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# Far-field vessel wakes in Tallinn Bay

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**Abstract.** The properties of wave fields induced by high-speed ferries and recently introduced conventional ferries with increased cruise speeds are analysed for a site in Tallinn Bay, the Gulf of Finland, the Baltic Sea, located about 3 km from the sailing line and up to 8 km from the wave production area. The analysis is based on high-resolution profiling of the water surface for about 650 wakes from fast ferries, measured during 4 weeks in June–July 2008. The new large conventional ferries with cruise speeds of 25–30 knots (~45–55 km/h) sail at near-critical speeds along extensive sections of eastern Tallinn Bay, and excite wakes equivalent to those of high-speed ferries. The peak periods of these wakes are between 10 and 13 s. The typical daily highest ship wave is approximately 1.2 m, measured prior to wake breaking. The largest recorded ship wave in calm conditions had a height of 1.5 m and in the presence of some wind wave background 1.7 m. The cumulative impact of ship wakes results in a gradual increase in the suspended matter concentration in near-bottom water over the course of a day. The largest and longest ship waves produce considerable wave runup at the coast and prevent several coastal sections from achieving an equilibrium state. The largest ship waves have an asymmetric shape both in terms of the water surface elevation above and below the mean level and in terms of the shape of the wave front and back. The overall intensity of anthropogenic waves has remained at the same level as it was in the year 2002, although the ships that produced the highest waves in the past are no longer in service.

**Key words:** ship wakes, fast ferries, Gulf of Finland, Tallinn Bay, wave measurements.

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## 1. INTRODUCTION

The importance of the contribution of ship traffic to the local hydrodynamic activity in confined waters has been recognized for a long time. Heavy ship traffic has the potential to cause environmental damage in the vicinity of vulnerable areas such as wetlands or low-energy coasts where wake-waves can cause extensive shoreline erosion, resuspend bottom sediments, trigger ecological disturbance and harm the aquatic wildlife [1–3].

The hydrodynamic influence of ship traffic on the marine and coastal environment is usually negligible in areas of high natural wave energy 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 and result in harmful algae blooms by causing the transport of nutrients from sediments into the euphotic layer [4], the enhanced resuspension of fine sediments and changes to the coastal processes in areas affected by ship wakes [1,3,5–7], and the direct impact on fish [8] and marine mammals [9]. Several aspects of the impact of ship traffic have been extensively studied in the Åland archipelago, the Baltic Sea, over several decades [10–13].

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 first identified a few years ago for several sections of Tallinn Bay [14,15]. This area is characterized by an overall mild, but largely intermittent, wave regime. While the annual mean significant wave height $H_s$ is well below 0.5 m, rough seas with $H_s$ exceeding 3–4 m occasionally occur in the inner sections of the bay. The daily highest ship waves (with a typical height of slightly over 1 m) are equivalent to the annual highest 1%–5% of wind-generated waves. Ship traffic is so intense that ship-generated waves contribute, 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 are exposed to dominant winds [16].

While the local influence of intense ship traffic on the water column and sediments has been 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, kilometres from the vessel track [14,16,17]. In areas of generally low natural waves, comparatively massive amounts of energy, released far from the sailing line a long time after the ship has passed, can be spectacular, but can also be a danger to lives and result in unusually high hydrodynamic loads in the marine environment [18,19]. The breaking of long ship waves, coming from atypical directions, may be responsible, for example, for drastic thermal changes in shallow inlets several kilometres away from the fairway [20] and even in the open sea [21]. The breaking of unexpectedly high wave humps (formed in the process of interaction of an incoming and reflected ship wave, or during crossing of two ship wave systems) can be a significant human hazard in shallow water [22].

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 [3] and Washington State, USA), or there have been significant speed limits introduced for sensitive sections of the vessel routes (for example, in New Zealand [23], Finland and Sweden). In other places, there have been attempts to optimize vessel operation or encourage operation in water depths (normally deeper water) that avoid critical[1] speeds [24]. New generations of vessels with ship hulls carefully optimized to reduce the wave resistance (and therefore the height of ship-induced waves) at specific speeds, have entered into service.

