosion or the necessity to protect or abandon some areas. Following Paper I, the factors that are created by various meteorological and hydrodynamic phenomena on the sea and that may harm the coastal ecosystem or cause economic damage or loss of life in the coastal zone are called (marine) coastal hazards.

The scale and damaging potential of different coastal hazards may be greatly different for different sea areas and/or coastal sections. For example, while storm surges may penetrate dozens of kilometres into lowlands in Bangladesh or Myanmar, such surges have almost no effect on high cliffs of the northern Estonian coast. Similarly, the damaging potential of ship-induced waves is obviously negligible on cliff coasts of western Ireland, but may substantially contribute to the loss of coastal wetlands along sheltered coasts of estuaries of the Gulf of Mexico (Bourne, 2000). Therefore, an adequate estimate of the damaging potential of any coastal hazard requires a thorough analysis of both its generation and developing mechanisms and the properties of the particular coastal section.

In order to reasonably position the damaging potential of ship waves, the major types of marine coastal hazards are reviewed in Paper I in the context of the Baltic Sea. In this area the potential effect of such hazards is usually much smaller than on the open ocean coasts; yet their joint influence with the consequences of global warming, sea level change and human activity may lead to considerable effects to the coastal zone.

The major marine coastal hazards are hurricanes, tsunami, storm surges and freak waves. These events have greatly different spatio-temporal scales and frequency of occurrence, but they all may obviously be very dangerous for the coastal zone and infrastructure located in its vicinity or for people on their way. All these hazards are often catastrophic and sometimes unpredictable, and almost always lead to adverse consequences. Their remarkable feature, however, is that most of them either have wave nature or are magnified by wavelike phenomena, especially by those that govern propagation and amplification of long waves.

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[1] http://en.wikipedia.org/wiki/List_of_deadliest_natural_disasters

Storm surges that cause severe flooding are one of the most destructive consequences of tropical and mid-latitude storms. A storm surge is created when high winds and low atmospheric pressure beneath the storm cause the local sea level to rise. As the storm approaches the coast, surface winds push water onto the coast. The height of the surge is amplified in areas with shallow waters, such as the coastal shelf in the Gulf of Mexico. Hurricane Katrina created the highest storm surge record in the United States—up to 9 m in some locations. This massive volume of water, allowing propagation of high storm waves far onshore, was responsible for most of the loss of life, and it inflicted overwhelming damage to coastal property. Extensive coastal areas of the Baltic Sea are also vulnerable to coastal flooding. Although the highest recorded water levels in the Baltic Sea basin (4.21 m in St. Petersburg or 2.75 m in Pärnu, Alenius et al., 1998; Suursaar et al., 2006) seem to be relatively low compared to those occurring under tropical hurricanes, unfortunate combinations of meteorological situation and hydrological parameters may lead to much higher surges in the mentioned areas of the Baltic Sea (Suursaar et al., 2006; Paper I).

Tsunami is an equally perilous coastal marine hazard that has led to loss of great many lives in the past (e.g., Levin and Nosov, 2009). A classical tsunami is a very long wave excited in deep water mostly by an earthquake or an underwater landslide. Its damaging potential usually becomes evident when this wave is approaching the shore: the wave height drastically increases and a huge amount of water hits the coast and leads to fatal consequences. This type of hazard is frequently observed in many coastal sections of the oceans but is very improbable in the Baltic Sea region. This is not only because strong earthquakes are extremely rare in this area but mainly because the entire water body is shallow. Consequently, no amplification of a deep-water tsunami wave occurs here either. A devastating tsunami could only appear if an asteroid fell into the sea. The example of an ancient meteorite crater on Saaremaa suggests that this is not completely impossible, but this type of tsunami is usually considered as almost improbable.

Another important tsunami source is underwater landslide. There is a remote possibility of large-scale underwater landslides in some parts of the Baltic Proper that hosts several steep underwater cliffs. Still the entire depth of the basin is fairly small and large-scale events such as the Storegga landslide (e.g., Dawson and Stewart, 2007) cannot take place here. As the coastal cliffs of the Baltic Sea are mostly of very moderate height, local landslide-generated tsunamis such as the event in Vajont reservoir, Italy (Panizzo et al., 2005), or the highest recorded tsunami in Lituya Bay, Alaska (Fritz et al., 2009), obviously will have almost no effect on the Baltic Sea coasts.

For the Baltic Sea community apparently the sea level change has the largest long-term impact among marine coastal hazards. Probably the largest number of local studies of long-term hazards are associated with various aspects of the water level rise (Gornitz, 1991; Zeidler, 1997; Thumerer et al., 2000; Kont et al., 2003; Dailidienė et al., 2006; Dinesh Kumar, 2006; Jarmalavičius et al., 2007). The sea level rise obviously will lead to a significant increase in the estimated damage costs of flood events. In the Baltic Sea, however, both sea level rise and fall may cause substantial problems (Kont et al., 2003; Johansson et al., 2004;); for example, land uplift leads to the necessity of more frequent dredging of harbours and waterways, or even of relocation of coastal infrastructures to meet the need for a free access to the open sea.

The sea level rise has a number of potential effects on coastal urban infrastructures, including accelerated erosion and increased occurrence of coastal flooding. While coastal flooding and its consequences are a general issue in coastal studies as discussed above, wind-induced low water levels and effects caused by postglacial land uplift are not very frequent in other water bodies.

The state-of-art estimates for the rate of the global sea level rise for the 21st century range from about 1.7 mm/year to about 5 mm/year (IPCC, 2007). As land is currently experiencing even a faster uplift in the northern part of the Baltic Sea, the global sea level change is dangerous neither for Finland nor for the northern part of Sweden. In the north-western part of Estonia, the land uplift rate is up to 2.8 mm/year (Zhelnin, 1966) and thus faster than the expected sea level rise according to a large part of the future scenarios. In most of Estonia, the expected net sea level rise is quite small because of a similar uplift. The global sea level change will apparently balance or weakly override the uplift there. Yet in the southern Baltic Sea, e.g. along the Polish (Zeidler, 1997) and Lithuanian coasts (that both experience a slow downlift), this rise apparently will cause problems within the coming decades (Paper I).

The most vulnerable with respect to the sea level rise are low-lying coastal areas where even a relatively small rise in the sea level could have significant adverse impacts if there is no adaptive response. The major long-term hazard accompanied with the gradual increase in the water level is the increased risk of coastal flooding. It is already high in several low-lying areas along the southern, eastern and northeastern coasts of the Baltic Proper, and for certain sections of the coasts of the Gulf of Riga and the Gulf of Finland. Most of the increase in the flood risk in the Baltic Sea basin is connected with a substantial change in the probability distribution of different sea levels within the last half-century. This is accompanied by an overall increase in the typical annual maximum sea level as observed during the last decades of the 20th century. In particular, the considerably increased probability of occurrence of high water levels within the last half-century (Johansson et al., 2001) means that coastal flooding will become more frequent and generally more devastating. This tendency apparently is a generic source for coastal hazards for the entire eastern part of the Baltic Sea (Paper I). An additional risk factor is the relatively fast water level rise during strong storms: sea level may rise at a rate of 0.2 m/hour. The maximum water level is usually reached within 6–7 hours (Dailidienė et al., 2004).

The most vulnerable in this respect are areas that may be jointly affected by direct storm-induced surge and long, basin-scale waves (e.g., seiches) eventually excited by other factors (Jonsson et al., 2008). A classical example is the eastern end of the Gulf of Finland, Baltic Sea, where St. Petersburg and its satellite cities are located. There are several factors that may cause long waves in the joint basin of the Baltic Proper and the Gulf of Finland, for example, cyclones moving over the Baltic Sea, the prevalence of westerly winds, which may cause a ‘slow’ Kelvin wave that moves towards Neva Bight, or release of local surges in other parts of the Baltic Proper. Such long waves meet the voluminous, opposite Neva River flow in the St. Petersburg area. The water level rise is further amplified by the joint influence of the shallowness of Neva Bight and geometrical focusing of the narrowing of the bight near the delta of the Neva River. The long wave approaching the mouth of the Gulf of Finland increases in height by 40–50% propagating across this gulf in the absence of wind (Averkiev and Klevanny, 2007).

A typical feature of coastal disasters in the Baltic Sea is that they happen under a joint influence of several dangerous factors. The storm surges in St. Petersburg, for example, develop under the joint impact of a direct storm surge, long waves approaching from other sea areas and then the inverted barometer effect born by low atmospheric pressure in the area in question. The most prominent flood occurred in St. Petersburg on 7 November 1824 and was 4.21 m above normal. During the whole history of St. Petersburg, there were three other floods higher than 3 m. These floods caused very great damage indeed.

Perhaps the most detailed study of such combinations has been performed for the surge created during the windstorm *Gudrun*, the fourth most expensive natural disaster in the world in 2005 that hit many areas in northern Europe on 7–9 January 2005, caused widespread property damage and exceptionally high coastal flooding on its way. The storm surge in the Estonian town of Pärnu (2.75 m over mean sea level) was the highest ever recorded in Estonia (Suursaar et al., 2006). An early forecast for the maximum surge height in St. Petersburg was 3.7 m, but owing to a more favourable trajectory and speed of the cyclone, the water level only reached 2.39 m (Averkiev and Klevanny, 2007). While the pressure change was responsible for the sea level increase by about 0.7 m, the rest was caused by the combination of wind surge and long wave.

A high water level alone is extremely dangerous only when it exceeds a certain threshold whereas a combination of unusually high water levels and rough seas presents acute danger to depositional coasts (Orviku et al., 2003). From the viewpoint of coastal processes, however, also relatively moderate surges may cause a large impact if they occur simultaneously with high waves. Even the floods that did not exceed 1.9–2.2 m in the vicinity of St. Petersburg but were accompanied by strong wind waves caused extensive coastal erosion and sediment resuspension processes in many coastal sections. Sequences of such events are particularly dangerous to the coastal zone, as they do not allow the recovery of beaches owing to constructive forces and may lead to destruction of buildings at the coast and to unrecoverable dune erosion.

1.2. The role of surface waves among coastal hazards

A substantial part of the energy and momentum submitted to the water masses by winds blowing over the sea surface is carried in the form of surface waves. They bring massive amounts of energy to the shore and thus form one of the generic sources of hazards in the coastal zone. On gently sloping coasts, high waves may significantly contribute to the above-discussed basic hazard (storm surge) by the local, wave-induced change in the sea level (wave set-up, Dean and Dalrymple, 2002). In general, however, the impact of wave activity becomes only evident as a significant coastal hazard in the long-time frame run.

Wave action is the principal driving force of the coastal processes. The largest waves can be observed along ocean coasts where wave heights over 10 m may occur regularly. As many beaches are vulnerable with respect to the joint occurrence of a high water level and large waves, even short-lived but ferocious storms can cause rapid erosion and accretion. The most extensive damage in vulnerable areas (such as low-lying atolls and the coastal fringes of high islands) usually occurs during short wave events created by strong cyclones. Even infrastructure perched on 20 m high cliffs may not be immune during severe storms (Solomon and Forbes, 1999). On the other hand, the role of even small waves may be very large under unfortunate conditions (Dean and Dalrymple, 2002).

The anisotropic nature of the Baltic Sea wind and wave fields (Soomere, 2003; Jonsson et al., 2002; 2005) suggests that the eastern coast of the Baltic Sea is probably under the largest natural pressure among the variety of the coasts of this water body. This coast is to a large extent in active evolution and the potential changes in the forcing are expected to become evident relatively fast. These parts of the coast host several major ports and cities, a part of which are still under vigorous development. The potential increase in the frequency and/or severity of marine coastal hazards may substantially affect the planning, operation, maintenance and reconstructions of the relevant infrastructure.

The patterns of changes in the eastern coast of the Baltic Sea and many coastal sections of its sub-basins are frequently modified by decadal and subdecadal water level changes (Paper I). Owing to the specific features of the Baltic Sea wind fields (Mietus, 1998; Soomere and Keevallik, 2001; 2003), even relatively sheltered bays are at times subject to extensive wave loads (Soomere, 2005a). For example, almost the entire coastal area of the City of Tallinn is completely sheltered from waves excited by predominating southern winds. As a result, the local wave climate is at places very mild compared to that in the open part of the Gulf of Finland. The annual mean significant wave height varies from 0.29 m to 0.32 m in different sections of Pirita Beach in the City of Tallinn (Soomere et al., 2007). North and north-western winds, however, may excite waves in this bay that are almost as high as the highest waves in the Gulf of Finland. The significant wave height exceeds 2 m each year and may reach 4 m in NNW storms in the central part of Tallinn Bay (Soomere, 2005a). As a result, most of the coasts of Tallinn Bay show features of intense erosion (Lutt and Tammik, 1992; Kask et al., 2003).

The possible effects of the changes in the wave regime in the entire Baltic Sea area are poorly understood. A number of observations can be related to a more frequent occurrence of marine hazards affecting the evolution of its coasts. Orviku et al. (2003) presented evidence that the apparently increasing storminess in the Baltic Sea (Alexandersson et al., 1998) has already caused extensive erosion of several depositional coasts. Several cases of hazardous wave conditions occurred at the turn of the millennium (Kahma et al., 2003). Also, ferocious winter storms in 2004/2005 (Suursaar et al., 2006; Soomere et al., 2008) enlivened the discussion about whether the extreme wave conditions in the Baltic Sea have become rougher compared to the situation a few decades ago. On the other hand, a decreasing tendency in the annual average wave heights since about the year 1997 has been recently found for the northern part of the Baltic Proper (Broman et al., 2006; Soomere and Zaitseva, 2007).

In the Baltic Sea conditions, the knowledge of the wave height only is not enough for coastal management. A variety of wave-induced processes, in particular the transport of sediments in the surf zone, largely depend on the height, length or period and propagation direction of waves and the water level during rough seas. The experience from the Baltic Sea basin is that even the quantification of the role of the ferry-induced waves requires extensive efforts from a large team of scientists (Soomere et al., 2003) and leads to quite a large uncertainty in estimates of the role of different wave parameters.

A large part of this uncertainty is due to the shortage of the information about the actual wave regime. The relevant knowledge of long-term wave climate can be to some extent extracted from the long-term statistics of wave properties at the few existing measurement sites in the Baltic Proper. The results of numerical studies (Soomere, 2005a) and the analysis of the longest available instrumentally measured time series of wave properties at Almagrundet (Broman et al., 2006) confirm that the wave periods in the entire Baltic Sea are relatively small. This is the key reason why waves from fast ferries have formed an appreciable portion of the total wave activity in Tallinn Bay since 1997. Their annual mean energy and its flux account for about 5–7% and 20–25% of that of the wind wave activity, respectively. The daily highest ship waves belong to the highest 5% of wind waves in this area (Soomere, 2005b).

The intense fast-ferry traffic, accompanied by high and long waves at times approaching from directions not common for wind waves, may stimulate sediment transport in the opposite direction to the natural littoral drift or current-induced transport of suspended matter during a relatively calm season (Elken and Soomere, 2004). The role of fast-ferry waves in coastal processes, which may be potentially substantial under certain circumstances (Soomere and Kask, 2003; Levald and Valdmann, 2005; Erm and Soomere, 2006), is poorly understood so far and needs further investigation.

It is well known that an increase in wave heights, changes in wave periods or in predominating directions are important for the functioning of the coasts. The generic dependence of the course of coastal processes on wave properties is especially important in the Baltic Sea where the existing wave patterns are substantially anisotropic (Soomere, 2003). A change in the climatic system may easily lead to changes in certain wave properties. In this context, an intense ship wave field may be used as an appropriate forcing case for studies of the impact of potential changes in the local wind climate on the wave influence on the coastal zone.

1.3. Ship wakes as a coastal engineering problem

The properties of approaching surface waves provide key information necessary for solving many coastal engineering problems. Vessel wake waves add energy to coastal systems wherever they occur. Their contribution is obviously negligible on high-energy coasts that are open to large ocean waves. Although many low-energy and medium-energy shorelines in the vicinity of fairways with intense ship traffic have been affected by vessel wakes for many years, the effects have either been negligible or accepted as reasonable.

However, following the introduction of high-speed passenger ferries in the 1980s and large and fast high-speed craft (HSC) capable of carrying passengers and vehicles, with service speeds approaching 50 knots, new and significant adverse effects were observed in numerous locations (Parnell and Kofoed-Hansen, 2001; Soomere, 2007). Their wakes can be a major contributor of energy to sections of coasts that are not exposed to significant natural hydrodynamic loads (Soomere, 2005b). The actual effect depends upon the features of the coastal environment and the existing hydrodynamic loads. As the periods of vessel-generated waves usually increase with the vessel’s speed, HSC may produce waves the like of which are extremely seldom found in some environments. In this context, specific types of disturbances occurring at higher speeds, such as dangerously high leading waves and highly monochromatic packets of relatively short waves (Brown et al., 1989; Soomere and Rannat, 2003), solitary and cnoidal wave trains ahead of the ship (Neuman et al., 2001) and associated depression areas (Garel et al., 2008), all qualitatively different from the usual wind waves or constituents of the linear Kelvin wake, are extremely important.

Waves excited by strongly powered ships sailing at high speeds at moderate depths can result in energy concentration not only in the vicinity of the fairways but also in remote sea areas. The major source of problems associated with ship-induced hydrodynamic activity is that long, solitonic wake waves generated by large vessels may create extremely strong impulse loads that at times exceed similar loads caused by natural factors. For example, the annual mass of sediment resuspended by these waves in Hillsborough Bay, a shallow microtidal subtropical estuary in West-Central Florida, is by one order of magnitude greater than the annual mass of sediment resuspended by wind waves (Schoellhamer, 1996). A secondary impact of the long waves is that sediments that are resuspended and newly deposited are more susceptible to resuspension by natural currents than undisturbed bottom sediments.

The basic method of management to prevent undesired impacts from vessel wakes consists in setting firm limits to certain properties of the wake. A variety of different criteria are used in various parts of the world. The Wash Rule employed in Denmark since 1997 and its modified version used in New Zealand limits the maximum height of wake components at a depth of 3 m so that the deep-water height limit is smaller for longer waves (Parnell and Kofoed-Hansen, 2001). Washington State Ferries compares wave height and wave energy in deep water at a distance of 300 m from the ship track (see e.g., Begovic et al., 2006).

The rules are based on the assumption that the wave effects caused by conventional ships are generally acceptable and tolerated by the public. In medium-energy environments a similar tolerable level should be established for each coastal section from the properties of natural waves. Many of the common practices of wind wave analysis, however, are difficult to apply as wake waves vary in their basic parameters not only over the course of a single wake event but also show extremely high spatial variability (Torsvik and Soomere, 2008). Moreover, many factors, both environmental (tidal currents, wind speed etc.) and operational (loading, trim etc.), affect actual wave characteristics. The HSC wakes generated at nearcritical speeds are usually thought to be the most sensitive with respect to minor alterations in the sailing regime: very small changes in the way the vessel is operated, such as displacement (loading) and trim, can have major consequences for wake height (Stumbo et al., 1999). Thus it is not surprising that a common feature of wake wave measurement programmes is a significant variability in the data records for the same vessel at different times in the same location and in different locations (Parnell and Koefoed-Hansen, 2001; Parnell et al., 2007).

On the one hand, this feature considerably complicates coastal management issues and creates the need for a substantial safety factor in the planning of local coastal engineering structures. On the other hand, it suggests that mitigation of the related problems can be achieved, at least in some places and for certain classes of vessels, by small changes in the sailing line or regime.

1.4. Potential of ship wakes for the mitigation of disasters

As discussed in Paper I and below in this study, ship-induced waves may, under certain circumstances, serve as a serious threat to the coastal ecosystem, coastal engineering structures, property and even to people (Soomere, 2007). This motivates proper positioning of the potential impact and necessary countermeasures from the viewpoint of coastal engineering.