There have been significant changes in the types of vessels operating in the traditional ‘fast-ferry’ market on the route between Tallinn (Estonia) and Helsinki (Finland) and elsewhere in the world. Firstly, the vessels that produced very dangerous and damaging waves (for example, the largest of the high-speed catamarans sailing between Tallinn and Helsinki in the late 1990s and early 2000s, which produced the highest waves [14]) have been taken out of service. Secondly, a new generation of high-powered conventional ferries with service speeds 25–30 knots (~45–55 km/h, see Table 1 below) has replaced the older conventional ferries that sailed at 15–20 knots (~25–35 km/h). Thirdly, the small hydrofoils have been replaced by much larger ships. As sailing lines have remained largely unchanged and no limitations have been imposed on the speed, the new ships may operate at near-critical speeds in areas where older ships were clearly subcritical. With these changes, the number of large vessels that are able to travel at near-critical speeds has almost doubled in Tallinn Bay since about the year 2000. The properties of the wakes of these vessels are largely unknown. Although earlier studies have indicated or hypothesized that ship wakes may serve as a major driver of sediment transport at certain depths [5] and directly or indirectly impact the coastal processes near the waterline [6,16,17,25], almost no unambiguous evidence exists about the behaviour and impact of ship wakes on realistic medium- or high-energy coasts.

The main aim of this study is to provide a brief overview of experiments undertaken in Tallinn Bay in the spring and summer of 2008 in order to (i) update the understanding of ship induced hydrodynamic activity in Tallinn Bay with respect to the new classes of ships that are now operating, and to

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[1] The characteristics of ship-generated waves are highly dependent on the depth Froude number $F_h = V/\sqrt{gh}$ where $V$ is the ship’s speed and $h$ is the water depth. The speed at which $F_h = 1$ is called critical. Subcritical speeds are characterized by $F_h < 1$ and supercritical speeds by $F_h > 1$. The near-critical regime corresponds to the vessel speed within ± 15% of the maximum phase speed $\sqrt{gh}$ of surface waves, or $0.84 < F_h < 1.16$.

**Table 1.** Ships operating the Tallinn-Helsinki ferry link in summer 2008. Data from www.tallink.ee, www.superseacat.com, www.eckeroline.ee, www.lindaliini.ee, and from the relevant ship operators. The displacement data for the hydrofoil and the conventional ferries are given in terms of net tonnage (NT) and gross tonnage (GT)

| Ship | Type | Departures, daily per direction | Length, m | Width, m | Draught, m | Displacement light, t | Displacement loaded, t | Operating speed*, knots |
|---|---|---|---|---|---|---|---|---|
| | | | | High-speed ferries | | | | |
| *SuperSeaCat* (2 ships) | Monohull | 6 | 100.3 | 17.1 | 2.6 + 1.4 | 900 | 1296 | 35/40 |
| *Baltic Jet*, *Nordic Jet*** | Catamaran | 3–6 | 60 | 16.5 | 2.22 | 515 | 635 | 36/38 |
| | | Hydrofoil | | | | NT | GT | |
| *Merilin* | Twin hull hydrofoil | 3 | 52.6 | 13 | 1.51 | 299 | 963 | 40 |
| | | | | Conventional ferries with increased cruise speed | | | | |
| *Star**** | Monohull | 5 | 186.1 | 27.7 | 6.75 | 13 316 | 36 249 | 27.5 |
| *Superstar**** | Monohull | | 176.9 | 27.6 | 7.1 | 14 073 | 36 277 | 27.5 |
| *Viking XPRS* | Monohull | 2 | 185 | 27.7 | 6.55 | 14 165 | 35 778 | 25 |
| *Superfast***** | Monohull | 1 | 203.3 | 25 | 6.5–6.67 | 10 703–10 793 | 30 285–30 441 | 25.5–27.1/30.4 |
| | | | | Conventional ferries | | | | |
| *Norlandia* (Eckerö Line) | Monohull | 1 | 153.4 | 24.7 | 5.8 | | 14 990 | 20 |
| *Baltic Princess* (Tallink) | Monohull | 1 | 212.1 | 29 | 6.4 | 30 860 | 48 915 | 24.5 |

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* Cruise/maximum speed, if given.