The role of vessel wakes in physical oceanography and coastal engineering is, however, much more multifaceted than simply being a potentially inconvenient phenomenon. It is well known that the leading long and high waves in wakes from high-speed vessels are almost perfect long shallow-water waves (Soomere, 2007). These waves usually approach the coast in groups consisting of a few wave crests and being dynamically similar to several types of tsunamis. Although parameters of classical, earthquake-induced tsunamis do not match those of vessel wakes, there is a clear similarity of some ship waves with landslide-induced tsunamis

(Didenkulova et al., 2009). This similarity opens a way to use vessel waves for studying certain properties of tsunami waves.

An important property that may be used in studies far beyond the scope of coastal engineering is that the highest vessel wakes are much longer than wind waves in semi-enclosed basins, the wave length reaches 250 m at a depth of 10–20 m and the wave period is about 10–15 s. These waves are completely different from typical wind generated waves in many semi-sheltered water bodies. Moreover, ship waves often approach from directions from which high wind waves are improbable. Therefore, an intense ship wake field may be used in studies of potential effects of changing wind climate and accompanying changes in the wave regime (Soomere et al., 2009).

There has been a discussion as to whether long, solitonic ship waves could be interpreted as analogues of freak waves in shallow water (Hamer, 1999; Peterson et al., 2003). In general, freak (rogue) waves are particularly high and steep structures on the sea surface, which are observed much more frequently than it might be expected from surface wave statistics. There have been numerous efforts to explain this interesting and dangerous phenomenon (Kharif and Pelinovsky, 2003; Kharif et al., 2009). Nevertheless, its nature is not yet properly understood. A partial answer to the problem of ship-induced freak waves is given in Paper V. Although waves in a wake from fast vessels may be relatively high and steep, they still normally resemble regular oscillations of water surface. The continuous recording of water surface time series described in Paper IV revealed that freak waves of moderate height (~1 m) do occur in the background wind field with the significant wave height of a few tens of centimetres (Didenkulova et al., 2009b).

1.5. Concluding remarks

Major potential marine hazards affecting the coasts of the northern and eastern parts of the Baltic Sea are reviewed in Paper I. While several classical hazards such as tsunamis are immaterial here, changes in sea level and its variability, wave regime and wind-induced coastal flooding can significantly impact coastal environments. Ship wakes play relatively great role in this shallow, semi-enclosed basin where they are often unusually long waves with wavelengths of up to 250 m at depths down to 10–20 m. In some sea areas such as Tallinn Bay the role of waves induced by high-speed ferries may become principal. They may strongly affect coastal environments and may be considered as a specific coastal hazard.

In many aspects, these wakes can be used for studies into other coastal hazards. Namely, they form a dynamically similar system to extreme, long, large-scale ocean waves, which allows modelling the shoaling and runup properties of certain types of tsunamis in safe conditions. The properties of corresponding tsunami waves can be found with the use of geometrical similarity. The vessel waves in question correspond to waves with a length of 50 km and a period of 10 min in a typical water depth of 4 km in the World Ocean, which can be recognized as tsunami waves (Didenkulova, 2009b).

2. Experimental study of ship wakes in Tallinn Bay

2.1. Study site

Tallinn Bay is a semi-open sea region in the central part of the Gulf of Finland, an elongated sub-basin of the Baltic Sea. It is approximately 10×20 km in size, with the City of Tallinn located at its southern end. The bay belongs to a family of semi-sheltered bays that penetrate deep into the southern coast of the Gulf of Finland (Fig. 2.1). The overall hydrodynamic activity is fairly limited in this almost tideless area where the tidal range usually is a few centimetres (Leppäranta and Myrberg, 2008). There are, however, extensive water level variations driven primarily by weather systems, with a maximum recorded range of 2.47 m. As very high (more than 1 m above the mean sea level) water level events are rare, the wind wave impact is concentrated into a relatively narrow area in the coastal zone.

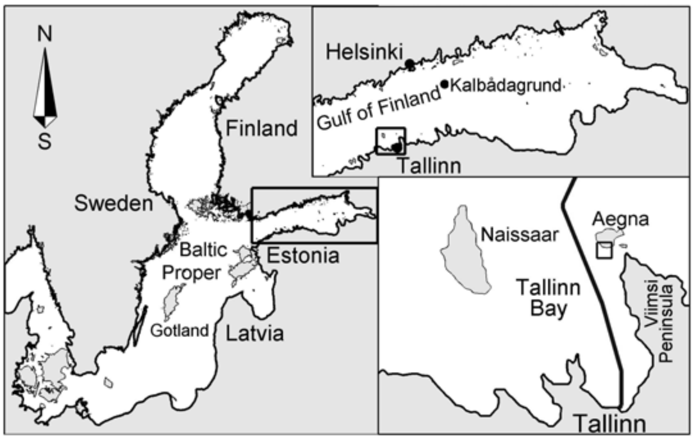

Fig. 2.1. The Baltic Sea and Tallinn Bay. The bold line in the lower right panel indicates the approximate route of fast ferries (Paper IV)

The complex shape of the Baltic Sea, combined with the anisotropy of predominant winds, results in a particular local wave climate in Tallinn Bay. Most storms blow from SW, but occasionally very strong NNW storms occur. Long and high waves, created in the Baltic Proper during SW storms, usually do not enter the Gulf of Finland owing to geometrical blocking (Caliskan and Valle-Levinson, 2008). Bottom refraction at the mouth of the Gulf of Finland may cause waves to enter the gulf under some circumstances (Soomere et al., 2008). However, on entering they keep propagating along the axis of the Gulf of Finland, and affect only very limited sections of the coast of Tallinn Bay, the northern part of which is additionally sheltered by the islands of Aegna and Naissaar (Fig. 2.1). The same is also true for the waves excited in the Gulf of Finland by easterly winds. The roughest seas in Tallinn Bay occur during NNW storms that have a fetch length of the order of 100 km and thus only produce waves with relatively short periods. These features severely limit the peak periods of the wave components that are usually well below 3 s, reach 4–6 s in strong storms and only in exceptional cases do they exceed 7–8 s (Soomere, 2005a).

As a result of these factors, the local wave climate is relatively mild in Tallinn Bay compared to the adjacent sea areas. The significant wave height 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, 2005a). On the other hand, very high (albeit relatively short) waves occasionally occur during strong NW-NNW winds, to which Tallinn Bay is fully open. The significant wave height typically exceeds 2 m at some time each year and may reach 4 m in extreme NNW storms in the central part of the bay. As a consequence, most of the coasts of Tallinn Bay can be considered to be a medium-energy coastal environment at the scale of the Baltic Sea.

The listed features make many sections of the coast of Tallinn Bay vulnerable to changes in wave properties, which may be caused also by intense ship traffic. The largest impact was suggested to occur in connection with an increase in wave periods (Soomere et al., 2003; Soomere and Kask, 2003), but it was also suggested that a change in the direction of wave propagation may substantially affect the longshore transport patterns (Elken and Soomere, 2004).

First high-speed ships were launched to serve the Tallinn–Helsinki link in the mid-1990s and since then Tallinn Bay has hosted extremely heavy fast-ferry traffic. During the high season, a variety of high-speed ferries crossed the gulf almost 70 times per day at the turn of the millennium (Soomere et al., 2003). Thus, region of the sea area between Tallinn (Estonia) and Helsinki (Finland) belongs to one of the most intensive fast-ferry traffic in the world. As discussed above, in many coastal sea areas the vessels' speed is strictly regulated. Regulations for Tallinn Bay have been thoroughly discussed during the last 10 years, but no decision has been made. As result, Tallinn Bay is one of a few places in the world where vessels may use high service speeds close to the shoreline. On the other hand, this feature makes Tallinn Bay a unique area where properties of wakes from different high-speed vessels and their impact on the coasts can be studied in detail.

2.2. The fleet: characteristics of the ships

The fleet operated in the Tallinn–Helsinki route around the year 2000 consisted of fast ferries and conventional ferries. The most common high-speed ferries were large (~80 m in length, ~1200 t displacement when fully loaded) and medium-sized (~60 m in length, ~600 t displacement) catamarans, and quite small hydrofoils during the high season (Soomere and Rannat, 2003). There was only one monohull high-speed ship that made 4–5 crossings a day, and a large conventional, but extremely high-powered ferry *Finnjet*, which crossed the bay a few times a week. The number of conventional ferry sailings at slow speed was about 20 per day.

During the last five years, there have been significant changes in the types of vessels operating in the traditional 'fast-ferry' market on the route between Tallinn and Helsinki and elsewhere in the world. Firstly, the vessels that produced very dangerous and damaging waves (for example, the largest of the high-speed catamarans *AutoExpress*, which produced the highest waves (Soomere and Rannat, 2003)) have been taken out of service. Secondly, the greatest change is the introduction of several vessels of a new generation of large, high-powered, mostly conventional ships operating at relatively high speeds of 25–30 knots (about 45–55 km/h, see Table 2.1). These ships have replaced almost all older conventional ferries that sailed at 15–20 knots (about 25–35 km/h), the number of which has decreased considerably. Thirdly, the small hydrofoils have been replaced by much larger ships (Paper IV).

The fleet operated in Tallinn Bay (Table 2.1) consisted of two families of vessels during the field measurements in summer 2008. There were four 'classic' HSC: two high-speed monohulls (*SuperSeaCats*) and two medium-sized twin-hull vessels (*Nordic Jet* and *Baltic Jet*), which operate at speeds of ~65 km/h and have been used on the route for several years. The twin-hull hydrofoil *Merilin* has a comparable service speed (Paper IV), but she is not considered in this study as she produced very small waves like smaller hydrofoils in 2002–2003 (Soomere and Rannat, 2003). The high-powered large conventional ships (*Star*, *SuperStar*, *Superfast* and *Viking XPRS*) are called High Speed Ferries (HSF) in what follows. The properties of the wakes of these vessels are largely unknown, and establishing their main features was one of the focuses of Paper IV.

Table 2.1. Ships operating the Tallinn–Helsinki ferry link in summer 2008. The *Superfast* represents a family of several sister ships

Ship	Type	Length, m	Width, m	Operating speed, knots
		'Classic' high-speed craft		
SuperSeaCat III and *IV*	monohull	100.3	17.1	35
Baltic Jet and *Nordic Jet*	catamaran	60	16.5	36
		Conventional ferries with increased cruise speed (HSF)		
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 total number of departures of passenger ships from Tallinn to Helsinki was 22–25 per day in summer 2008 (Fig. 2.2). The decrease in the frequency of departures from a peak of around 35 per day in the early 2000s was mostly due to a significant reduction in the number of conventional ferry and hydrofoil crossings. As sailing lines have remained largely unchanged and no limitations have been imposed on the speed, the new ships may operate at nearcritical speeds in areas where older ships were clearly subcritical (Torsvik and Soomere, 2008; 2009; Torsvik et al., 2009). With the described changes, the number of bay crossings by large vessels that are able to occasionally enter the nearcritical regime has almost doubled in Tallinn Bay since about the year 2000.

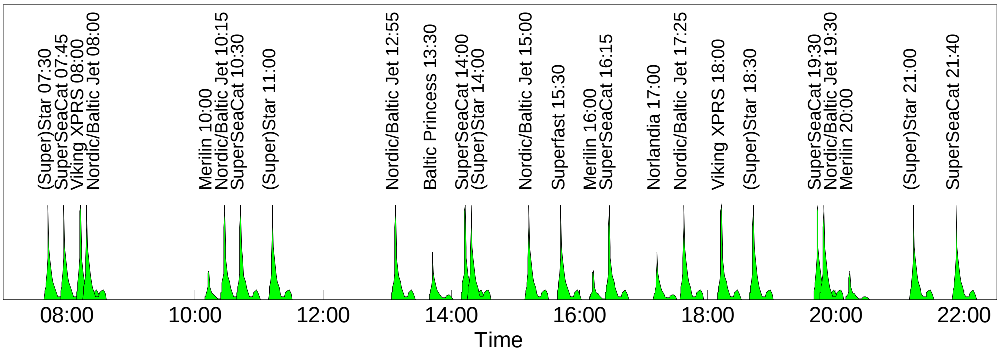

Fig. 2.2. Sequence of vessel wakes on weekdays in summer 2008 (Paper IV)

The described changes have led to the necessity of further studies of the potential of ship wakes for contributing to the existing wind wave regime and coastal processes in Tallinn Bay. The first step towards clarifying the situation should be an adequate estimate of the main parameters of wakes from new ships and their variation. This task was accomplished by means of careful, high-resolution measurements of properties of ship wakes in the coastal zone of Tallinn Bay (Paper IV) followed by statistical analysis of wake properties in Papers II, III and V. The relevant data set and the outcome of the analysis in the form of average and extreme characteristics of ship wakes and distributions of many parameters provides important information for the coastal zone development and management in Tallinn Bay.

2.3. Wave measurements

Modelling of the properties of ship wakes (Torsvik and Soomere, 2008; 2009; Torsvik et al., 2009) indicates that there is significant spatial variation in the wake loads on the coasts of Tallinn Bay. The faster vessels usually operate in the transcritical regime close to the port for vessels sailing to Tallinn and in the vicinity of Aegna for vessels sailing to Helsinki.

The SW coast of Aegna is fully open to the wakes of ships sailing from Tallinn to Helsinki but somewhat sheltered from waves produced by ships sailing to Tallinn. For that reason, the measurements in Paper IV and the subsequent analysis concentrate on the properties of waves produced by vessels sailing from Tallinn to Helsinki (called outbound vessels or outbound wakes below).

This coastal section is separated from the Viimsi Peninsula by a shallow-water (typical depth 1–1.5 m) channel with two small islands. As a result, practically no wave energy enters Tallinn Bay from the east. The orientation of isobaths in this area is virtually perpendicular to the crests of the larger vessel waves, and an approximately linear underwater slope allows good wave transmission along a trench between Aegna jetty and a shoal at a distance of ~100 to the west from the jetty. The immediate nearshore contains a belt of boulders westwards from the beach. Together with a tetrapod protected jetty to the east of the beach it provides good energy dumping and almost excludes wave reflection from the adjacent shore sections to the study site (Paper IV).

These features, therefore, make a small beach adjacent to the jetty (Fig. 2.3) a suitable place for measurements of vessel wakes and for estimating their runup heights. The area in question has also been the subject of several previous studies (Soomere and Rannat, 2003; Erm and Soomere, 2006).

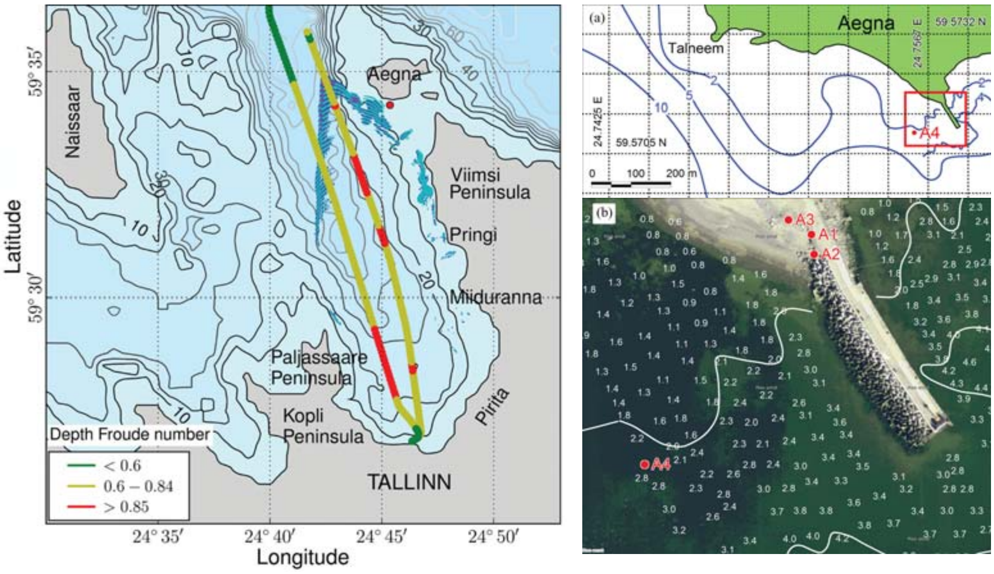

Fig. 2.3. The recorded sailing line and depth Froude numbers of the *SuperSeaCat* on 29–30 June 2008 (left). The eastern track is used by outbound ships and the western track by inbound ships. A simulation shows wake-waves at a single point (Torsvik et al., 2009). The SW coast of Aegna (a) and water depths around Aegna jetty (b) showing the location of runup measurements (A3) and tripod (A4)

A detailed description of the field experiment site in the summer 2008 is presented in Paper IV. The properties of approaching vessel waves in the nearshore were measured by means of high-resolution tracking water-surface elevations using a downward-looking ultrasonic echosounder (LOG_aLevel® from General Acoustics Co., Germany). The device was mounted on top of a heavy, rigid tripod (total weight about 150 kg) at a location about 100 m from the shore and 60 m from the southern end of the jetty (59°34.259'N, 24°45.363 E) (Fig. 2.3). The tripod's legs were equipped with 20 cm long spikes that penetrate into the seabed and prevent horizontal shift of the entire structure. Plates with a diameter of about 25 cm prevented the legs from sinking deeper into soft sediments. The seafloor around the device had a gently sloping gravel bottom. The water depth at the exact location of the sensor was approximately 2.7 m with respect to the long-term average sea level. The maximum water level variation over the experimental period was 37 cm (30 cm above long-term average on 25 June to 7 cm below on 7 July).

Initially, the sensor was mounted at a distance of ~1.5 m from the calm water surface. The combined effect of a relatively high water level on several days, high ship waves and considerable wind wave background resulted in a too low clearance to the water surface. The system failed to adequately measure distances <60 cm from the sensor, which led to underestimation of the largest elevations and therefore also to underestimation of the maximum heights of vessel wakes. This was corrected on 7 July by increasing the clearance between the sensor and the water surface by 1 m.

The system was able to operate without attention for about two weeks. The measurement range of the sensor is 0.5–10 m to the water surface with a field accuracy of 1 cm and a resolution of single measurements of ±1 mm. Water surface elevation was recorded at 5 Hz almost continuously over 30 days during the period from 21 June to 20 July 2008. The recording was only stopped for short time service intervals lasting typically a few tens of minutes.

Totally, the record contains more that 650 outbound wake events from fast ferries. As a substantial wind wave background was present on several days, not all the recorded wakes were available for the analysis.

2.4. Data processing

The raw record from the water level gauge was first quality-checked and reformatted so that each data point could be time-synchronized with the runup measurements. The record contained only one short unreliable section with a duration of 5 min and less than ten unrealistic negative spikes with a duration of a few seconds, which were excluded from the analysis (Paper IV).

A major challenge in the analysis was separation of wakes from single vessels not only because of the presence of a wind wave background and operational changes to the ferry timetable (and therefore the actual arrival time of wakes at the study site), but also because of large variations in the duration of the wakes and partial overlapping of wakes from different ships (Fig. 2.2). In several cases two or more ships passed the measurement site almost simultaneously so that their wakes were inseparable. Such situations and groups of wakes are called ‘double’ vessels and wakes below.

The separation of wakes from the wind wave background was performed manually based on different kinds of visualization of the water level data. It was straightforward on relatively calm days (Fig. 2.4a) 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, spectral filters with different properties (elliptical filters in the Matlab environment, to dump shorter waves) 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. The shorter components of wakes were sometimes completely masked by wind waves

(Fig. 2.4b). Also, it was not clear how to determine the height of vessel wakes on days when there were wind and swell waves with overlapping periods.

As a result, wake records on 15 days were selected for the analysis of their properties and variability. The total number of clearly identified wakes (418) contained 21 ‘double’ wakes, and 157 wakes of unidentified origin. Among the latter were wakes from the hydrofoil *Merilin*, conventional passenger and cargo ferries and wakes from ships sailing to Tallinn.

An attempt was made to specify a section of the record of pure background wind waves with a duration of 10–20 min related to each single vessel wake, preferably just before the start of the wake. The properties of this background were used to quantify the mean water level during the wake and the spectral composition of the wind-wave field. As ship traffic was very intense, it was frequently necessary to use one background interval for several wakes.

Data from each wake event were then adjusted to a mean of 0 (zero level) with the use of the closest section of the background and, if necessary, the water level trend was removed. Then, a Matlab low-pass elliptic filter of 9th order with at most 0.1 dB passband ripple, 60 dB stopband attenuation, a ±10% width of the cutoff band and a 2.5 s cutoff frequency was used to remove most of the wind wave components from the recorded signal. As the proportion of the wave components from fast ferries with periods <2.5 s is very small (Soomere and Rannat, 2003), such a filtering almost exactly conserves the energy of the wake. The majority of wind wave components on relatively calm days have periods below 2 s and are effectively removed from the signal. An example of the filtering procedure is presented in Fig. 2.5 for waves from the *SuperSeaCat* on 3 July 2008 at 21:40.

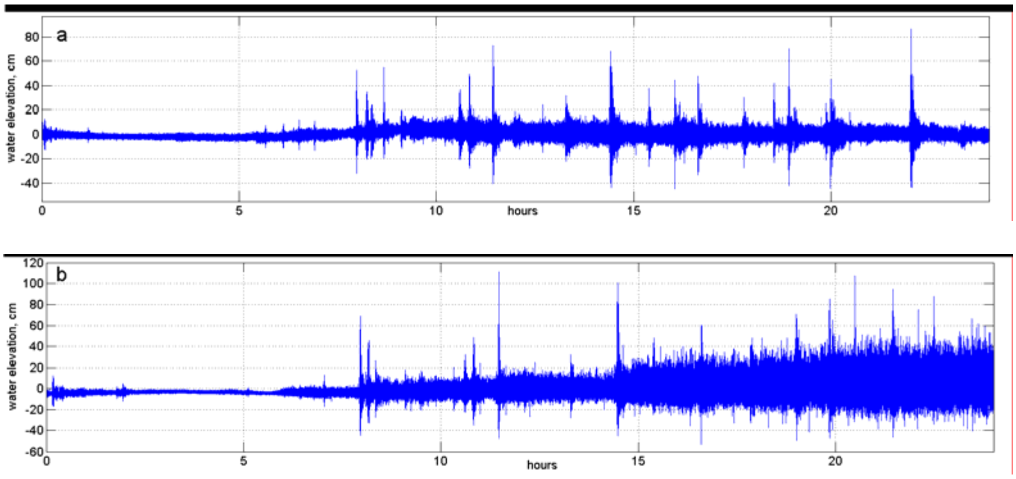

Fig. 2.4. (a) Record of water surface elevation on 5 July 2008, calm conditions and (b) 9 July 2008, transition to storm conditions

The unfiltered signal correctly reflects the short-term changes of the position of the water surface and related characteristics (such as the wave shape or asymmetry). The filtered signal (that is phase-shifted by the filtering process) often locally distorted the wave form and frequently led to unrealistic wave shapes with deep troughs and moderate elevations. This distortion is not unexpected: similar effects are customary in filtering elevation data derived from narrow wave groups, where the use of high-order filters results in a large phase shift of the signal.

For exactly periodic signals the phase shift has no dynamic relevance, but for highly peaked and/or asymmetric waves (see below and in Paper V) the large phase shifts may cause substantial changes in the wave shape and even an inversion of the crest-to-trough asymmetry. The information extracted from the filtered data, however, contributed substantially to the analysis. In particular, the filtered data frequently gave much better information about the role of long wave components in a particular wake in terms of both their local height and duration of presence, and in many cases allowed more exact determination of the end of the wake. Further analysis of each wake event was performed in parallel on the original data and on the filtered signals.

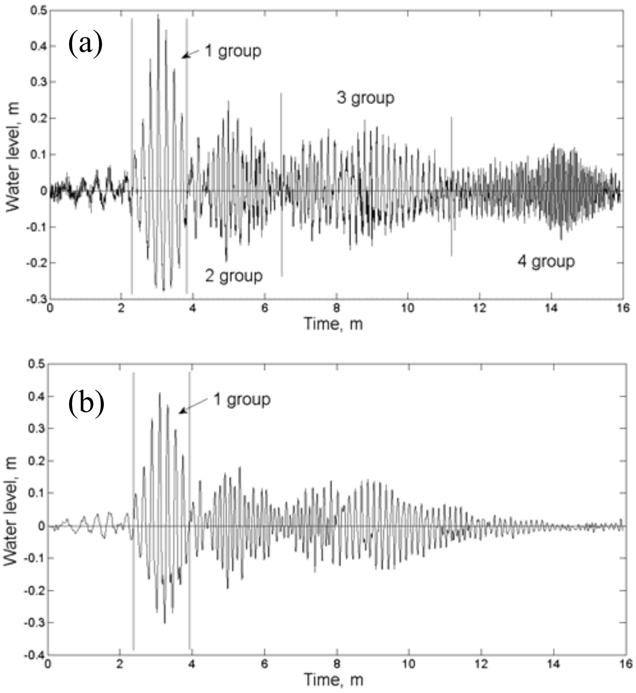

Fig. 2.5. Waves from the *SuperSeaCat* on 3 July 2008 at 21:40: (a) original, (b) after filtering

3. Statistical properties of ship wakes

3.1. Wave heights

Single waves in each wake were extracted using both zero-upcrossing and zero-downcrossing methods (IAHR, 1989). The maximum vessel wave height was defined as the maximum of wave heights obtained by these methods. On days with a strong wind wave background, this estimate was replaced by the maximum variation of the water surface within 30 s intervals. For the largest waves in each wake, this quantity almost always coincides with the maximum wave height obtained by the above methods (Paper IV).

The maximum wave height of single wakes varied significantly within each day, and frequently was substantially different for different departures of the same ship (Fig. 3.1).

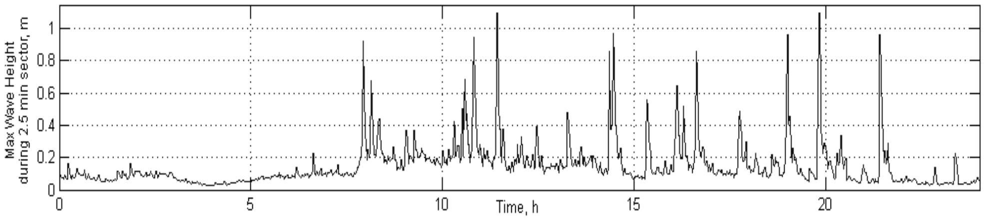

Fig. 3.1. Maximum wave height within 2.5-min sections on 5 July 2008. Almost all spikes higher than 15 cm correspond to ship wakes (Paper II)

The daily maxima of ship wave heights occurred exclusively for the longest waves of the wakes, with periods >10 s. The daily maxima extracted from nonfiltered data all exceeded 1 m and were typically approximately 1.2 m (Fig. 3.2). 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 estimated significant height of the background about 0.5–0.6 m. The maxima extracted from the spectrally filtered signal were typically about 15% smaller, but on many days these values almost coincided. The lowest daily maxima correspond to weekends (Sunday, 6 July, and the weekend 19–20 July) when the number of ships was somewhat smaller and the loadings were likely to be less. The low height of the echosounder above the water surface may have caused some erroneously low values for the maximum elevations before 7 July, in particular, on the relatively windy days, 25–26 June; for this reason the maxima are apparently better characterized in data for 8–20 July.

On average, the highest waves of a single ship were generated by the *SuperStar* with the overall mean of the highest waves being 98 cm (Table 3.1). 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. The double wakes were typically the highest.

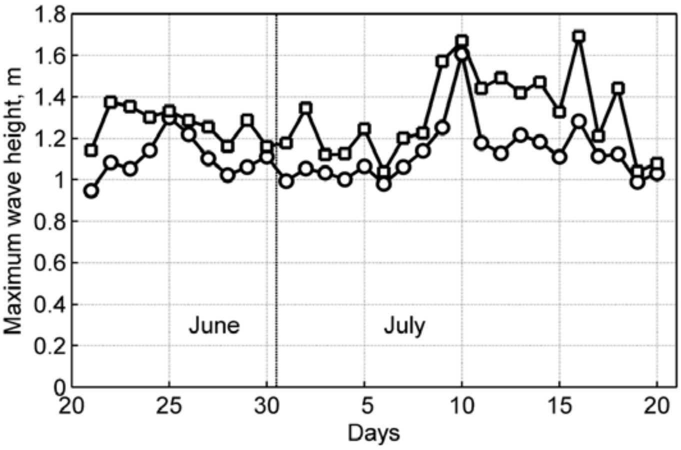

Fig. 3.2. Daily maximum ship wave heights. Squares reflect unfiltered data and circles, data filtered using a low-pass filter with a cut-off frequency at 0.4 Hz (Paper IV)

Table 3.1. High speed ships operating the Tallinn–Helsinki ferry link in summer 2008 (Paper IV) and wave height on days with a comparatively low wind wave background (28–30 June, 1–9, 12, 13 and 20 July 2008). Unidentified wakes belong to smaller or slower ships sailing to Helsinki or to ships sailing to Tallinn

Vessel	Number of wakes	Maximum wave height, m	
		Average	Standard deviation
SuperSeaCat	55	0.85	0.18
Nordic Jet, Baltic Jet	70	0.59	0.16
Star	25	0.89	0.26
SuperStar	28	0.98	0.11
Viking XPRS	27	0.58	0.23
Superfast	14	0.70	0.14
Unidentified wakes	157	0.32	0.12
Double wakes	42	1.01	0.19

Based on the discussion of the sensitivity of wake parameters to operational details at nearcritical speeds one could, intuitively, expect that the wakes of ships that produce larger average values of the maximum wave height would have also larger variation. The relevant analysis is performed in Paper II. Remarkably, however, the variation in the maximum wave heights (indicated by the standard deviation) of different ships was small. Moreover, it was almost uncorrelated with the typical wave height from these ships. It was very small for the *SuperStar*, indicating that the highest waves from this ship were always of almost the same height. The large variation for double wakes is not unexpected, because such wakes contained waves from different ships. The standard deviation of maximum wave height was relatively large for the *Star*, *SuperSeaCat* and *Viking XPRS*.

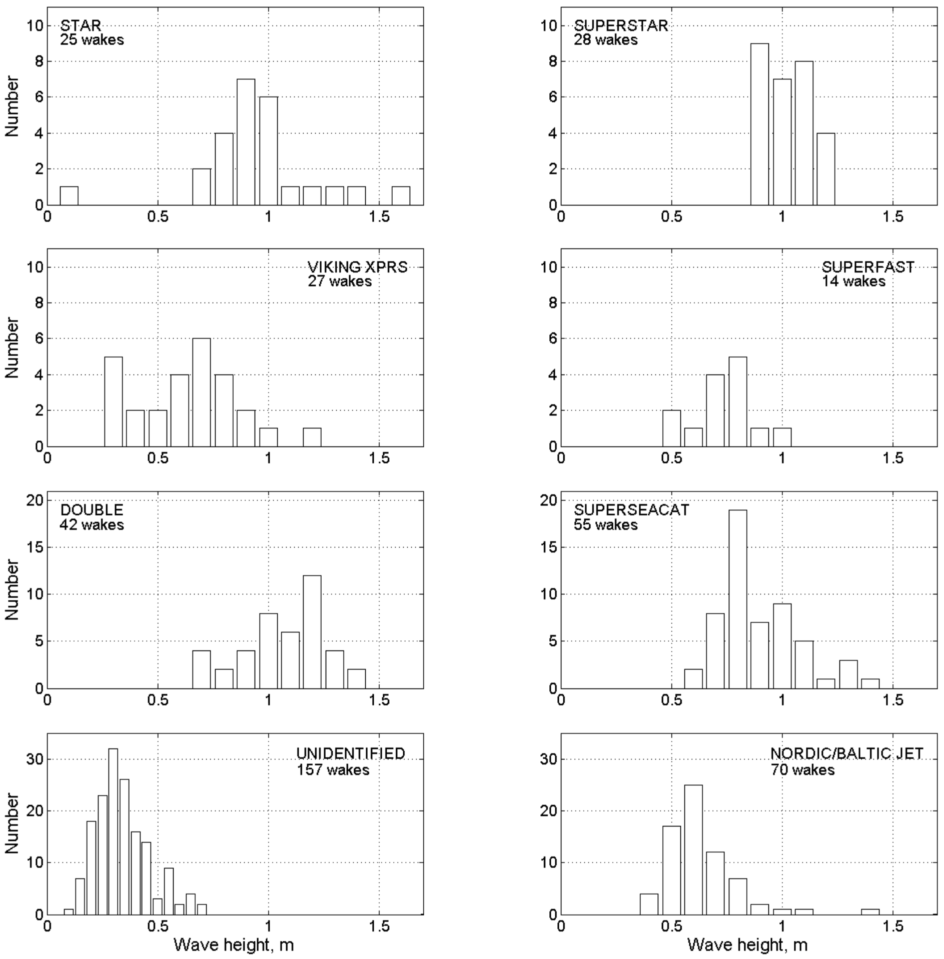

Fig. 3.3. Frequency of occurrence of maximum wave heights in wakes from different ships (Paper II)

The histograms of the frequency of the occurrence of different maximum wave heights (equivalent to the relevant empirical probability distribution functions, Fig. 3.3) also show some interesting features. The maximum height of wakes from *SuperStar* lies in quite a narrow range, from 0.81 to 1.17 m. The range for *Superfast* is somewhat wider, but still concentrated between 0.41 and 0.97 m. Both distributions are almost symmetric and contain no outliers. The distribution for unidentified wakes is somewhat wider and skewed, but it also contains no clear outliers.

The distinguishing feature of the distributions for other ships is the presence of a number of significant outliers – very high waves. Their number is relatively small for the *Nordic Jet* and the *Baltic Jet*, yet these ships produced up to 1.32 m high waves (that is more than twice the average). The waves from the *Viking XPRS* were usually reasonable (0.2–0.8 m), but at times this ship produced up to 1.2 m high waves. Such a large variability of the maximum wave heights for the *Viking XPRS* may stem from the use of different operating speed during the measurement period, but there is no direct evidence supporting this opinion.

The largest number of significant outliers was recorded for the *Star* and the *SuperSeaCats*. While the distribution of maximum wave heights is more or less symmetric for the *Star*, it is substantially skewed towards large values for the *SuperSeaCats*. 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.

The use of a continuous water surface profiling technique, which allows direct and high resolution measurement of incident wave properties (including asymmetry), mostly well before breaking, and the analysis of a large number of wakes from different high-speed ships has advanced the knowledge of the wave height potential of new, high-powered ships operating on the Tallinn to Helsinki route. Both direct measurements of speed made onboard several vessels (Torsvik et al., 2009) and the analysis of ship wakes confirm that an increasing number of ships sail in the near-critical regime along extensive sections of the ferry route in Tallinn Bay. Although some ships that previously created the largest waves in this bay (Soomere and Rannat, 2003) are no longer in service, the maxima of ship wave heights have not decreased. As detected at Aegna in 2002 with the use of a pressure sensor at a depth of 6.7 m (Soomere and Rannat, 2003), the maximum wave height was about 1.3 m (Paper IV). At the location of the water surface profiler used in this experiment at a depth of 2.7 m, the wave heights close to 1.5 m on calm days confirm that the maximum ship wave heights have increased.

3.2. Wake energy

While the maximum wave height characterizes the magnitude of the potential impulse loads on the coastal ecosystem or the extent of specific effects such as high runup or overtopping of coastal structures, a more relevant measure of the overall increase in the intensity of the local wave fields can be obtained using integral characteristics (such as energy and energy flux) of the wakes. Another important measure is the typical period of the largest waves, established by analysing the spectral composition of the wakes in Paper IV.

The wave energy density of each wake was calculated from the power spectrum of the water elevation record during the wake using the standard procedures of spectral analysis. An estimate of the energy density of ship waves was found by means of subtraction of the energy density of the wind wave background from the total energy density. The total energy of a wake was then found as a product of the vessel wave energy density and the duration of the wake. The details of the procedure are described in Paper IV.

The separation of ship waves from the wind wave background was problematic on many days during the experiment. The relatively calm days of 4–6 July were the most favourable for the comparison of the total wave energy spectra (over 72 h of continuous wave recording) with spectra of wind waves during the nights (00:30–07:30). Ship wakes almost totally dominated in the wave field on these days (Fig. 3.4).

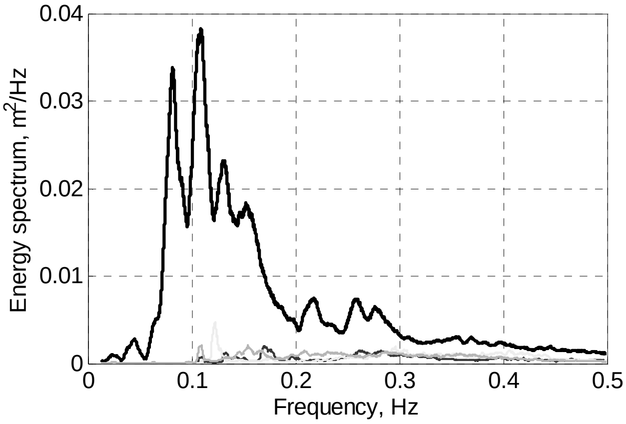

Fig. 3.4. Total wave energy density on 4–6 July (black line) and the energy density of wind wave fields at 00:30–07:30 on the same days (grey lines) (Paper IV)

The overall mean energy density of the wave field was 15.3 J/m^2 (15.4, 16.4 and 14.0 J/m^2 on 4, 5 and 6 July, respectively), which corresponds to a significant wave height of 0.176 m. The wind wave field contributed from 1.2 J/m^2 on 4 July to 2.3 J/m^2 on 5 July. Moreover, part of the energy (~0.6 J/m^2) of these weak waves at night was excited by ships. As 6 July was Sunday, with somewhat less intense ship traffic than on weekdays, the weekly mean energy density of ship waves apparently is close to 15 J/m^2.

As in previous experiments in this area (Soomere and Rannat, 2003), the major component (about 70%) of ship wave energy was concentrated in the frequency range of 0.06–0.2 Hz (periods T = 5–16 s, Fig. 3.4). The energy spectrum within this range contains four peaks. The highest peak is located at T = 9.2 s. A peak of comparable height is at T = 12.3 s. Two minor peaks are located at T = 7.6 and T = 6.6 s.

The two peaks for longer waves apparently reflect the typical properties of leading waves of ship wakes whereas the two peaks around 7 s represent wave components from the second group of high-speed ferry wakes that usually have periods of 6–8 s (Soomere and Rannat, 2003). The presence of two clearly separated peaks for both long waves and for periods around 7 s suggests that the high-speed ships sailing in Tallinn Bay represent two families of vessels, the members of which produce leading waves with similar properties (and which apparently travel at more or less equal speeds).

Comparison of the cruise speeds of different ships (Table 2.1) suggests that the classic HSC *SuperSeaCats*, *Nordic* and *Baltic Jet* belong to the faster group, the wakes of which mostly form a peak at $T = 12.3$ s (0.08 Hz). Ships sailing at 25–30 knots (about 45–55 km/h) are apparently responsible for the other, slightly higher peak in Fig. 3.4. Note that the numbers of departures of ships of both groups are approximately equal each day (Paper IV).