** *Nordic Jet* was moved to another service from 21 July 2008.

*** *Star* and *Superstar* are sister ships, and operate on alternating schedules each day.

**** Three sister ships in the family, typically travelling at speeds ~20 knots (~35 km/h) near the measurement site.

(ii) re-assess the properties and overall changes of the wake wave climate in this bay based on systematic measurements over a longer time interval. A novel aspect of this study is an attempt to relate the properties of measured ship waves before significant shoaling to their character and the resulting runup at the shoreline.

The paper is organized as follows. The environment of Tallinn Bay, the reasons for the choice of the experiment site and the details of the fast ferry operations are described in Section 2. The experimental setup at the Island of Aegna in spring and summer 2008 and the basic geological and morphological features of the site are discussed in Section 3. The procedure of recording and analysis of the wake parameters and the typical and extreme features of wakes of individual ships are described in Section 4. Section 5 contains an analysis of the properties of the wave fields extracted from the water surface time series (such as an estimate of the daily maximum ship wave height and the shape of the energy spectrum of ship wakes) and from typical daily and average characteristics of the ship-induced waves. This is followed by a discussion of the results and an indication of further studies in Section 6.

## 2. WIND WAVES AND SHIP WAKES IN TALLINN BAY

Tallinn Bay is a semi-enclosed body of water, 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. 1), an elongated sub-basin of the Baltic Sea. The overall hydrodynamic activity is fairly limited in this almost tideless area. 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. 1.** The Baltic Sea and Tallinn Bay.

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 [26]. Bottom refraction at the mouth of the Gulf of Finland may cause waves to enter the gulf under some circumstances [27]. 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). 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 fetch length of the order of 100 km and thus only produce waves with relatively short periods. These features severely limit the periods of the wave components. The peak periods of wind waves are usually well below 3 s, reaching 4–6 s in strong storms and only in exceptional cases do they exceed 7–8 s [28].

As a result of these factors, the local wave climate is relatively mild in Tallinn Bay compared with 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% [28]. 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 coast of Tallinn Bay has preserved features indicative of periods of intense erosion [29,30] and as such it can be considered to be a medium- or high-energy coastal environment.

The sea area between Tallinn and Helsinki is one of the most intense ship traffic regions in the world with about 65 000 ship crossings annually. Tallinn Bay is one of the few places in the world where high-speed ferries continue to operate at, or close to, service speeds close to the shoreline. High-speed (fast) ferries are interpreted here as the vessels, the regular sailing regime of which contains extensive sections with the depth Froude number $F_h = V\big/\sqrt{gh} > 0.6$. When this threshold is exceeded, the classical, linear Kelvin wave system is modified and specific, non-linear components of wakes frequently exist [31,32].

During the high (summer) season, the number of passenger ferries and hydrofoils, servicing the Tallinn-Helsinki route cumulatively traversing Tallinn Bay, was up to 70 per day around the year 2000 [15]. 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 [14]. There was only one monohull high-speed ship, 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 low Froude numbers was about 20 per day.