The largest ship wakes were frequently preceded by relatively low waves (typically below 5 cm) with very long periods (20–30 s). Such waves can be seen in Fig. 2.5 before the first group. This part of the wake may be associated with the precursor solitons (long solitary waves propagating ahead of high-speed ships) that are customary for near-critical speeds but which may be produced at as low depth Froude numbers as 0.2 (Ertekin et al., 1986). At least one disturbance of this type was normally (in about 70% of cases) present in the wakes of faster ships whereas in the wakes of the *Viking XPRS* and *Superfast* and in unidentified wakes they occurred in very few cases (about 10%). A small peak at $T \approx 20$ s (0.05 Hz) in the spectrum in Fig. 3.4 may be interpreted as reflecting the energy of these solitonic waves.

The range of frequencies 0.2–0.4 Hz ($T = 2.5$–5 s) also contains an appreciable amount (close to 25%) of the total ship wave energy. As the sampling rate is quite high, part of the wave energy (about 5% in the case in question) is attributed by the Fourier transform to high-frequency waves with periods well below 2 s, but which apparently do not exist in reality.

Data collected on 4–6 July with low wind-wave energy, makes it possible to approximately estimate the distribution of ship wave energy between different wave components through identification of the proportion of ship wave energy on days with considerable wind wave background under the reasonable assumption that the distribution of wave energy between different wake components does not change significantly. A natural separation frequency for different ship wave components is 0.125 Hz. The long-wave components of wakes with periods exceeding 8 s carry about 38% of the total wake energy in the analysed data on all three days. This proportion is almost constant over these days although the number of departures varied. On the other hand, appreciable wind waves with periods exceeding 8 s occur very infrequently in Tallinn Bay, and are virtually non-existent in midsummer (Soomere, 2005a).

The variation of daily average ship wake energy at the study site (Fig. 3.5) shows that the overall mean ship wake energy is about 16 J/m^2. This value varied between 10 and 23 J/m^2 on different days; however, the weekly average of vessel-wake energy density differed only a few percents from its overall average during the entire experiment. The relatively high values of energy density on 10–11 July may reflect problems with separating the vessel wakes from the wind-wave background. The lowest daily energy densities occurred on weekends, with somewhat less intense ship traffic than on weekdays. This estimate shows that the annual mean of the ship-induced wave energy at this site, estimated as 15.8 J/m^2 in (Soomere and Rannat, 2003), has remained basically the same.

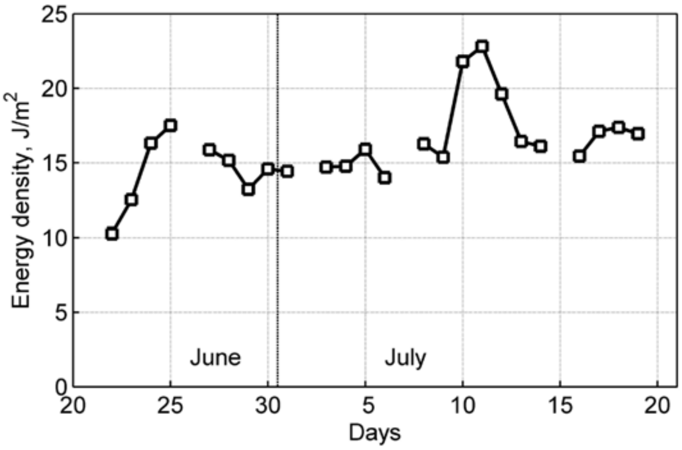

Fig. 3.5. Daily average energy density of ship wakes, estimated from the energy in long components with periods >8 s. Days with missing data due to maintenance are not represented (Paper IV)

The above-described procedure of calculation of wake energy E from the average spectral density of energy during the wake is equivalent to calculation of this measure directly from the time series of surface wave elevation η within one wake:

$$E = \rho g \int_{T_0}^{T_0+Tw} \eta^2(t)dt\,, \tag{3.1}$$

where T_0 marks the start of the wake, T_w is the duration of the wake, ρ is the water density, g is gravity acceleration and t is time. The calculations were performed for original and filtered signals. The relevant empirical probability functions of wake energy are presented in Fig. 3.6.

It follows from Fig. 3.6 that the total wake energy distributions for single wakes are similar to the corresponding distributions of the maximum wave height. Interestingly, both the most intense and the smallest wakes in terms of the average total wake energy are produced by ships from the HSF family: the minimum average wake energy stems from the *Viking XPRS* and the maximum from the *SuperStar*.

The amount of energy in wakes from unidentified wakes is just a few percents of a typical energy in wakes of HSC or HSF. This feature shows that the wakes from the new, twin-hull hydrofoil *Merilin* have much less energy than those stemming from ships in Table 2.1.

While the daily average ship wave energy varies insignificantly, the energy contained in a single wake of a particular ship varies considerably (Table 3.2). In general, the *SuperSeaCat*, *SuperStar* and *Star* produce single wakes with greatest energy. This is consistent with experience gathered from the observations from Aegna jetty with the largest visually observed breaking waves usually produced by these ships. The wakes of the *Nordic Jet*, *Baltic Jet* and *Superfast* contain less (by about 50% in average) energy than wakes of the *SuperStar* (Table 3.2). The wakes from the *Viking XPRS* are usually much smaller than the wakes from the above ships. The total energy of wakes from a specific ship typically varies by up to 6 times, but even larger variability (up to ten times) exists for wakes from the *Star*.

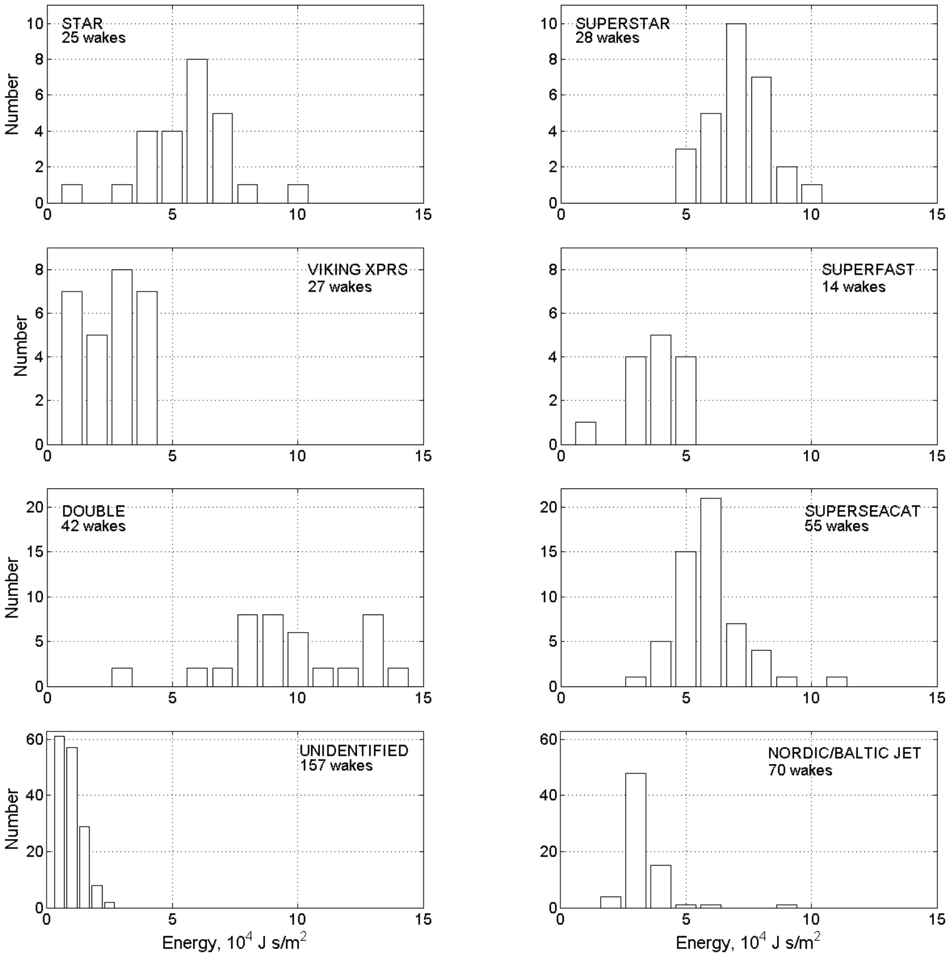

Fig. 3.6. Frequency of occurrence of total energy in wakes from different ships

A large part of the variability of the observed wave patterns occurred owing to the simultaneous arrival of waves from two vessels that leave Tallinn at the same time (for example, at 14:00 the *SuperStar* or the *Star* and the *SuperSeaCat*, and at 19:30 the *SuperSeaCat* and the *Baltic Jet* or the *Nordic Jet*). In contrast to the distribution of the maximum wave heights, the energy of such double wakes was approximately equal to the sum of typical wave energies of single wakes. This is not unexpected, because the total energy of the two wake constituents is simply superposed whereas the highest waves usually do not arrive simultaneously. Still in many cases such combined wave systems resulted in the highest waves of the day.

Table 3.2. Wake energy and power integrated over the duration of the wakes

Vessel	Energy, 10^4 J·s/m^2		Energy flux, 10^4 W·s/m	
	Average	Standard deviation	Average	Standard deviation
SuperSeaCat	5.4	1.3	27.4	7.2
Nordic Jet, Baltic Jet	2.8	0.9	13.6	4.8
Star	5.0	1.8	24.0	9.5
SuperStar	6.6	1.2	30.7	6.4
Viking XPRS	2.0	1.0	8.9	4.7
Superfast	3.3	0.9	14.8	4.4
Unidentified wakes	0.7	0.5	3.0	2.0
Double wakes	9.1	2.5	46.0	12.7

3.3. Energy flux

An energy-based comparison of waves is equivalent to a comparison of the relevant root-mean-square wave heights. Comparison of wave energy flux (which characterizes the rate of supply of the wave energy to the coast) implicitly takes into account the wave periods since longer waves have larger group velocities. Therefore, the variability and the distribution of the total energy or its flux do not necessarily correspond directly to the similar properties of wave height and the distributions of energy and energy flux may also provide essential information necessary for the planning of coastal engineering structures and for coastal zone management in general.

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 differently contribute to the total wave energy flux (Dean and Dalrymple, 1991). This feature has been only partially accounted for in previous studies. For example, in (Soomere and Rannat, 2003), for wind wave fields it is assumed that the wave energy propagates at the group velocity of the wave corresponding to the spectral maximum whereas for ship wakes it is assumed that energy propagates at the group velocity of the wave, whose period equals the mean weighted period of the wake.

While all other wake parameters discussed in this study can be extracted from the surface elevation time series, an adequate calculation of energy flux is only possible when the water depth is known. As mentioned above, the water level fluctuated by about 15% from the mean water depth at the location of the sensor.

The water depth for calculations was chosen in order to obtain the most correct estimate of the daily mean energy flux (wave power) for the time interval of 4–6 July, during which the wind wave background was small and the separation of ship and wind waves was straightforward. The mean water level (taken as the basis for the calculation of group velocity also on other days) was 2.7 m on these days. Further discussion of this choice is presented in Paper IV.

As ship wakes usually are transient wave groups with largely varying spectral composition of different parts of the wake and with high persistence of single wave crests (Didenkulova et al., 2009), it is generally inappropriate to use standard spectral decomposition for the calculation of the ship wave energy flux. Based on the high persistence of single wave crests in the nearshore, the following method was adopted for straightforward calculation of the wake energy flux for every single wake directly from the surface elevation record:

$$P = \rho g \int_{T_0}^{T_0+Tw} \eta^2(t) c_{gr}(t) dt, \tag{3.2}$$

where c_{gr} is a group velocity for each single wave extracted with the use of zero-upcrossing or zero-downcrossing method from the filtered signal. The group velocity generally is different for every wave. Equivalently, the wave energy flux was calculated for each wake by means of summing the power carried by each single wave for the given water depth.

The properties of the very low wind wave background (significant wave height is between 6–8 cm) were almost unchanged during the night and day of 4–6 July. This allowed the estimation of the ship-induced energy flux as the difference between the daily average energy flux and the mean energy flux during the night (from 00:30 to 07:30). As the waves produced by ships sailing at night were much shorter than the leading waves from high-speed ships, the contribution of ship wakes to the night-time wave energy flux can be neglected. This procedure resulted in the estimate of the daily average ship wake energy flux for 4–6 July as 78, 45 and 57 W/m, respectively (Paper IV). The night-time average wave power was 17, 8 and 8.6 W/m on these days. Since 5–6 July were weekend days with a few departures of ships, the weekly average of ship wave energy flux is probably close to 70 W/m. These results suggest that the daily average wake energy (Fig. 3.5) is not necessarily well correlated with the wake energy flux on the same day.

The empirical probability distribution functions of the total ship wake energy flux, calculated with Eq. (3.2) for different vessels, are presented in Fig. 3.7. It is noteworthy that the distribution functions of the total wake energy flux have a similar shape to the corresponding distributions of the wake energy. This feature suggests that the spectral composition of ship wakes insignificantly varies for different departures. The maximum and minimum of the average wake power are again produced by the new class of HSF ships: the highest being from the *SuperStar* ($30.7 \cdot 10^4$ W·s/m) and the smallest is for the *Viking XPRS* ($8.9 \cdot 10^4$ W·s/m).

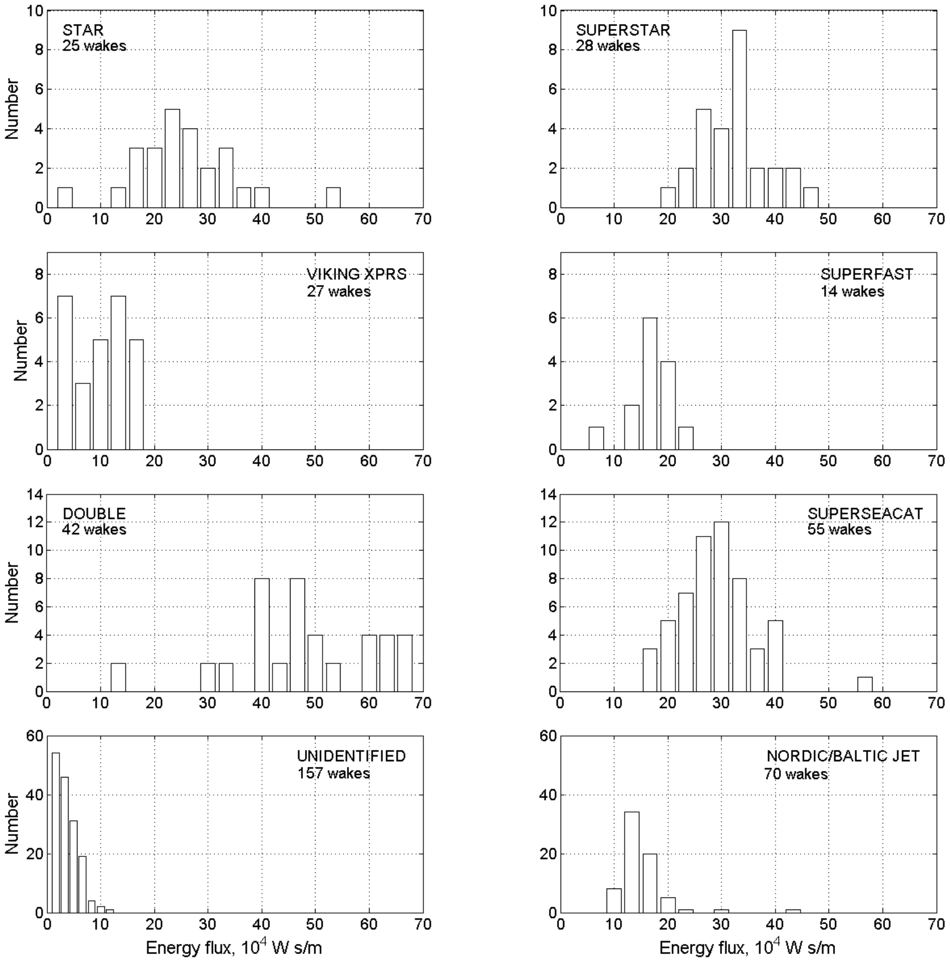

Fig. 3.7. Frequency of occurrence of total energy flux in wakes from different ships

The overall average wave energy flux produced by the classical HSC and HSF is almost the same, close to $20 \cdot 10^4$ W·s/m. At the same time there is large variability of the average wake power for different HSF as well as for different HSC. For example, the *SuperSeaCat* creates, in average, twice as large energy flux as the *Nordic Jet* ($27.4 \cdot 10^4$ W·s/m and $13.6 \cdot 10^4$ W·s/m, respectively).

As in the case of wake energy, the largest values for the wake energy flux were observed for double wakes. The distribution of the energy flux for double wakes is more irregular than the one for wave energy, and contains many outliers. As above, this feature is not unexpected and reflects the wide shape of wave energy flux distributions for different ships. It is also an expected feature that wake energy in the unidentified wakes usually forms a few percent of typical ship wave energy flux for the discussed ships.

3.4. Concluding remarks

The statistical analysis of the ship wakes performed over 418 clearly identified wakes shows that the daily maxima of ship wave heights (i) occurred exclusively for the longest waves, with periods >10 s, (ii) all exceeded 1 m and (iii) were typically approximately 1.2 m. The largest ship wave heights in 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 0.5–0.6 m. Double wakes had maximum wave heights close to those of the relevant single wakes.

The periods of the highest ship waves vary insignificantly and are apparently closely related to the cruise speed of the vessels. The presence of two distinguished peaks for both long waves and for periods around 7 s suggests that the high-speed ships sailing in Tallinn Bay represent two families, the members of which produce leading waves with similar properties.

The largest waves on average are produced by highly powered but otherwise conventional ferries (HSF). The largest variability in wave heights is observed in the properties of the ‘classic’ high-speed craft (HSC). The overall mean wake energy density over the entire measurement session was 15.3 J/m^2 and thus it has not changed since about 2000 although the fleet has undergone major modification. The average of ship wave energy flux (~70 W/m) is somewhat smaller than in the past, apparently because of a more sheltered measurement site, which only takes into account wakes from high-speed vessels sailing from Tallinn to Helsinki.

Empirical probability distribution functions for the energy and energy flux for single wakes are very similar to those for the maximum wave height. An appropriate measure of variability and basic properties of wakes in question, therefore, is the maximum wave height at some distance from the sailing line.

The largest average values of wake energy and its flux are produced by the HSF *Star* and *SuperStar*. The average of the energy flux for HSC and HSF is almost identical. The energy and its flux contained in double wakes were on average about 1.6 times larger than the energy or its flux in single wakes.

The variability of properties of single wakes from particular ships is relatively large. While there are usually no clear outliers in the HSF family, the HSC have a large number of high outliers. The largest variability is in the properties of wakes from ‘classic’ HSC with a relatively small tonnage (~1,000 tonnes) and very high cruise speeds (35–40 knots). The frequent occurrence of very high waves suggests that management of threats associated with their wakes poses a serious problem and substantial changes or limitations to the sailing regime may be required to ensure an acceptable level of wake intensity. On the other hand, the properties of wakes from most large, basically conventional, but strongly powered ferries show quite limited variability. Although they may create relatively high waves under present sailing conditions, it is natural to expect that both the average and extreme wake properties can be more easily adjusted by changing either their speed or sailing line.

4. Nonlinear (cnoidal) waves in ship wakes

4.1. Introduction

Generally, a moving ship generates a sequence of almost linear surface gravity waves (Lighthill, 1978). Strongly nonlinear disturbances of water surface are exited relatively infrequently. Specific types of ship-induced disturbances, such as high, transient leading waves (Paper IV), monochromatic packets of relatively short waves (Brown et al., 1989), solitary and cnoidal wave trains preceding a ship (Neuman et al., 2001) and their associated depression areas (Garel et al., 2008), all qualitatively differ from typically occurring wind waves and from constituents of linear Kelvin wake, have been studied extensively during the last decades (Soomere, 2007). In special cases, a single water elevation with a stable profile or highly nonlinear wave groups can arise that mimic solitons of different kinds (Soomere, 2007).

As typical for large-amplitude waves in shallow water, waves from fast ferries frequently have a substantially nonlinear nature. Nonlinearity (characterized in terms of wave asymmetry in Paper V) of vessel wakes is highly important for coastal zone management because nonlinear wakes are considered as being able to seriously damage the coastal environment (Parnell and Kofoed-Hansen, 2001; Soomere, 2006; Parnell et al., 2007). It was demonstrated that the longest and largest waves generated by the high-speed ferries on the Tallinn–Helsinki route exhibit nonlinear features and resemble cnoidal waves in the coastal area of Tallinn Bay (Soomere et al., 2005). Yet very little is known about how often ship wakes show strongly nonlinear features.

A primary indicator of the appearance of nonlinearity in the generation and propagation of surface waves is the potential asymmetry of the wave shape. The shape of the waves is extremely important, because many properties of water particles in long linear and weakly nonlinear waves (in particular, velocity components) linearly depend on the surface displacement (Massel, 1989). Moreover, the difference of the steepness of the wave front and its back may substantially modify the wave runup properties (Didenkulova et al., 2006; 2007).

One of the simplest means for adequate description of long nonlinear waves is the framework of the Korteweg de Vries equation, which has a rigorous periodic solution in the form of a cnoidal wave (Massel, 1989). Cnoidal waves have relatively high and narrow crests and wide troughs, the dropdown of water surface in which is less than the elevation in crest (Fig. 4.1). Equivalently, the wave-induced water surface depression lasts longer than the elevation with respect to the calm water level.

Theoretically, the shape and properties of long ship waves propagating in a shallow area with an ideal flat bottom should match those of cnoidal waves. In real conditions, however, the sea bottom is never perfect and it is not clear in advance what exactly will happen when waves approach coastal areas.

Although the presence of cnoidal waves in the nearshore of Tallinn Bay resulting from fast ferries wakes is well known (Soomere et al., 2005), little research has been conducted into their properties in the deeper nearshore. Their presence, through creation of unexpectedly large near-bottom velocities (Soomere et al., 2005) or large impulse loads (Schoellhamer, 1996), may cause dangerous and environmentally damaging circumstances in coastal areas not normally affected by commonly occurring shorter, albeit higher, wind waves.

An attempt is made in Paper V to present the properties of vessel waves studied in Section 4.2 in terms of the cnoidal wave theory. The analysis below is an extension of a similar research performed for a small set of ship waves near Aegna jetty in (Soomere et al., 2005).

Fig. 4.1. Cnoidal ship waves in Tallinn Bay

The aim of this chapter is to examine the actual appearance of long ship wave shapes produced by high-speed ferries in Tallinn Bay. The research, details of which are presented in Paper V, is focused on determining the asymmetry coefficient of these waves (the ratio of the crest height over the trough depth with respect to the calm water surface) directly from the water surface time series. This analysis makes sense in an intermediate, relatively shallow region of the nearshore where nonlinear effects become substantial but the wave profile remains smooth. The main idea is to find out whether the possible adverse influence of long ship-generated waves can be quantified in terms of the cnoidal wave theory.

4.2. Crest-trough asymmetry of ship waves

While the earlier studies of the potential appearance of nonlinear features of ship waves are based on a few wave recordings, the experiment described above and in

Paper IV allowed collecting a large high-quality data set of time series of water surface elevation in the ship wave field in Tallinn Bay. This data set has a high enough resolution to make possible a statistical analysis of the shapes of typical ship waves. In this study the focus is on the simplest measure characterizing how ‘nonlinear’ a particular wave is – the crest–trough asymmetry of the longest components of ship wakes.

A typical wave record (Fig. 2.5) shows a group structure of the wake, which usually consists of at least three wave groups with varying wave parameters (amplitude, period and symmetry properties). The amplitudes of the so-called precursor solitons that arrive before the highest waves are usually negligible in the open sea conditions (Soomere, 2007). The highest waves at distances of a few kilometres from the ship lane usually are the longest waves concentrated in the first group of the wakes (Soomere and Rannat, 2003). They are also asymmetric with a clear prevalence of the crest height over the trough depth and apparently are able to carry additional water mass to the shore (Torsvik et al., 2009) and, therefore, cause the greatest implications at the shoreline. Waves belonging to all other groups are mostly symmetric to the calm water surface.

The listed features motivate to focus on the first group of waves. In the analysis below the unidentified wakes (for example, from ships sailing to Tallinn) and double wakes (which usually do not show a clear group structure and in which adequate detection of leading waves is not always possible) are left out. In addition, as the wind wave background may easily distort the actual ship wave shape, only wakes recorded in days with a low wind wave background when the identification of ship waves was straightforward, are analysed. As a result, 163 wake records, each representing a single ship, collected on 15 days and containing 1346 waves from the first group, were selected for this analysis.

Differently from the analysis of maximum and integral characteristics of the wakes in Chapter 3, the analysis of wave asymmetry (in terms of the ratio of the crest height over the trough depth) was performed separately for each wave of the first group within each detected wake. As described above, a low-pass elliptical filter with a relatively low cut-off frequency was used to separate single waves from the raw data. The filtering procedure resulted, as expected, in a time shift of the filtered signal compared to the original record. Its magnitude is defined by the parameters of the filter and it was removed from the filtered data. The zero-crossing time instants were detected from the resulting time series. Single waves were separated next by means of applying both the zero-upcrossing and zero-downcrossing methods (IAHR, 1989) to the filtered record. Finally, the crest heights, trough depths and the corresponding asymmetry coefficients for each full wave were calculated from the original, unfiltered record.

The presence of small wind waves may to some extent affect the results of the described procedure. The above procedure allowed the removal of the influence of the wind wave background on the process of detecting of the beginning and the end of the long waves. It is easy to see that if a long wave is superposed by a very short wave, both crest heights and trough depths are overestimated by ½ of the height of the short wave. As wind wave heights on the days in question were below 10 cm, their presence apparently results in a certain reduction of the asymmetry coefficient. Still, it was decided not to use any smoothing procedure because the nonlinear waves intrinsically contain a certain amount of higher harmonics that may be distorted through the filtering process.

The average values and standard deviation for the asymmetry coefficient calculated through the application of zero-upcrossing and zero-downcrossing methods differ insignificantly (Fig. 4.2). Therefore, the results of the described analysis of the asymmetry of ship waves are almost insensitive to the particular method for wave separation. This property shows that the highest crests and deepest troughs usually occur in succession. On the other hand, this feature indicates that the vessels' waves, by nature, are more akin to regular oscillations than to freak waves (which frequently are characterized as specific sequences in which a deep hole is followed by a high, steep crest; Kharif and Pelinovsky, 2003).

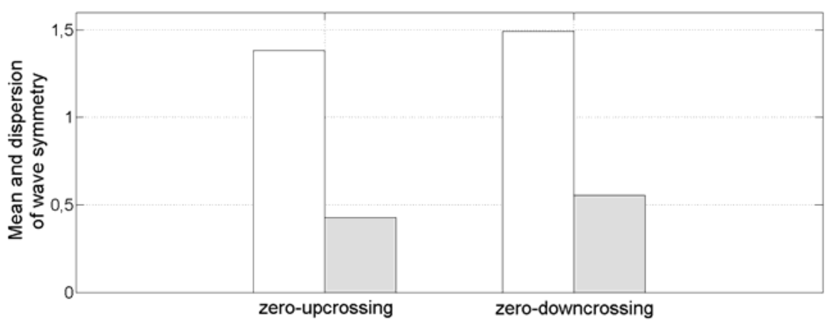

Fig. 4.2. Average values and standard deviation of asymmetry coefficients calculated with the use of zero-upcrossing and zero-downcrossing methods

Generally, all the vessels generate asymmetric waves. The empirical distributions of asymmetry coefficients for the different vessels (Fig. 4.3) demonstrate that the most frequent values for the ratio of the crest height over the trough depth lie between 1.2 and 1.6. The crest height of waves in question therefore exceeds approximately 30–40% the trough depth. Although most of the waves have relatively high crests, there are also waves the crest of which is fairly low compared with the trough.

A joint distribution of the probability of the occurrence of wave asymmetry for waves with different heights for the entire set of waves in question (Fig. 4.4) shows that the most frequent value of the asymmetry coefficient is about 1.4. In general, as expected from the cnoidal wave theory, waves with higher amplitudes have larger asymmetry.

The smallest most frequent value of the asymmetry coefficient is characteristic of wakes from the *Nordic Jet* and *Baltic Jet.* These ships and the *SuperSeaCats* have a relatively large number of cases with the asymmetry coefficient below 1 (Fig. 4.3). The relevant distributions have somewhat different shapes. The distributions for the *Star*, *SuperStar*, *SuperSeaCat, Nordic* and *Baltic Jet* are unimodal and have a bell-like shape, close to normal, mostly symmetric and relatively narrow (Fig. 4.3).

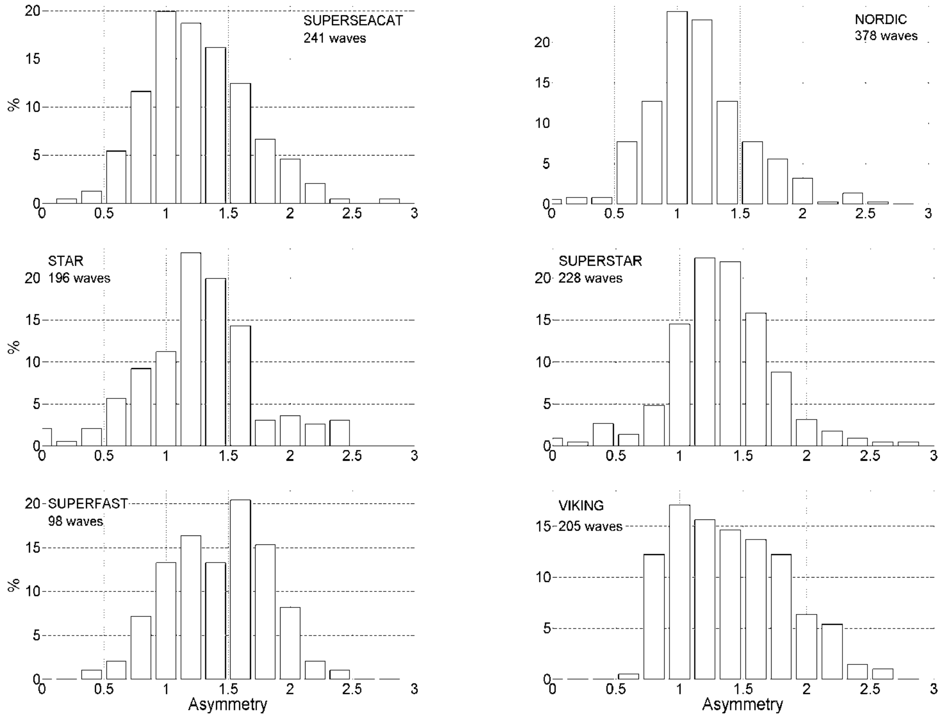

Fig. 4.3. Empirical distributions of the asymmetry coefficient for the waves from the first group of the wake for different vessels

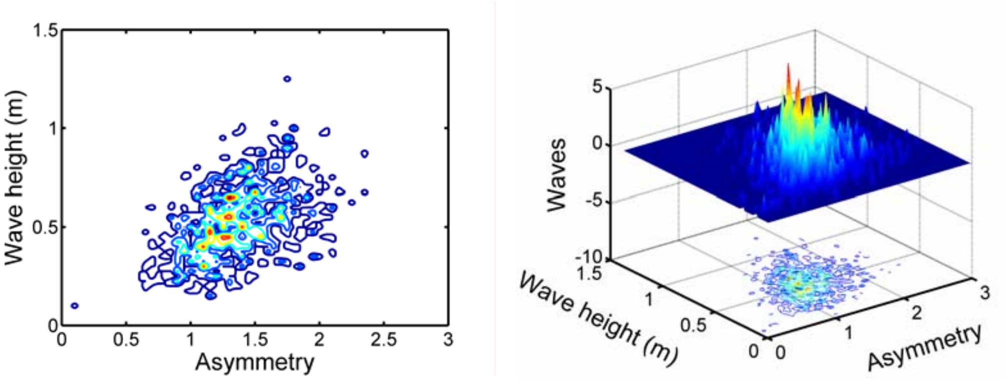

Fig. 4.4. Scatter diagram of the occurrence of different values of the asymmetry coefficient for waves with different height from the first group of the wakes: contour plot (left); 3D surface plot (right)

Interestingly, there is no evident correlation of the wave asymmetry with the wave period (Fig. 4.5). The entire set of waves in question contains two major groups of long waves with periods about 8 s and 12 s, respectively. Within these groups, the wave asymmetry coefficient changes significantly (from 1 to 2.5) but there is no clear difference between the periods for these groups.

This feature is somewhat unexpected because an increase of the length of an ideal cnoidal wave in water of constant depth is accompanied by an increase of the crest height and a decrease of the trough depth. A possible explanation of this nonalignment is that the approaching waves are being shaped by a longer section of the coastal slope and that the 'effective' depth defining the wave asymmetry is larger for longer waves. This argument is discussed in more detail in Paper V.

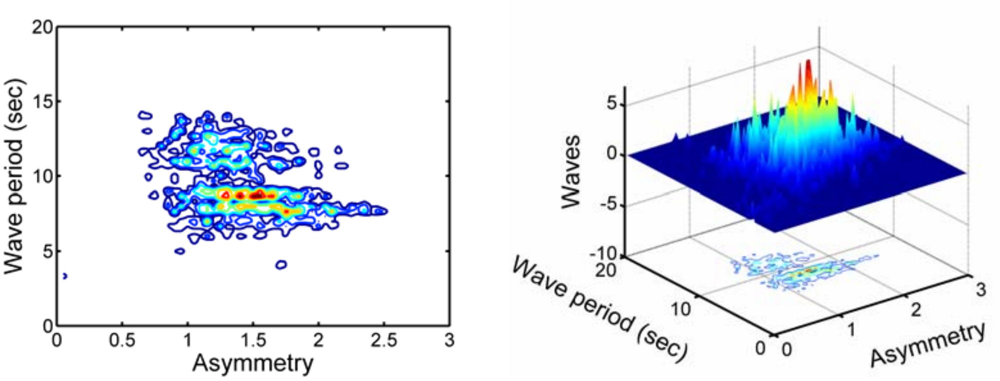

Fig. 4.5. Scatter diagram of the occurrence of different values of the asymmetry coefficient for waves of different periods from the first group of the wakes: contour plot (left); 3D surface plot (right)

4.3. Cnoidal wave theory: an application to ship waves

Linear wave theory, which has been widely used for the description of surface waves and their interactions, is only applicable provided the wave height is small compared to the wave length and water depth. The basic requirement $\kappa H/2 << 1$, where $\kappa = 2\pi/L << 1$ is the wave number, L is the wave length and H is the wave height (Massel, 1989), is frequently violated for ship waves in the nearshore. The length of a typical wave from a fast ferry with a period of about 10 s (Soomere and Rannat, 2003; Paper IV) is $L \geq 30\sqrt{h}$ m; thus water with the depth $h \leq 10$ m can be already considered as shallow. An appropriate parameter in shallow areas is the Ursell number $U = HL^2h^{-3}$ (Massel, 1989). When $U \approx 1$, the linear theory is useful in many aspects, even when the condition $\kappa H/2 << 1$ is violated. For moderate Ursell numbers (up to $U \approx 75$) and $L/h < 8-10$, various modifications of the Stokes wave theory can be used (Massel, 1989). The Ursell number for such a wave in the coastal area ($h \approx 3$ m) is $U \approx 100H$ and already ship waves of moderate height ($H \approx 0.5$ m) correspond to $U \approx 50$ (Soomere et al., 2005). For even longer or higher waves, or for lesser depths, the Stokes wave theory is generally incorrect (Massel, 1989) and the cnoidal wave theory is preferable.

The ratio of the crest height A_+ and the trough depth A_- for an ideal cnoidal wave propagation over an area of constant depth can be calculated from the following equation (Massel, 1989):

$$\frac{A_+}{A_-} = \frac{m}{m + E/K - 1} - 1 . \tag{4.1}$$

Here K and E are complete elliptic integrals of first and second kind, respectively:

$$K(m) = \int_0^{\pi/2} \frac{du}{\sqrt{1 - m\sin^2(u)}}, \qquad E(m) = \int_0^{\pi/2} \sqrt{1 - m\sin^2(u)}\,du , \tag{4.2}$$

and the values of the parameter $m = \sqrt{k}$ can be found for different values of the wave height H and period T from the following relation:

$$\frac{H}{h}\frac{gT^2}{h} = \frac{16}{3} mK^2(m) \tag{4.3}$$

for the given water depth h.

When a cnoidal wave propagates over a sea area of variable depth, its parameters obviously change with changes in the water depth. The measurement site of the water surface elevation is located in a 2.7 m deep area (Paper IV) on a coastal slope. The actual water depth may vary over the typical length (~80 m) of a ship wave with a period of 10 s from about 5 m to about 2 m. This is the most probable reason why the water depth, estimated from Eqs. (4.1)–(4.3), systematically exceeds the actual water depth at the measurement site. Namely, it is natural to assume that the instantaneous properties of waves propagating along a coastal slope express the variations of the depth over a longer section of the slope.

Equations (4.1)–(4.3) make it possible to calculate the 'effective' depth for the ship waves the parameters of which (period, height and asymmetry coefficient) are detected at the tripod. This depth for most of the waves in question is between 2.7 and 5 m as shown in Fig. 4.6. As data points representing the properties of most of the analyzed waves fit into the sector defined by these depths in Fig. 4.6, one can conclude that the cnoidal wave theory is a suitable frame for their description in the realistic conditions of the changing water depth.

While the asymmetry coefficient for most of the ship waves fits into the sector defined by these lines, a substantial part of waves from the *Nordic Jet* and *Baltic Jet* do not. Moreover, waves from these sister ships frequently have the asymmetry coefficient below 1, that is, the wave troughs are systematically deeper than the crest heights.

This peculiarity is also visible in Fig. 4.6, confirming once more that the wave asymmetry is an important characteristic of wakes from different ships that does not necessarily correlate with the maximum wave height of the wakes.