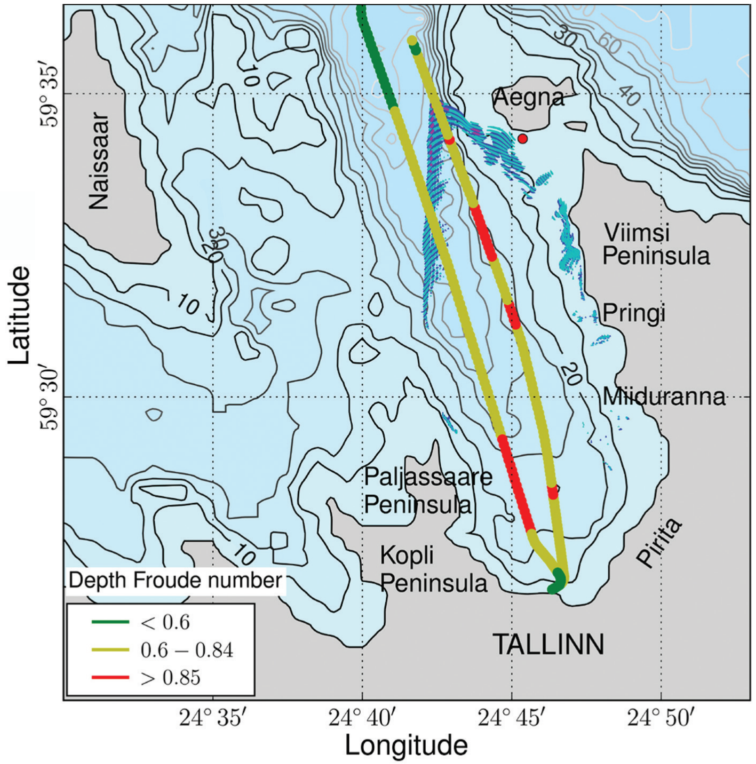

**Fig. 2.** The recorded sailing line and depth Froude number of *SuperSeaCat* on 29–30 June 2008. The eastern track is used by outgoing ships and the western track by incoming ships. A simulation using COULWAVE shows wake-waves at a single point [37], where contour lines are drawn at –0.25 m (blue), 0.25 m (cyan), and 0.75 (magenta).

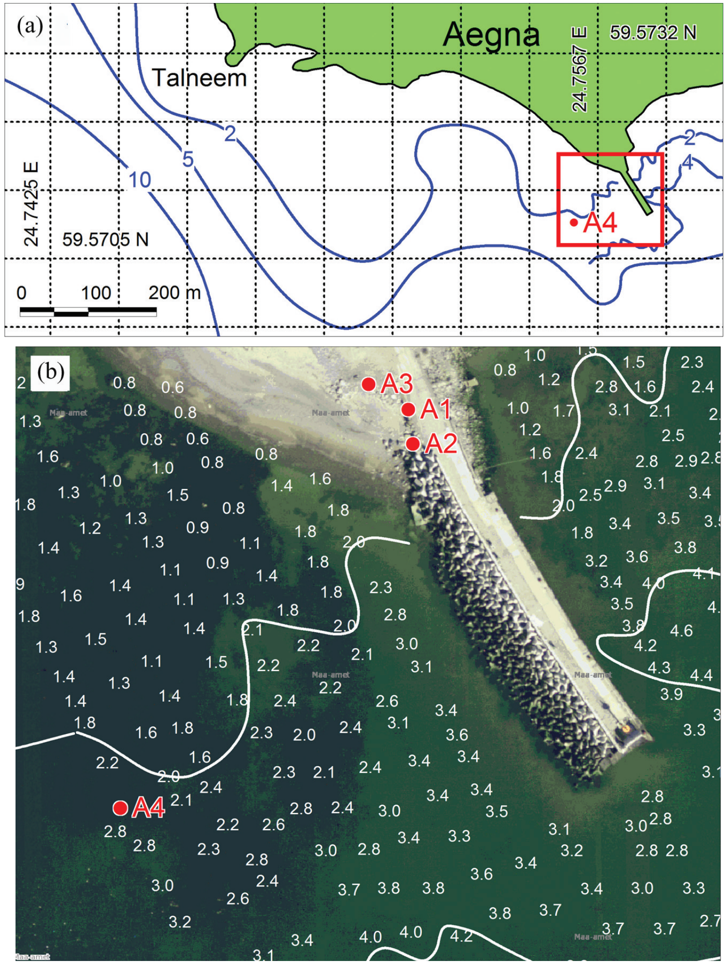

**Fig. 5.** (a) The SW coast of Aegna; (b) Water depths around Aegna jetty showing the location of: the video camera (A1), rangefinder (A2), runup measurements (A3), and tripod (A4).