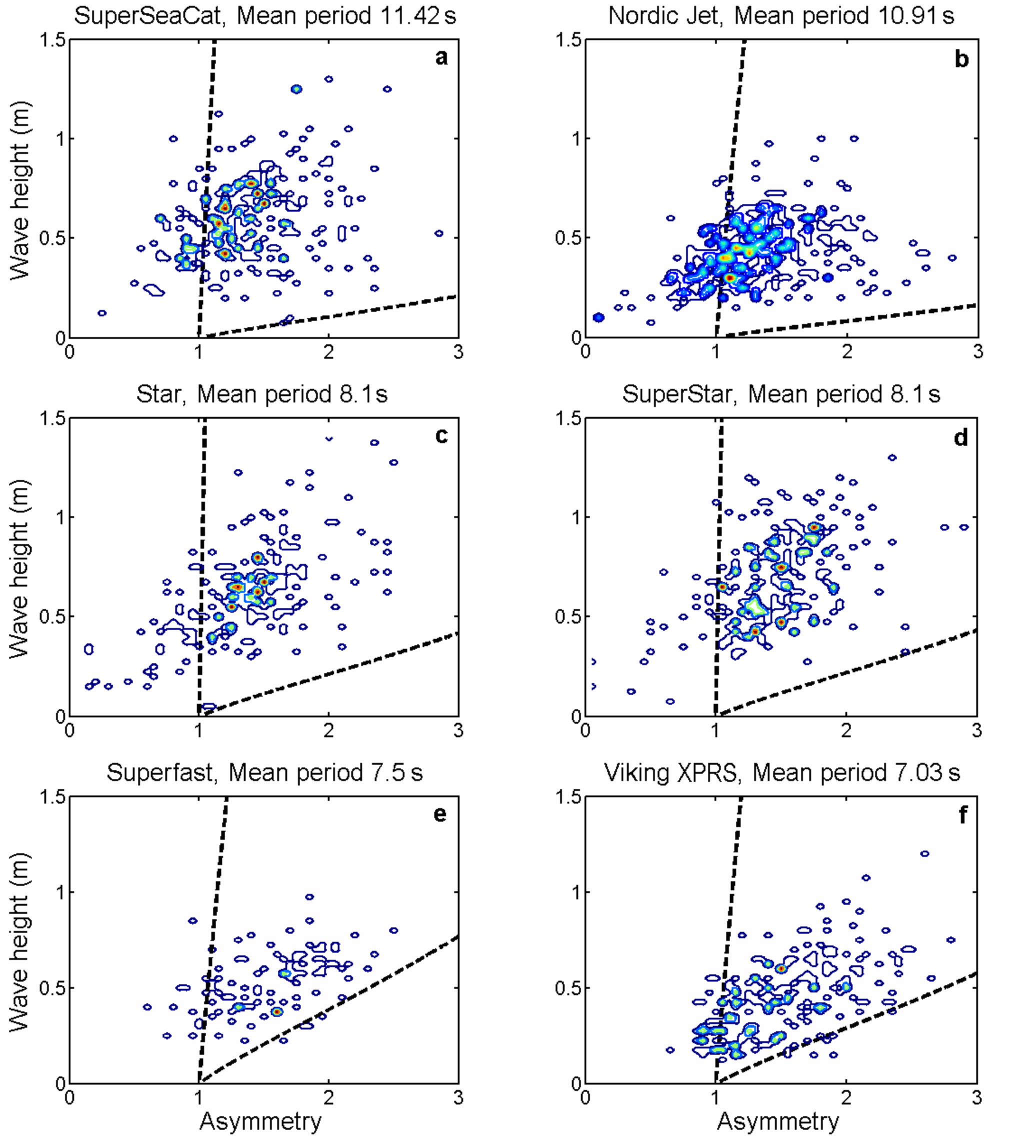

Fig. 4.6. Scatter diagram of the occurrence of different values of the asymmetry coefficient for waves with different height from the first group: (a) *SuperSeaCat*, maximum and minimum periods 17.2 s and 3.2 s, (b) *Nordic Jet* and *Baltic Jet* (19.6 s and 4.2 s), (c) *Star* (12.2 s and 2 s), (d) *SuperStar* (12 s and 2 s), (e) *Superfast* (9 s and 4.2 s), (f) *Viking XPRS* (10.4 s and 4 s). The dashed lines correspond to the asymmetry coefficient of cnoidal waves with maximum (the lower line) and minimum (the almost vertical line) periods of waves analyzed for the particular ship at a water depth of 2.7 m and 5 m

As *Nordic Jet* and *Baltic Jet* are the only catamarans among the fleet, it may be hypothesized that the frequent occurrence of deep troughs in the wakes is caused by the interference of wave systems created by the two hulls.

4.4. Concluding remarks

Analysis of the wave shape was performed for 1346 long and high waves from the first group of 163 single wakes. These waves are of clearly asymmetric shape. On average, the wave crests are by 40% higher than the trough depths. This indicates a substantial level of nonlinearity of the otherwise perfectly smooth waves and confirms the necessity of using appropriate nonlinear methods to adequately describe the influence of such waves on the coastal zone. The cnoidal wave theory is appropriate for analysing and forecasting properties and impact of the leading waves from fast ferries in real conditions in the nearshore.

The empirical probability distributions of asymmetry have considerably different shapes compared to the corresponding distributions of energy, energy flux and wave height. The asymmetry coefficient of the leading ship waves, thus, is an additional, essentially independent indicator of the properties of ship wakes. In particular, its distribution may serve as a key for deciding from the wake structure whether the ship was a catamaran or a monohull. Although this feature was observed in specific conditions of Tallinn Bay, the Baltic Sea, it apparently is universal for any kind of fast ferry traffic.

The concordance of the values for the asymmetry coefficient obtained using the zero-upcrossing and zero-downcrossing methods suggests that ship waves are more similar to regular wave trains or groups than to freak waves.

5. Runup of ship waves on a beach

5.1. Introduction

In the coastal zone, ship waves are frequently 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 high near-bottom velocities in shallow water and induce sediment resuspension and 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).

Understanding shoaling and runup of long waves on a beach is a classic problem in coastal engineering. Although empirical formulae have been constructed for wind waves (Stockdon et al., 2006) and for many other wave classes (see Didenkulova et al., 2007 for overview and references), forecasting of runup characteristics still remains a challenge. Large runup of long waves (such as tsunami waves) can lead to significant changes in the coastal morphology and to an intensification of coastal processes. The major obstacle on the way to better understanding of their impact is the uncertainty in the determination of 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 potentially hazardous incident waves far from the shore are difficult, costly and often dangerous, it is an attractive option to study such waves under controlled conditions. In this context, field studies of large ship waves are the most promising. The leading groups of HSC wakes are effectively long waves (wavelengths up to 250 m), and at depths not greater than 10–20 m can be considered as almost perfect examples of long waves in shallow water. As long waves typically break before reaching the coast, most of the existing theories are only conditionally applicable for the description of their properties at the coastline. There is an acute need to develop an adequate theory for long wave runup that would take into account the wave shoaling and breaking processes. A first step towards such a theory is an attempt to relate the runup properties of real, partially breaking waves with their properties offshore. As long waves from fast ferries preserved well their identity when propagating from the tripod location to the coast, experimental studies of their runup presented in Paper III serve as a convenient case for establishing such a relationship.

5.2. Measurements of wave runup on a beach

The runup of individual ship-induced waves on the study site (Figs. 2.1 and 2.3) in Tallinn Bay was measured using two 5-metre survey staffs joined together (Fig. 5.1; Paper V). The runup height was recorded manually based on the observer’s estimate of the highest position of the waterline along the staff and double-checked with the use of a video recorder. The variations of the water level over the experiment (from –7 cm to +30 cm) caused certain variations of the position of the waterline along the gently sloping coast of the measurement site (Fig. 5.1). This variation was removed from the recorded data and the runup height was calculated from the still water level for each wake.

Fig. 5.1. Runup of the *Nordic Jet* ship wake on 14 July, 10:40

Typically, the highest and longest ship waves break before they reach the coast. Usually the long ship waves did not break offshore from the tripod; thus it can be assumed that wave breaking, if it occurred, took place between the tripod and the coastline. A few waves were breaking already relatively close to the tripod about 100 m from the shore (Fig. 5.2). The breaker type varied for different weather conditions and different vessels and both plunging and spilling breakers occasionally occurred (Fig. 5.2).

The runup of 212 ship wake events was analysed, including 59 wakes of the *Nordic Jet* and *Baltic Jet*, 11 wakes of the *Superfast*, 45 wakes of the *SuperSeaCats*, 47 wakes of the *Star* and *SuperStar*, 13 wakes of the *Viking XPRS* and 37 double wakes. In most cases, only the relationship between the maximum recorded wave height and the maximum runup height was established. For a few wakes, also details of runup and rundown were restored from video recordings. The results showed that usually the highest waves also produce the largest runup heights.

A typical example of the wave runup heights above still water level of the waves from *Star* at 11:24 on 14 July is shown in Fig. 5.3. The long waves from the first wave group (waves No. 50–60) form a clearly identifiable set of large runup events (0.60–1.4 m). It is noteworthy that the runup heights of the rest of the wake were equivalent to those of wind waves, even when waves belonging to the ‘tail’ of a ship wake had clearly larger periods than wind waves.

Fig. 5.2. Plunging waves from the *Nordic Jet* wake approaching the coast on 27 June, 20:00 (left) and spilling waves from the wake from *Star* approaching the coast on 14 July, 11:24 (right).

The typical maximums of the runup height for both single and double wakes were over 1 m above still water level. The overall maximum observed runup was about 1.4 m over still water level for the wake represented in Fig. 5.3. These values largely exceed the analogous values for wind waves with the typical height of close to 0.5 m that produced runup of up to 20–30 cm. This feature suggests that ship wakes play a significant role in the formation of the beach profile in the upper swash zone. Several extreme runup events caused by ship wakes in otherwise almost calm conditions were evidenced by overwash deposits (Soomere et al., 2009). In such cases, waves evidently reached far more than 1.5 m above still water level.

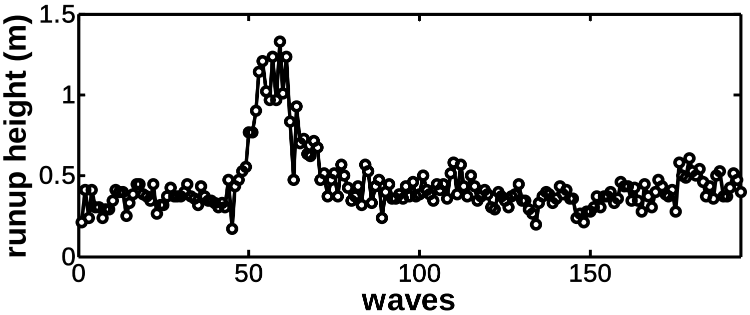

Fig. 5.3. Distribution of runup heights of ship wakes from the *Star* on 14 July 2008, 11:24.

5.3. Wave runup data

The largest waves in the wake from a fast ferry usually belong to the first group. Parameters of these waves can be reproduced numerically with an acceptable accuracy (Torsvik et al., 2009), and they often cause the largest impact on the beach in terms of the wave runup.

An interesting feature, established qualitatively from the recordings of waves and their runup, is that the highest non-breaking waves and largest wake energy are not necessarily correlated with the properties of breaking waves, wave runup and the impact of these waves on the coast. For example, the observers on the coast noted that, as a rule, waves from the *Viking XPRS* were frequently so small that they were completely masked by about 20–30 cm high wind waves. On one occasion, however (27 June 2008 at 08:00), the waves excited by this ship detached the measurement staffs from the buried anchors and knocked over the field personnel working on the beach. The wake parameters recorded for this case were not exceptional and these waves were not even the highest of the day (Paper III).

This feature motivates a more detailed analysis of the relationship between the measured properties of the waves and their runup along the coast. As the properties of the shoaling and/or breaking of waves induced by high-speed ferries were highly variable, such a relationship is not necessarily clearly defined for each single wave or wake.

As a first approximation, the correlation between the maximum wave height at the tripod and the maximum runup height above still water level at the study site is analysed in Paper III. While such a relationship did not become evident for single ship types, the analysis undertaken for all types of high-speed ferries and for superimposed wake events shows that there is an observable, albeit relatively weak, correlation between the maximum wave height and the maximum runup height (Fig. 5.4).

At the same time there is a rather wide interval of waves in Fig. 5.4 with the height varying from 0.4 m to 1.6 m, which may cause the same runup height at the coast. This feature can be explained by the impact of wave breaking on the runup height. Namely, larger waves start breaking at a larger distance offshore and a relatively large portion of their energy is dissipated until the runup event starts.

A much more clearly defined relationship exists between the measured wave height H and wave amplification (understood as the larger values of the runup height compared to the wave height). The latter is defined as the ratio R/H of the maximum runup height R and the wave height. This ratio decreases with an increase in the wave height (Fig. 5.5). The data presented in Fig. 5.5 can be fitted by the following line:

$$\frac{R}{H} = 2.08 - 0.94H\,, \tag{5.1}$$

where both the wave height and the maximum runup height are expressed in metres. The correlation coefficient between R/H and H is about 0.6. From Eq. (5.1) and Fig. 5.4 it follows that waves of smaller height usually cause relatively large runup values whereas the runup of higher waves may be severely limited. This limitation obviously is due to the damping wave energy down during wave breaking and bottom friction. This process is more pronounced for high waves.

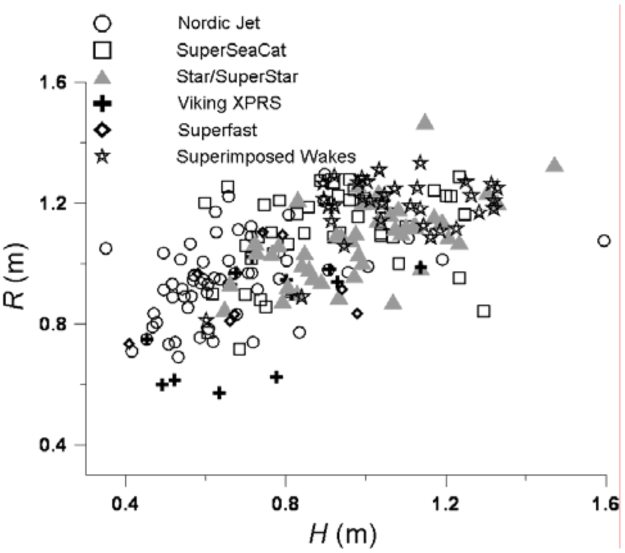

Fig. 5.4. The maximum runup height (*R*) plotted against the maximum wave height (*H*)

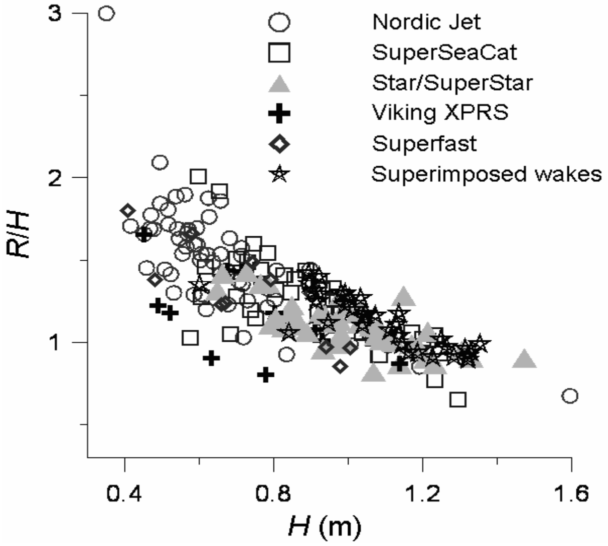

Fig. 5.5. The ratio of maximum runup (*R/H*) plotted against the maximum wave height (*H*)

Equation (5.1) suggests that a relatively good fit between the maximum wave height and the runup height might be obtained in terms of parabolic approximation $R = 2.08H - 0.94H^2$. This approximation evidently is valid for a very limited range of the approaching wave heights. Still, it apparently expresses well the basic properties of data presented in Fig. 5.4: almost twofold amplification of smaller waves and a maximum of the runup heights occurring approximately for 1 m high waves.

The typical runup height within the analysed data set, on average, is higher than the wave height at the tripod. The mean value of the amplification factor is 1.3. Therefore, one may usually expect wave amplification at the runup stage.

5.4. Concluding remarks

Waves dynamically similar to hazardous long waves that produce relatively large runup heights are frequently generated by high-speed ferries in Tallinn Bay.

Data from 212 ship wake events demonstrate that the largest ship generated waves approaching the coast break (plunging or spilling breaking) in the nearshore and have only a weak wave amplification at the beach. On average, the runup height of ship wakes exceeds the wave height offshore at a depth of 2.7 m by a factor of 1.3. This amplification factor decreases with increasing wave height and is below 1 for waves higher than about 1 m. This effect can be explained by a joint influence of wave breaking and wave energy dissipation owing to wave-bottom interaction. As a result, waves of moderate height (~0.6 m) may cause the same runup height as the highest waves (~1.6 m). This feature can be unpredictable for people at the coast and suggests that unexpectedly high runup of some ship waves may serve as a source of specific danger in the coastal zone.

Conclusions

Summary of results

A part of waves induced by high-speed ferries in Tallinn Bay, the Baltic Sea, represent an extremely interesting phenomenon from both scientific and coastal engineering points of view. Since there are no speed restrictions in most of the bay, vessels can sail at speeds that are close to the maximum phase speed of long waves in the bay (so-called near-critical speeds). Sailing at such speeds often leads to the generation of long (periods 7–15 s, wavelength up to 250 m at a depth of about 20 m) and high waves. Waves with such properties occur very infrequently in natural conditions. They may be interpreted as a class of waves that are not only new in shallow water bodies like the Baltic Sea but also present considerable marine hazard to the coastal zone, people and their property. A more detailed knowledge about their specific features and governing parameters is an important contribution towards mitigation of their potential impact and thus a valuable task of coastal engineering.

A thorough investigation of ship-induced waves on the coast of the Island of Aegna at the entrance of Tallinn Bay was performed based on a large data set of 418 ship wakes collected during an experimental study of ship wave properties in the sea and on the beach in 2008. It comprised 219 wakes attached to known single ships, 42 double wakes containing signals from two ships and 157 wakes not attached to particular ships (unidentified wake events).

Analysis of basic properties of ship waves comprises evaluation of average and extreme values and empirical probability distributions of the maximum wave height, wave energy and energy flux within each ship wake, the maximum runup height on a beach, and the crest–trough asymmetry of the largest waves. The shape of the largest waves in terms of the crest–trough asymmetry matches well the prediction of the cnoidal wave theory.

The periods of the highest ship waves vary insignificantly, being typically in the range of 9–12 s, and evidently are closely related to the cruise speed of the vessels. It is shown that the maximum ship wave height at the study site apparently has increased since about the year 2000. The largest waves are 1.5 m high in calm situations and reach 1.7 m in moderate wind conditions. The total vessel-induced energy and energy flux in this area have not changed significantly during the decade.

The variability of the properties of single wakes from particular ships is the largest for wakes from ‘classic’ high-speed vessels having relatively small tonnage (~1,000 tonnes) and using very high cruise speeds (35–40 knots). The frequent occurrence of very high waves, as well as noticeable outliers in the distributions of other wake parameters, suggests that management of threats associated with their wakes poses a serious problem and substantial changes or limitations to the sailing regime may be required to ensure an acceptable level of wake intensity. On the other hand, the properties of wakes from most large, basically conventional, but strongly powered ferries show much lower variability. Although such ferries may create relatively high waves under present sailing conditions, it is natural to expect that both the average and extreme wake properties can be more easily adjusted by changing either their speed or sailing line.

A clear similarity between the distributions of energy, energy flux and maximum wave height for vessels of the same type suggests that the maximum wave height can be used as an appropriate parameter to characterize the basic integral ship wake properties such as energy and energy flux and their variability. This distribution, therefore, can be used as a tool for managing vessel waves and their impacts in the nearshore and on the coast.

The shape of the incoming waves is another important parameter, which can strongly influence the wave impact (incl. runup height) on a beach. This property is studied in terms of the ratio of the wave crest height over calm water level and the trough depth. It is established that all the largest ship generated waves are asymmetrical. The average value of the asymmetry coefficient is 1.4 and almost the same for the analysis performed with the use of the zero-upcrossing or zero-downcrossing methods. This feature suggests that ship waves are more similar to regular wave trains or groups than to freak waves.

Interestingly, the empirical distributions of this coefficient for certain vessels are quite different from analogous distributions of other above-mentioned characteristics of wakes. Therefore, the asymmetry coefficient, if available, serves as an independent parameter to characterize vessel wakes. In particular, the distributions of asymmetry coefficients for catamarans and monohull vessels are fairly different. Thus, the shape of this distribution can be used as an indicator of the type of the vessel.

The experimentally obtained values of the asymmetry coefficient are compared with estimates derived from the cnoidal theory of long, weakly nonlinear waves. The measured and theoretically estimated properties generally match well each other showing that the cnoidal theory is an adequate model for this kind of waves in the nearshore.

Most of the long and high ship waves start breaking at least several tens of metres offshore and lose a large part of their energy before hitting the coast. The larger waves are more apt to breaking. For the listed reasons, only weak wave amplification is observed on the beach and waves of quite a wide range of heights (from 0.4 m to 1.6 m) lead, on average, to the same runup height. The runup height of ship waves typically exceeds the wave height offshore at a measurement depth of 2.7 m by a factor of 1.3. This factor decreases with increasing in wave height.

Main conclusions proposed to be defended

1. An extensive database of properties of single waves and entire wakes from high-speed vessels in the nearshore and on the beach of the Island of Aegna at the entrance of Tallinn Bay, the Baltic Sea, over 30 days has been collected and analysed. It comprises 219 wakes attached to particular ships, 42 events containing wakes from two ships and 157 wakes from unidentified ships.
2. Waves induced by the new generation of large, basically conventional but strongly powered ferries are similar to waves from classic high-speed ships: they are unusually long (period 7–15 s, length 250 m at a depth of 20 m) and high (up to 1.5 m) in the Baltic Sea conditions.
3. The maximum height of ship waves at the study site has considerably increased since about the year 2000. In summer 2008 typical daily maximum wave height was 1.2 m. The largest waves in calm conditions reached 1.5 m. At the same time the total energy and energy flux in this area have not decreased.
4. The distributions of energy, energy flux and maximum wave height for vessels of the same type are clearly similar. The maximum wave height can be used as an appropriate parameter to characterize the properties and variability of ship wakes and its distribution can be used for managing vessel waves and their impacts.
5. The variability of the properties of wakes from classic high-speed ships is relatively large whereas the properties of wakes from conventional, strongly powered ferries show quite a limited variability. Therefore, the average and extreme wake properties of conventional ferries can be relatively easily controlled whereas reaching tolerable levels of these properties for classic high-speed ships may need much more severe limitations of their sailing regime.
6. The largest ship waves show an essential crest-to-trough asymmetry, the crests being on average about 40% higher than the troughs. The overall properties of the asymmetry in the sloping nearshore match well the predictions of the cnoidal wave theory.
7. The distributions of the asymmetry coefficient do not match similar distributions of the wake energy, energy flux and maximum wave height. This coefficient, thus, serves as an independent parameter to characterize vessel wakes.
8. The distributions of asymmetry coefficients for catamarans and monohulls are largely different. This feature can be used as an indicator of the type of the vessel.
9. The largest ship waves usually break before reaching the coast and waves of quite a wide range of heights (0.4–1.6 m) create almost the same runup height. The runup height of ship wakes typically exceeds the wave height offshore at the measurement depth of 2.7 m by a factor of 1.3. This factor decreases with an increase in the wave height.

Recommendations for further study

It has been well known already for decades that ship-induced waves may, under certain circumstances, serve as a serious threat to the coastal ecosystem, coastal engineering structures, property and even to people. Wakes generated by vessels operating close to so-called critical speeds (that is, the maximum phase speed of linear waves for the given depth) in relatively shallow waters are usually the most dangerous.

An important, albeit qualitative, aspect of studies and ideas presented above is that in coastal engineering the role of vessel wakes is much wider than a simple inconvenience. On the one hand, these waves serve as a specific type of coastal hazard. On the other hand, the dynamical similarity of the parameters of some ship waves with parameters of certain wave-based coastal disasters (for example, tsunami waves caused by landslides; Didenkulova et al., 2009), opens a promising way towards the use of ship wakes as a safe, controlled, small-scale model for studies of the damaging potential of certain classes of natural disasters. The dynamical similarity of long ship waves and landslide-caused tsunami waves apparently becomes especially important in the coastal zone where the processes of tsunami wave dissipation, breaking and runup could be studied. The theory of runup of partially breaking waves, especially when such waves approach in groups of a small number of wave crests, is not well developed yet and there is an obvious need for further research. Joint analysis of wave properties offshore and breaking and runup properties of ship waves might make an important contribution to studies of coastal hazards.

Another important topic for further studies is the analysis of the properties and extent of nonlinear wave interaction in cases when several wakes occur simultaneously. The potential effects of interactions of long, highly nonlinear waves in shallow water have been extensively studied theoretically (see, for example, Biondini et al., 2009; Kharif et al., 2009 and references therein). In particular, it was shown by Peterson et al. (2003) that interaction of two long waves may lead to an up to fourfold amplification of the wave amplitude for a certain angle of their crossing. As shown above, a large part of the data set analysed in the thesis represents double wakes coming from two different ships, which may result in an unexpected and extremely dangerous local wave height amplification. The consequences of this phenomenon of nonlinear interaction and potential generation of a new, much higher solitonic wave (Soomere and Engelbrecht, 2006) on the runup properties are unknown.

An important parameter of the wave nonlinearity is its back–front asymmetry, which plays a key role in the case of wave runup (Didenkulova et al., 2006; 2007). Such asymmetric waves penetrate inland over larger distances and with greater velocities than symmetric waves of the same height and length do. The method used in this study apparently is able to detect also this type of wave asymmetry. Relevant joint analysis of the wave shape and runup could essentially contribute to the understanding of the general problem of wave runup.

Another issue that obviously needs further consideration is the statistics of properties of single waves in different groups of a ship wake. A ship wake usually consists of three or four wave groups, which have different properties. The largest and longest, also most asymmetric (in terms of both trough–crest and back–front asymmetry) waves usually come in the first group. There are, however, high and dangerous waves also in other groups. It would be important to explore in detail the statistics of waves within each group (how many waves are in the group, which one is the largest, which one is the longest, how the parameters of the waves change for different ships, etc.) and to compare their properties between the groups. Such study is evidently important for a better understanding of the dynamics of wave trains and the formation of extreme waves by wave focusing.

The study of ship waves can provide insights into sediment transport and coastal profile changes under realistic, but controlled, conditions. The outcome of such studies can be significant for coastal construction and development.

As ship wakes often hit a coastal zone from directions from which wind waves do not come, a study of the impact of ship wakes can serve as a pilot research of the impact of the changing wind climate and consequent changes in the wave regime.

In general, data obtained from such studies can be used to further develop an appropriate theory to describe and characterize long waves in the nearshore as well as to contribute to the prevention of some marine hazards under well controlled and safe conditions.

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Abstract

This study explores the properties of a large ensemble of ship wakes (418 wakes on 15 days) in Tallinn Bay with the basic goal to quantify their potential impact by means of building reliable statistics of their properties and variability and to identify the ways of their use for the benefit of coastal management. The greatest impact on the coast is usually caused by the highest and longest components of wakes generated at near-critical speeds (depth Froude numbers ~1).

The time series of water surface elevations was collected at the entrance of Tallinn Bay at ~2.7 m water depth, ~100 m offshore and ~2700 m from the sailing line simultaneously with runup data on an almost non-reflecting beach in June–July 2008. Waves induced by the new generation of large, basically conventional but strongly powered ferries resemble waves from 'classic' high-speed ships: they are unusually long (period 10–15 s) in the Baltic Sea conditions. The periods of the highest waves vary insignificantly. The maximum height of ship waves at the study site has considerably increased since about the year 2000. The typical daily maximum wave height was 1.2 m in 2008. The largest waves in calm conditions reached 1.5 m. The total energy and energy flux of ship waves have not changed.

The analysis of empirical distribution functions of key properties of the wakes (maximum wave height, wake energy and energy flux) revealed that appropriate measures characterizing all the listed properties and their variability are the maximum wave height and its distribution function. Wakes from 'classic' high-speed vessels sailing at >30 knots are very variable and the distributions of their properties contain many outliers. Wakes from strongly powered but otherwise conventional ferries have much less variability and contain almost no outliers.

The shape of waves from high-speed ferries is analysed by considering the match of the crest heights and trough depths over 1346 waves from 163 wakes. The highest and the longest waves contained in the first wave group of the wake are essentially asymmetric. On average, the wave crests are by 40% higher than the wave troughs. In extreme cases, the crest heights exceed the trough depth by up to a factor of 3. In general, ship waves are more similar to groups of regular waves than to freak waves. The crest–trough asymmetry is an independent parameter of the wakes. It is demonstrated that the cnoidal wave theory is an appropriate model for describing the shape and other properties of long ship-induced waves in the nearshore.

The largest ship waves usually break before approaching the shore. Waves of a quite wide range of heights (0.4–1.6 m) create almost the same runup height. On average, the runup height of ship wakes exceeds the wave height offshore at the measurement depth of 2.7 m by a factor of 1.3. This factor decreases with an increase in wave height.

Finally, the role of ship wakes among various marine-induced hazards in the context of the Baltic Sea and the potential of studies into ship waves for a better understanding, modelling and mitigation of coastal disasters under safe, controlled conditions is discussed.

Resümee

Töö eesmärgiks on hinnata kiirlaevalainete parameetrite muutlikkust ning laevalainete potentsiaalset mõju Tallinna lahe rannikute jätkusuutliku haldamise ja planeerimise kontekstis. Töö põhineb peamiselt 2008. a juunis–juulis Aegna muuli lähistel ligikaudu 2,7 m sügavuses vees 100 m rannast ja 2,7 km laevateest tehtud laevalainete kõrglahutusega (5 Hz, täpsus ±1 mm) salvestustel ja samaaegselt mõõtmiskoha vahetus läheduses läbi viidud lainete uhtekõrguse vaatlustel. Töös on analüüsitud 15 päeva jooksul salvestatud 418 laeva lainete parameetreid.

Uue põlvkonna kiirekäiguliste (ristlemiskiirus 25–28 sõlme) parvlaevade (*Star*, *Superstar* ja *Viking XPRS*) järellainetusel on põhiosas samad omadused, mis nn klassikalistel suhteliselt kergetel kiirlaevadel, nagu *SuperSeaCat* või *Nordic Jet*, mille ristlemiskiirus on üle 35 sõlme. Nende laevade kõrgeimate lainete perioodid (10–15 s) ei ole viimase kümnendi jooksul muutunud ning on endiselt märksa suuremad Läänemere lainete omadest. Laevalainete maksimaalne kõrgus on aastail 2001–2003 tehtud mõõtmistega võrreldes suurenenud. Päeva kõrgeimad laevalained on nüüd ligikaudu 1,2 m kõrgused. Mõõteperioodi kõrgeimad lained ulatusid 1,5 meetrini. Laevalainete koguenergia ja selle voog ei ole siiski oluliselt muutunud.

Laevalainete peamiste omaduste (maksimaalne lainekõrgus, energia ja selle voog) empiirilised jaotusfunktsioonid on põhijoontes sarnased. Kõiki nimetatud omadusi ja nende muutlikkust saab adekvaatselt hinnata suhteliselt kergesti mõõdetava parameetri – lainekõrguse alusel. Klassikaliste kiirlaevade (*SuperSeaCat*, *Nordic Jet*) järellainetuse omadused varieeruvad väga suures ulatuses ning järellainetus sisaldab sageli kõrgeid ja/või intensiivselt energiavoogu tekitavaid laineid. Seevastu uue põlvkonna parvlaevade järellainetuse parameetrid varieeruvad märksa vähem ning keskmistest väärtustest palju suuremaid kõikumisi ei täheldatud.

Laevalainete kuju analüüsiti nende vertikaalse asümmeetria kaudu harja kõrguse ja talla sügavuse suhte alusel. Vaadeldi 1346 üksiklainet kokku 163 laeva vaiksel merel salvestatud järellainetusest. Järellainetuse esimesse, suhteliselt kõrgete ja pikkade lainete rühma kuuluvad lained on üldiselt tugevalt asümmeetrilised. Laineharjad on keskmiselt 40% võrra kõrgemad lainete taldadest. Üksikute laineharjade kõrgus ületas kuni kolm korda talla sügavuse. Laevalained sarnanevad regulaarsete lainete jadaga ning vähem hiidlainete rühmadega. Töös järeldati, et lainete asümmeetria on sõltumatu kiirlaevalaineid iseloomustav parameeter ja näidati, et knoidaalne pikkade lainete teooria sobib nii kiirlaevalainete kuju kui ka muude omaduste kirjeldamiseks rannalähedases vööndis.

Kõrgeimad laevalained enamasti murduvad enne rannajoonele jõudmist. Seejuures tekitavad võrdlemisi erineva kõrgusega (0,4–1,6 m) lained peaaegu sama kõrge uhtekõrguse. Keskmiselt ületab laevalainete uhtekõrgus ligikaudu 1,3 korda 2,7 m sügavusel mõõdetud lainete kõrguse, kusjuures kõrgemate lainete puhul on erinevus väiksem. Lõpuks analüüsiti kiirlaevalainete kui spetsiifilise merelt lähtuva ohufaktori rolli teiste ohtude seas ning sõnastati kiirlaevalainete uuringute tähtsus mitmete muude rannavööndit ähvardavate tegurite uurimise, modelleerimise ja neutraliseerimise seisukohalt.

Appendix A: Curriculum Vitae

1. Personal data

Name	Dmitry Kurennoy
Date and place of birth	24.01.1981, Leningrad
Citizenship	Russia

2. Contact information

Address	Akadeemia tee 21, 12618, Tallinn
Phone	+(372) 6204169
E-mail	dmitry@cs.ioc.ee

3. Education

Educational institution	Graduation year	Education (field of study/degree)
St. Petersburg State University	2004	MSc in Applied Mathematics

4. Language skills

Language	Level
Russian	native language
English	average

5. Further training

Period	Educational or other institution
June 2009	Field training in measurements of ship waves, Tallinn Bay, Estonia
June – July 2008	Field training in measurements of ship waves, Tallinn Bay, the Island of Aegna, Estonia
June – July 2008	Summer school “Dynamics of coastal zone of non-tidal seas”, Baltiysk, Russia
June 2008	Summer School on Environmental Dynamics, Venice, Italy
August – September 2007	Summer School “Waves and Coastal Processes”, Tallinn, Estonia
April – September 2006	Field survey on water level rise and sediment transport in the Eastern part of the Gulf of Finland, Russia

6. Professional employment

Period	Organization	Position
2008 – to date	Institute of Cybernetics, Tallinn University of Technology	Extraordinary researcher
2006 – to date (on leave)	A.P. Karpinsky Russian Geological Research Institute, Federal Agency of Mineral Resources	Engineer

7. Scientific work

Conference presentations

VII Baltic Sea Science Congress 2009, 17–21 August, 2009, Tallinn, Estonia, poster presentation: “Variability in wake properties of long waves generated by high-speed ferries” (2009).

VII Baltic Sea Science Congress 2009, 17–21 August, 2009, Tallinn, Estonia, oral presentation: “Submarine terraces of the Eastern Gulf of Finland: results of survey and reconstruction of evolution in Holocene” (2009).

International Conference “Construction of the Artificial Lands in the Coastal and Offshore Areas”, 20–25 June, 2009, Novosibirsk, Russia, oral presentation: “Variability in wake properties generated by high-speed ferries in Tallinn Bay” (2009).

X International Coastal Symposium 09 (ISC’09), 13–18 April, 2009, Lisbon, Portugal, oral presentation: “Variability in the properties of wakes generated by high-speed ferries” (2009).

XL International Conference on Control Processes and Stability (CPS’09), 6–9 April, 2009, St. Petersburg, Russia, oral presentation: “Изучение свойств судовых волн в Таллинском заливе” (On the properties of vessel waves in Tallinn Bay, in Russian) (2009).

SEAMOCS network meeting and conference on fatigue, 22–25 October, 2008, Oslo, Norway, oral presentation: “Variability in wake properties generated by high-speed ferries” (2008).

III International Student Conference “Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region”, 9–12 October, 2008, Juodkrante, Lithuania, oral presentation: “Coastal processes in the Gulf of Finland” (2008).

International Conference (school-seminar) “Dynamics of Coastal Zone of Non-tidal Seas”, 30 June – 4 July, 2008, Baltiysk (Kaliningrad Oblast), Russia, poster presentation: “The litho-dynamic modelling for the coastal zone of the Gulf of Finland, Kurortny area, St. Petersburg” (2008).

XXXVIII International Conference on Control Processes and Stability (CPS’07), 9–12 April, 2007, St. Petersburg, Russia, oral presentation: “Разработка методики определения участков аккумуляции и размыва береговой зоны на основе факторного анализа” (Development of a method for detecting of accumulation and erosion coastal sections based on factor analysis, in Russian) (2007).

XXXVII International Conference on Control Processes and Stability, 10–13 April, 2006. St. Petersburg, Russia, oral presentation: “Problem setting for litho-dynamic modelling” (2006).

VII International Ecological Seminar “The Baltic Sea Day”, 22–23 March, 2006, St. Petersburg, Russia, oral presentation: “Geological Hazards in the Gulf of Finland” (2006).

XXXV International Conference on Control Processes and Stability, 14–16 April, 2004, St. Petersburg, Russia, oral presentation: “Statistical data processing for fiber-optic line installation in Arctic” (2004).

Peer-reviewed publications

1.1. Articles indexed by ISI Web of Science (1.1)

Valdmann, A., Käärd, A., Kelpšaitė, L., Kurennoy, D. and Soomere, T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. Baltica 21/1-2, 3–12.

Didenkulova, I., Parnell, K. E., Soomere, T., Pelinovsky, E. and Kurennoy, D. 2009. Shoaling and runup of long waves induced by high-speed ferries in Tallinn Bay. Journal of Coastal Research, Special Issue 56/I, 491–495.

Kurennoy, D., Soomere, T. and Parnell, K. E. 2009. Variability in the properties of wakes generated by high-speed ferries. Journal of Coastal Research, Special Issue 56/I, 519–523.

Zhamoida, V. A., Ryabchuk, D. V., Kropatchev, Y. P., Kurennoy, D., Boldyrev, V. L. and Sivkov, V. V. 2009. Recent sedimentation processes in the coastal zone of the Curonian Spit (Kaliningrad region, Baltic Sea). Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 160/2, 143–157.

Leont’yev, I. O., Ryabchuk, D. V., Spiridonov, M. A. and Kurennoy, D. 2009. Coastal profile in the Eastern Gulf of Finland: Results of survey and reconstruction of evolution in the Later Holocene. Oceanology, submitted.

1.2. Peer-reviewed articles in other international research journals (1.2)

Kurennoy, D., Didenkulova, I. and Soomere, T. 2009. On the crest–trough asymmetry of waves generated by high-speed ferries. Estonian Journal of Engineering 15/3, 182–195.

Parnell, K. E., Delpeche, N., Didenkulova, I., Dolphin, T., Erm, A., Kask, A., Kelpšaitė, L., Kurennoy, D., Quak, E., Räämet, A., Soomere, T., Terentjeva, A., Torsvik, T. and Zaitseva-Pärnaste, I. 2008. Far-field vessel wakes in Tallinn Bay. Estonian Journal of Engineering 14/4, 273–302.

3.4. Articles published in conference proceedings (3.4)

Куренной, Д. и Соомере, Т. 2009. Измерение судовых волн в Таллиннском заливе. Труды международной конференции “Литодинамика контактной зоны океана”, 14–17 сентября 2009, Москва, Россия, in press (in Russian).

Ryabchuk, D., Sukhacheva, L., Lukyanov, S., Spiridonov, M., Pnuyshkov, A., Nesterova, E. and Kurennoy, D. 2009. The history of development and the recent coastal zone geological processes for the Saint-Petersburg Curortny region. Proceedings of RSHU, in press (in Russian).

Kurennoy, D. and Soomere, T. 2009. Variability in wake properties generated by high-speed ferries in Tallinn Bay. In: Artificial beaches, artificial islands and other structures in the coastal and offshore areas (Khabidov, A.Sh., ed.). Proceedings of the International Conference “Construction of the Artificial Lands in the Coastal and Offshore Areas,” July 20–25, 2009, Novosibirsk, Publishing House of the Siberian Branch of Russian Academy of Sciences, p. 89–97.

Didenkulova, I., Kurennoy, D. and Soomere, T. 2009. Freak waves in Tallinn Bay, the Baltic Sea. In: Geophysical Research Abstracts, 11, EGU2009-2024.