**Fig. 6.** (a) The SW coast of Aegna: view from Talneem towards the jetty and the study area; (b) the SW coast of Aegna showing a mixed sand and gravel beach; (c) the beach immediately adjacent to the jetty after a period of fine sediment removal caused by ship wakes; the measuring staff is used for runup experiments; (d) the echosounder mounted on the tripod (prior to a 1 m extension being fitted).

The structure of the fleet has changed considerably in the last five years. The largest catamarans *AutoExpress* are not in operation any more. The fleet now consists of a range of vessel types (Table 1). There are two high-speed monohulls (*SuperSeaCat*, until 2006 operated by Silja Line, since then by SeaContainers, operating speed ~65 km/h), and two medium-sized twin hull vessels (*Nordic Jet* and *Baltic Jet*, operating speeds ~60 km/h) which have been used on the route for several years. Small monohull hydrofoils have been replaced by a twin-hull hydrofoil *Merilin*, operated by Linda Line.

The number of conventional ferries (operating at speeds at or below ~30 km/h) has decreased considerably. The biggest change is the introduction of several vessels of a new class of large, mostly conventional ships operating at relatively high speeds (~50 km/h). During this experiment, the vessels operating were *Star*, *Superstar*, and *Superfast* (Tallink), and *Viking XPRS*.

The total number of departures of passenger ships from Tallinn to Helsinki was 22–25 per day in summer 2008 (Table 1, Fig. 3). 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. However, the number of departures of large ships occasionally entering the near-critical regime has almost doubled.

The basic properties of the waves of the largest ships, sailing at speeds below critical, can be adequately estimated with the use of the classical theory of Kelvin wakes. The largest waves usually occur at the border of the Kelvin wedge. Their period

$$T = 2\pi V g^{-1}\sqrt{\frac{1+\sin\alpha}{2}}, \tag{1}$$

increases linearly with the increase in the ship speed $V$. Here, $\alpha$ is the apex half-angle of the Kelvin wedge (that also reflects the dependence of the wake system

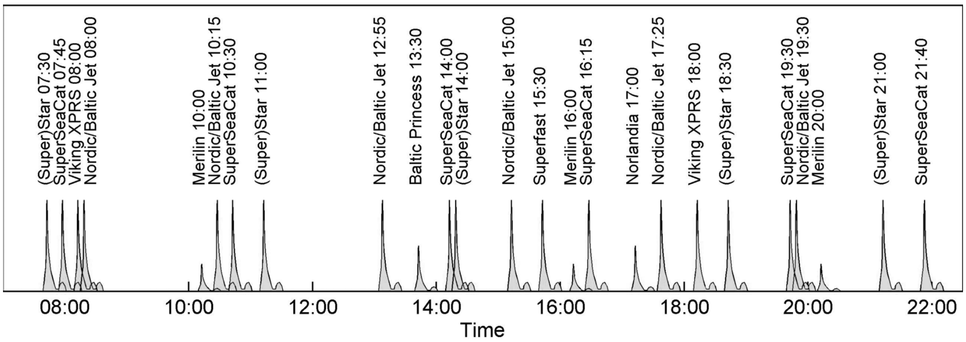

**Fig. 3.** Scheme of the timing, duration and relative height of wakes arriving at the study site, generated by passenger ships travelling from Tallinn to Helsinki on weekdays in June–July 2008 according to the schedule (www.webmarine.ee).