Куренной, Д. и Соомере, Т. 2009. Изучение свойств судовых волн в Таллиннском заливе. In: Proceedings of XL International Conference on Control Processes and Stability, April 6–9, 2009, St. Petersburg, Russia, p. 314–319 (in Russian).

Kurennoy, D. 2008. Coastal processes in the Gulf of Finland. In: Materials of 3rd International student conference “Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region”, October 9–12, 2008, Juodkrante, Lithuania, p. 15–16.

Kurennoy, D. and Ryabchuk, D. 2008. The litho-dynamic modeling for the coastal zone of the Gulf of Finland, Kurortny area, Saint-Petersburg. In: Materials of International Conference “Dynamics of Coastal Zone of Non-tidal Seas”, June 30 – July 4, 2008, Baltiysk (Kaliningrad Oblast), Russia, p. 88–91.

Куренной, Д. и Рябчук, Д. 2008. Литодинамическое моделирование на побережье Финского залива, Курортный район г. Санкт-Петербурга. In: Materials of International Conference “Dynamics of Coastal Zone of Non-tidal Seas”, June 30 – July 4, 2008, Baltiysk (Kaliningrad Oblast), Russia, p. 91–95 (in Russian).

Ryabchuk, D., Spiridonov, M., Kurennoy, D. et al. 2007. Lithodynamics of the northern coastal zone of eastern Gulf of Finland. In: Materials of the XVII International Scientific Conference on Marine Geology, November 12–16, 2007, Geology of Seas and Oceans 4, p. 167–169 (in Russian, English Abstract).

Kosheleva, V., Kurinnyi, N., Kurennoy, D. et al. 2007. Engineering-geological features of the bottom sediments developed in the Tatarskyi Strait of the Okhotsk Sea. In: Materials of the XVII International Scientific Conference on Marine Geology, November 12–16, 2007, Geology of Seas and Oceans 1, p. 53–55 (in Russian, English abstract).

Куренной, Д. Н. 2007. Разработка методики определения участков аккумуляции и размыва береговой зоны на основе факторного анализа. In: Proceedings of XXXVIII International Conference on Processes of Control and Stability, April 9–12, 2007, St. Petersburg, Russia, p. 155–161 (in Russian).

Kurennoy, D. 2007. The litho-dynamic modeling task for the coastal zone of the Gulf of Finland. In: Proceedings of XXXVIII International Conference on Processes of Control and Stability, April 9–12, 2007, St. Petersburg, Russia, p. 162–167 (in Russian).

Kurennoy, D. Problem setting for litho-dynamic modelling. 2006. In: Proceedings of XXXVII International Conference on Processes of Control and Stability, April 10–13, 2006, St. Petersburg, Russia p. 225–229 (in Russian).

Other publications

Кошелева, В. А., Куринный, Н. А., Куренной, Д. Н. и др. 2008. Особенности прокладки продуктопровода по дну Татарского пролива. Сборник научных трудов, посвященных 75-летию профессора В.Н. Шванова, Литология и палеогеография 6, с. 110–121 (in Russian).

Неизвестнов, Я. В., Кошелева, В. А., Черкашев, Г. А., Куренной, Д. Н. и др. 2008. Геологическая изученность южной части республики Гвинея с целью предварительного проектирования и строительства портового комплекса. Сборник научных трудов, посвященных 75-летию профессора В.Н. Шванова, Литология и палеогеография 6, с. 94–109 (in Russian).

Спиридонов, М. А., Рябчук, Д. В., Нестерова, Е. Н., Куренной, Д. Н. и др. 2007. Развитие проекта “ТЭО берегоукрепления восточной части Финского залива” (Исследование береговой зоны восточной части Финского залива). Известия ВСЕГЕИ 7/55, 166–171 (in Russian).

Ryabchuk, D., Nesterova, E., Kurennoy, D. et al. 2007. Project development for coastal strengthening in the Eastern part of the Gulf of Finland. Proceedings of VSEGEI, 7/55, 135–142 (in Russian).

Спиридонов, М. А., Тимофеева, Д. М., Куренной, Д. Н. и др. 2006. Выявление затопленных предметов на акватории Итальянского пруда и Обводного канала в г. Кронштадт. Известия ВСЕГЕИ 6/54, 152–154 (in Russian).

Спиридонов, М. А., Тимофеева, Д. М., Куренной, Д. Н. и др. 2006. Выявление затопленных предметов на акваториях рек Карповка, Охта, Б. Невка и

Обводного канала в Санкт-Петербурге. Известия ВСЕГЕИ 6/54, 150–152 (in Russian).

Спиридонов, М. А., Тимофеева, Д. М., Куренной, Д. Н. и др. 2006. Выявление затопленных предметов на акваториях рек Смоленка, Нева, М. Нева, М. Невка. Известия ВСЕГЕИ 6/54, 148–150 (in Russian).

Спиридонов, М. А., Тимофеева, Д. М., Мануйлов, С. Ф., Куренной, Д. Н. и др. 2006. Выявление затопленных предметов на акваториях рек Нева, Фонтанка, Ждановка, Черная, Пряжка, в Кронверкском проливе, каналах Крюковом, Екатерининском. Известия ВСЕГЕИ 6/54, 146–148 (in Russian).

Спиридонов, М. А., Шахвердов, В. А., Кропачев, Ю. П., Куренной, Д. Н. и др. 2006. Поиск и обследование подводных потенциально опасных объектов на мелководье Балтийского моря. Известия ВСЕГЕИ 6/54, 143–146 (in Russian).

Спиридонов, М. А., Рябчук, Д. В., Нестерова, Е. Н., Куренной, Д. Н. и др. 2006. Развитие проекта “ТЭО берегоукрепления восточной части Финского залива”. Известия ВСЕГЕИ 6/54, 136–143 (in Russian).

Grigoryev, A., Kurennoy, D. and Suslov, G. 2006. Geological and radio-geochemical accompanying of the investigation works for potentially dangerous underwater objects in Novaya Zemlya bays. Proceedings of VSEGEI 5/53, 239–248 (in Russian).

Ryabchuk, D., Spiridonov, M., Nesterova, E., Kurennoy, D. et al. 2006. Estimates and forecast for the Gulf of Finland high level sedimentation zones with consideration of KZS. Proceedings of VSEGEI 5/53, 227–231 (in Russian).

Kropachev, Y., Nesterova, E., Kurennoy, D. et al. 2006. Geo-ecological waterside monitoring in the zones of Saint-Petersburg flood protection constructions. Proceedings of VSEGEI 5/53, 221–226 (in Russian).

8. Defended theses

MSc thesis “Statistical data processing for fiber-optic line installation in Arctic” (2004).

9. Main areas of scientific work and current research topics

Experimental study of waves, wave statistics, data processing, waves in the coastal zone, waves induced by high-speed ferries, wind waves, sediment transport.

10. Other research projects

January – March 2008	Engineering survey for a cargo port design, Benti, Guinea
May – July 2007	Engineering survey for submerged fiber-optic communication lines between Russia and Japan, Far East, Russia

September – October 2006	Engineering survey for an oil-platform design in the Barents Sea, Russia
November – December 2005	Engineering survey for submerged fiber-optic communication line in Tatarskiy Strait, Far East, Russia
December 2004 – January 2005	Engineering survey for a design of the oil-loading terminal in the Gulf of Finland, Russia
May – July 2004	Engineering survey for a design of the oil-loading terminal in the Caspian Sea, Ekerem, Turkmenia
July – September 2003; August – October 2002	Engineering survey for the POLARNET (submerged fiber-optic communication cable with repeaters) design, Kirkenes (Norway) – Nome (USA), Arctic

11. Honours and awards

Marie Curie Fellow, 2008–2009.

Appendix B: Elulookirjeldus

1. Isikuandmed

Ees- ja perekonnanimi	Dmitry Kurennoy
Sünniaeg ja -koht	24.01.1981, Leningrad
Kodakondsus	Venemaa

2. Kontaktandmed

Aadress	Akadeemia tee 21, 12618, Tallinn
Telefon	+(372) 6204169
E-posti aadress	dmitry@cs.ioc.ee

3. Hariduskäik

Õppeasutus	Lõpetamise aeg	Haridus (eriala/kraad)
Sankt-Peterburgi Riiklik Ülikool	2004	Rakendusmatemaatika; magister

4. Keelteoskus

Keel	Tase
Vene	emakeel
Inglise	kesktase

5. Täiendusõpe

Õppimise aeg	Täiendusõppe läbiviija ja nimetus
Juuni 2009	Välitingimustes väljaõpe laevalainete ja nende uhtekõrguse mõõtmiseks Tallinna lahel, TTÜ Küberneetika Instituut
Juuni – juuli 2008	Välitingimustes väljaõpe laevalainete mõõtmiseks Tallinna lahel, TTÜ Küberneetika Instituut
Juuni – juuli 2008	Suvekool "Dynamics of coastal zone of non-tidal seas", Baltiisk, Venemaa
Juuni 2008	Rahvusvaheline suvekool: keskkonna dünaamika, kliima-muutuste mõjutegurid ja globaalsed mustrid Veneetsia, Itaalia
August – september 2007	Rahvusvahelise suvekool "Lained ja rannikuprotsessid", TTÜ
Aprill – september 2006	Välitingimustes väljaõpe veetaseme ja setete transpordi mõõdistuste alal, Soome lahe idaosa, Venemaa

6. Teenistuskäik

Töötamise aeg	Tööandja	Ametikoht
2008 – praeguseni	TTÜ Küberneetika Instituut	Erakorraline teadur

2006 – praeguseni (leping peatatud)	A.P. Karpinsky nim. Venemaa Geoloogiliste Uuringute Instituut, Sankt-Peterburg	insener

7. Teadustegevus

Konverentsiettekanded

VII Läänemere mereteaduse kongress, 17–21 august 2009, Tallinn, suuline ettekanne “Submarine terraces of the Eastern Gulf of Finland: results of survey and reconstruction of evolution in Holocene” ja poster “Variability in wake properties of long waves generated by high-speed ferries” (2009).

Rahvusvaheline konverents “Construction of the Artificial Lands in the Coastal and Offshore Areas”, 20–25 juuni 2009, Novosibirsk, Venemaa, suuline ettekanne: “Variability in wake properties generated by high-speed ferries in Tallinn Bay” (2009).

X rahvusvaheline rannikuteaduse sümpoosium (ICS’09), 13–18 aprill, 2009 Lissabon, Portugal, suuline ettekanne: “Variability in the properties of wakes generated by high-speed ferries” (2009).

XL rahvusvaheline konverents “Control Processes and Stability 09” (CPS’09), 6–9 aprill 2009, St. Petersburg, Venemaa, suuline ettekanne: “Изучение свойств судовых волн в Таллинском заливе” (vene keeles) (2009).

Marie Curie võrgustiku SEAMOCS koosolek ja teaduskonverents konstruktsioonide väsimuse alal, 22–25 oktoober 2008, Oslo, Norra, suuline ettekanne: “Variability in wake properties generated by high-speed ferries” (2008).

III rahvusvaheline üliõpilaskonverents “Biodiversity and Functioning of Aquatic Ecosystems in the Baltic Sea Region”, 9–12 oktoober 2008, Juodkrante, Leedu, suuline ettekanne: “Coastal processes in the Gulf of Finland” (2008).

Rahvusvaheline kool-konverents “Dynamics of Coastal Zone of Non-tidal Seas”, 30 juuni – 4 juuli 2008, Baltiisk, Venemaa, poster “The litho-dynamic modelling for the coastal zone of the Gulf of Finland, Kurortny area, St. Petersburg” (2008).

XXXVIII rahvusvaheline konverents “Control Processes and Stability” (CPS’07), 9–12 aprill 2007, St. Petersburg, Venemaa, suuline ettekanne: “Разработка методики определения участков аккумуляции и размыва береговой зоны на основе факторного анализа” (vene keeles) (2007).

XXXVII rahvusvaheline konverents “Control Processes and Stability”, 10–13 aprill 2006, St. Petersburg, Venemaa, suuline ettekanne: “Problem setting for litho-dynamic modelling” (2006).

VII rahvusvaheline ökoloogia seminar “The Baltic Sea Day”, 22–23 märts 2006, St. Petersburg, Venemaa, suuline ettekanne: “Geological hazards in the Gulf of Finland” (2006).

XXXV rahvusvaheline konverents “Control Processes and Stability”, 14–16 aprill 2004, St. Petersburg, Venemaa, suuline ettekanne: “Statistical data processing for fiber-optic line installation in Arctic” (2004).

Artiklid, mis on indekseeritud ISI Web of Science andmebaasis (1.1)

Valdmann, A., Käärd, A., Kelpšaitė, L., Kurennoy, D., Soomere, T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. Baltica 21/1-2, 3–12.

Didenkulova, I., Parnell, K. E., Soomere, T., Pelinovsky, E., Kurennoy, D. 2009. Shoaling and runup of long waves induced by high-speed ferries in Tallinn Bay. Journal of Coastal Research, Special Issue 56/I, 491–495.

Kurennoy, D., Soomere, T., Parnell, K. E. 2009. Variability in the properties of wakes generated by high-speed ferries. Journal of Coastal Research, Special Issue 56/I, 519–523.

Zhamoida, V. A., Ryabchuk, D. V., Kropatchev, Y. P., Kurennoy, D., Boldyrev, V. L., Sivkov, V. V. 2009. Recent sedimentation processes in the coastal zone of the Curonian Spit (Kaliningrad region, Baltic Sea). Zeitschrift der Deutschen Gesellschaft für Geowissenschaften 160/2, 143–157.

Leont’yev, I. O., Ryabchuk, D. V., Spiridonov, M. A., Kurennoy, D. 2009. Coastal profile in the Eastern Gulf of Finland: Results of survey and reconstruction of evolution in the Later Holocene, esitatud avaldamiseks ajakirja Oceanology (Moskva, vene keeles).

Artiklid muudes rahvusvahelise levikuga eelretsenseeritud teaduslikes ajakirjades (1.2)

Kurennoy, D., Didenkulova, I., Soomere, T. 2009. On the crest–trough asymmetry of waves generated by high-speed ferries. Estonian Journal of Engineering 15/3, 182–195.

Parnell, K. E., Delpeche, N., Didenkulova, I., Dolphin, T., Erm, A., Kask, A., Kelpšaitė, L., Kurennoy, D., Quak, E., Räämet, A., Soomere, T., Terentjeva, A., Torsvik, T., Zaitseva-Pärnaste, I. 2008. Far-field vessel wakes in Tallinn Bay. Estonian Journal of Engineering 14/4, 273–302.

Avaldatud konverentsiettekannete tekstid (3.4)

Куренной, Д., Соомере, Т. 2009. Измерение судовых волн в Таллиннском заливе. Труды международной конференции “Литодинамика контактной зоны океана”, 14–17 september 2009, Moskva (trükkimisel, vene keeles).

Ryabchuk, D., Sukhacheva, L., Lukyanov, S., Spiridonov, M., Pnuyshkov, A., Nesterova, E., Kurennoy, D. 2009. The history of development and the recent coastal zone geological processes for the Saint-Petersburg Curortny region. Proceedings of RSHU (trükkimisel, vene keeles).

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8. Kaitstud lõputööd ja väitekirjad

Magistritöö "Statistical data processing for fiber-optic line installation in Arctic" (2004).

9. Teadustöö põhisuunad

Lainete eksperimentaalne uurimine, lainete statistika, andmetöötlus, lained rannikuvööndis, kiirlaevalained, tuulelained, settetransport.

10. Teised uurimisprojektid

Jaanuar – märts 2008	Kaubasadama planeeringu eeluuringud, Benti, Guinea
Mai – juuli 2007	Vene-Jaapani merealuse optilise kaabli paigaldamise eeluuringud, Kaug-Ida, Venemaa
September – oktoober 2006	Naftaplatvormi eeluuringud, Barentsi meri, Venemaa
November – detsember 2005	Tatari väina merealuse optilise kaabli paigaldamise eeluuringud, Kaug-Ida, Venemaa
Detsember 2004 – jaanuar 2005	Õliterminaali planeeringu eeluuringud, Soome lath, Venemaa
Mai – juuli 2004	Õliterminali planeeringu eeluuringud, Kaspia meri, Ekerem, Turkmeenia
Juuli – september 2003; August – oktoober 2002	Merealuse optilise kaabli POLARNET planeeringu eeluuringud, Kirkenes (Norra) – Nome (USA)

11. Honours and awards

Marie Curie stipendiaat (SEAMOCS, TTÜ Küberneetika Instituut, 2008–2009).

Paper I

Valdmann, A., Käärd, A., Kelpšaitė, L., Kurennoy, D. and Soomere, T. 2008. Marine coastal hazards for the eastern coasts of the Baltic Sea. Baltica 21/1-2, 3–12.

Paper II

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Paper III

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Paper IV

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Paper V

Kurennoy, D., Didenkulova, I. and Soomere, T. 2009. On the crest-trough asymmetry of waves generated by high-speed ferries. Estonian Journal of Engineering 15/3, 182–195.

DISSERTATIONS DEFENDED AT TALLINN UNIVERSITY OF TECHNOLOGY ON *CIVIL ENGINEERING*

1. **Heino Mölder**. Cycle of investigations to improve the efficiency and reliability of activated sludge process in sewage treatment plants. 1992.

2. **Stellian Grabko**. Structure and properties of oil-shale Portland cement concrete. 1993.

3. **Kent Arvidsson**. Analysis of interacting systems of shear walls, coupled shear walls and frames in multi-storey buildings. 1996.

4. **Andrus Aavik**. Methodical basis for the evaluation of pavement structural strength in Estonian Pavement Management System (EPMS). 2003.

5. **Priit Vilba**. Unstiffened welded thin-walled metal girder under uniform loading. 2003.

6. **Irene Lill.** Evaluation of Labour Management Strategies in Construction. 2004.

7. **Juhan Idnurm**. Discrete analysis of cable-supported bridges. 2004.

8. **Arvo Iital**. Monitoring of Surface Water Quality in Small Agricultural Watersheds. Methodology and optimization of monitoring network. 2005.

9. **Liis Sipelgas**. Application of satellite data for monitoring the marine environment. 2006.

10. **Ott Koppel**. Infrastruktuuri arvestus vertikaalselt integreeritud raudtee-ettevõtja korral: hinnakujunduse aspekt (Eesti peamise raudtee-ettevõtja näitel). 2006.

11. **Targo Kalamees**. Hygrothermal criteria for design and simulation of buildings. 2006.

12. **Raido Puust**. Probabilistic leak detection in pipe networks using the SCEM-UA algorithm. 2007.

13. **Sergei Zub**. Combined treatment of sulfate-rich molasses wastewater from yeast industry. Technology optimization. 2007.

14. **Alvina Reihan**. Analysis of long-term river runoff trends and climate change impact on water resources in Estonia. 2008.

15. **Ain Valdmann**. On the coastal zone management of the city of Tallinn under natural and anthropogenic pressure. 2008.

16. **Ira Didenkulova**. Long wave dynamics in the coastal zone. 2008.

17. **Alvar Toode**. DHW consumption, consumption profiles and their influence on dimensioning of a district heating network. 2008.

18. **Annely Kuu**. Biological diversity of agricultural soils in Estonia. 2008.

19. **Andres Tolli**. Hiina konteinerveod läbi Eesti Venemaale ja Hiinasse tagasisaadetavate tühjade konteinerite arvu vähendamise võimalused. 2008.

20. **Heiki Onton**. Investigation of the causes of deterioration of old reinforced concrete constructions and possibilities of their restoration. 2008.

21. **Harri Moora**. Life cycle assessment as a decision support tool for system optimisation – the case of waste management in Estonia. 2009.

22. **Andres Kask**. Lithohydrodynamic processes in the Tallinn Bay area. 2009.

23. **Loreta Kelpšaitė**. Changing properties of wind waves and vessel wakes on the eastern coast of the Baltic Sea. 2009.