on the water depth), $V$ is the ship speed and $g$ is the acceleration due to gravity [31,32]. In deep water, $\sin\alpha = 1/3$ and Eq. (1) is approximately

$$T = \frac{4\pi}{\sqrt{6}g} V \cong 0.523V, \tag{2}$$

where the proportionality coefficient has the dimension of $s^2$/m. From Eq. (2) it follows that the periods of the largest waves, excited by ships sailing faster than 6 m/s (~20 km/h or ~12 knots), exceed the typical periods of wind waves in Tallinn Bay. Periods of waves of ships, sailing over 12 m/s (~45 km/h or ~24 knots), match those of wind waves in strong storms whereas ships sailing faster than about 50 km/h may excite waves of periods that are extremely seldom found under natural conditions in Tallinn Bay, even if they sail at low depth Froude numbers over the deepest part of the bay. This estimate is slightly modified in water of finite depth $h$, where the Kelvin wake apex half-angle is

$$\sin\alpha = (1+Q)/(3-Q), \tag{3}$$

$$Q = 2kh/\sinh(2kh), \tag{4}$$

where $k$ is the wave number and the product $kh$ is determined from the transcendental equation [31]

$$(3-Q)\tan(kh) = 2khF_h^2. \tag{5}$$

The relevant corrections to Eqs. (1), (2) are of the order of a few per cent unless the depth Froude number reaches about 0.95 [33,34].

For much of the time ships in Tallinn Bay operate in the so-called low speed sub-critical regime $(F_h < 0.84)$. However, there are sections both on the inbound and outbound tracks where many of the vessels travel in the near-critical regime. The depth Froude number exceeds 0.84 in some places for all tracked ships (Figs. 2, 4). At these speeds, ships tend to generate packets of large, solitonic, very long and long-crested waves [24,31]. The periods of the leading waves, excited at near-critical speeds, may be much larger than those of conventional ferries or vessels travelling at even slightly slower speeds [34].

Another important parameter of the sailing regime is the length Froude number $F_L = V/\sqrt{gL}$, where $L$ is usually interpreted as the length of the ship waterline. A specific regime called hump speed occurs when the wavelength of transverse Kelvin waves, propagating along the sailing line, is about twice the ship's length $2L$. This happens when $F_{Lhump} = 1/\sqrt{\pi} \cong 0.56$. Sailing at this speed means that the ship is continuously moving 'upwards' along the slope of its own wake. Wave resistance is usually relatively high for $0.4 < F_L < 0.6$ and increases fast when $F_L \to \pi^{-1/2}$. The increase is particularly significant in shallow water conditions [31]. Approaching either the critical speed or the hump speed is commonly accompanied by a drastic increase of wave resistance, or equivalently, released wave energy. The highest waves eventually occur when the hump and the critical speed coincide [24,31]. For the ships operating in Tallinn

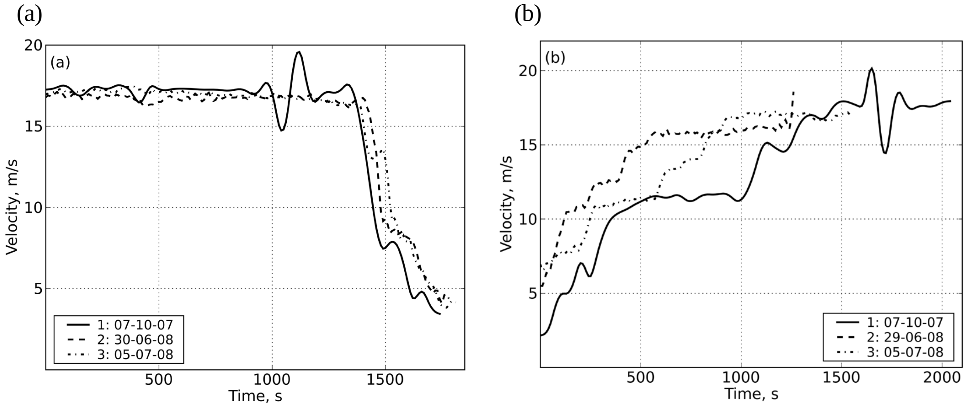

**Fig. 4.** Ship velocity along three recorded ship tracks in Tallinn Bay: (a) for the incoming leg; (b) for the outgoing leg. The zero point is the first GPS record point along the leg used for the simulation (59.448°N for the incoming simulations; 59.670°N for the outgoing simulations).

Bay (Table 1), the *SuperSeaCats* operate near the upper limit of the length-based range of generation of high waves. *Baltic Jet* and *Nordic Jet*, and *Merilin* operate in the range of $F_L$ about $0.8–0.9$, whereas the conventional-hulled ships operate with $F_L < 0.35$.

The observed periods of the highest vessel waves are up to $T \cong 15$ s in Tallinn Bay [14], much larger than the wave periods of 3–8 s typically found for conventional ship wakes or for wind-generated waves in this sheltered body of water [28]. The high peak period of these ship waves is the main reason for the large difference between the shares of ship-induced and wind-wave generated waves in the annual mean wave energy and power (5%–8% versus 18%–35%, respectively [16]). Wind waves, similar to the leading ship waves (with a height of about 1 m and a period exceeding 10 s), occur very infrequently in this semi-sheltered bay, and for this reason ship wakes form a qualitatively new component of marine hydrodynamic activity in this environment [16].

The typical ship tracks in Tallinn Bay were determined based on the information from the sailing directions [35] and verified by means of direct GPS-measurements onboard several randomly chosen ships (Fig. 2). A total of eight track records have been collected, six of which contain enough data to reconstruct the ship position and velocity along the entire length of the bay. The three incoming leg records are in fairly good agreement, whereas significant differences appear for the three outgoing leg records in terms of location of the track and the speed of the ship along the track (Fig. 4).

Ships, proceeding towards Tallinn, mostly sail along a deep trench in the section between the islands of Aegna and Naissaar (Fig. 2). The most sensitive section of the incoming leg is located at the southern end of the trench at a distance of 2–4 km from the port, where operation in the supercritical regime (defined as sailing at the depth Froude numbers larger than 1) is possible. The near- and supercritical wakes mostly impact the southern coast of the bay, extending from the Kopli and Paljassaare peninsulas to Pirita [34]. Some fairly large waves may also reach the southern end of Naissaar.

Vessels, departing from Tallinn towards Helsinki, sail along the eastern slope of the trench, where they may frequently enter the near-critical regime (Fig. 2). The slope causes asymmetry of the wake system [36]. Detailed simulations of wake patterns have been made based on a recorded *SuperSeaCat* sailing to Helsinki on 29 June 2008, using the long wave model COULWAVE. This extension of previous work [34] takes full advantage of the parallelization of the model that enables us to include the entire Tallinn Bay area in the computational domain. In contrast to the results presented in [36], a larger wedge apex angle appears at the right-hand side of the wave fan in the relatively shallow area [37].

The southern part of the Viimsi Peninsula receives relatively little wake-wave energy from outbound ships because of the finite extension of the wave fan. The highest waves for ships on the outgoing leg are generated at the SW and W coast of Aegna. Some locations along the Viimsi Peninsula (Pringi Jetty and to the north of Miiduranna) also receive fairly large waves. Ship travel direction varies to a degree and this results in significant spatial variability in the important ship wake parameters [37]. However, intense wakes from outbound ships reach the SW shore of Aegna in most cases. Details of the relevant research and comparisons between measured and simulated wave properties can be found in [37].

## 3. STUDY SITE, EXPERIMENTAL SET-UP AND OBSERVATIONS AT THE COAST

The northern Viimsi Peninsula and the WSW end of Aegna are protected by very shallow waters. No such protection exists adjacent to Aegna jetty on the SW coast of the island. The SW coast of Aegna and the isobaths in its vicinity are predominantly (albeit not perfectly) oriented perpendicular to the ship wave rays (Fig. 5) and it is therefore a suitable place for measurements of both ship wave parameters in the nearshore and wave-induced impact on the coast (including wave runup patterns). This area has also been an object of several previous studies [5,14].

The measurement site was located on the SW coast of Aegna, at a small mixed gravel-sand beach immediately west of the jetty (Figs. 5, 6b,c, 59°34′50″N, 24°45′28″E). The island, about 1.5 × 2 km in size, is located 1.5 km north of the Viimsi Peninsula, at the northern entrance of Tallinn Bay. It is separated from the Viimsi Peninsula by a shallow-water (typical depth 1–1.5 m) channel with two small islands. Effectively, no wave energy enters Tallinn Bay from the east.

The study site for this research was determined using two criteria. The site had to be mostly open to the ship wakes and the slope in the immediate vicinity of the shoreline and beachface had to be approximately linear in order to adequately record the runup height. These conditions excluded the western coast of Aegna, the southern section of which has a significant scarp near the waterline, and the northern section of which is sheltered by an area of boulders in the nearshore.

The experimental site is fully open to the south. The maximum fetch length in this direction, however, is only some 10 km. Although the majority of storms blow from the SW, they produce no large waves. Moreover, these waves approach the shore perpendicularly and result in negligible longshore sediment transport. Owing to their small lengths, they only affect sediments at the coastline and in very shallow water. Significant wave energy enters Tallinn Bay from the north but the study site is sheltered from these waves by the island and shallow water about 300 m to the west. The most significant waves at the study site and along the adjacent shore to the west, come from the west, entering Tallinn Bay between the mainland and the Island of Naissaar. Waves from the NW are effectively blocked by Talneem Point (the WSW end of Aegna, Fig. 5) and even if they reach the SW coast owing to refraction, they impact the coast in a way similar to waves approaching from the west. The western side of the jetty is protected by tetrapods which effectively damp wave energy so that there is no visible reflection of wave energy back to the study beach.

The littoral drift, therefore, is from west to east. Along the shoreline to the west of the study site there is an evident sediment deficit (Fig. 6a) and coastal erosion [30]. Long-term accretion occurs only in a short section immediately adjacent to the jetty, where the beach is much wider (up to 25 m, Fig. 6b) than along the rest of the SW coast. This deposit consists of a relatively thin coating of finer sediment, with cobbles and boulders (~20–50 cm in diameter) permanently visible (Fig. 6c), indicating that the beach immediately adjacent to the jetty is not currently accreting.

A belt of boulders at water depth of 0.5–3 m, 50–150 m from the shoreline, is found between the jetty and Talneem. This belt occurs in other areas around Aegna, becoming visible when sea levels are low. The seabed at 2–4 m depth in the vicinity of the wave recording device comprises some cobbles and boulders (some >1 m height above the seabed), interspersed amongst sand and small gravel. While cobbles, pebbles and boulders dominate the rest of the beach and to depths of a few (usually 6–10) metres, the seabed in deeper waters (from 7 to at least 16 m) SW of Aegna comprises a relatively thin (usually 0.2–0.3 m) but almost continuous sheet of mixed finer sediments, dominated by sand (finer in deeper areas), with gravel sized sediment being less than 15% (decreasing with depth [38]), at times containing small pebbles, and overlying postglacial clay or till. Ripples on sand-covered areas at depths of 10–12 m indicate that wave activity regularly reaches these depths [30].

Towards Talneem from the study site, a very shallow area extends up to 300 m from the coast, seaward of which water depths increase over a short distance. In the vicinity of the jetty, water depths increase over a short distance to approximately 2 m (Fig. 5), beyond which there is a more or less linear slope from the position of the tripod down to depths of 6–8 m and a gently sloping terrace 0.5–1 km wide to about 15 m water depth. Beyond this is a steep slope on the edge of the trench referred to in Section 2 above.

The bathymetric variability causes significant differences in the nature of ship wakes reaching the SW shore of Aegna. At the western end of the coastal section, waves break at 100–300 m from the beach whereas in the immediate vicinity of the jetty they propagate to within a few tens of metres of the beach without breaking.

The Aegna study site is appropriate for this investigation as it receives significant wave energy from vessels that may be operating in the near-critical regime and the waves shoal and break at, or very near to, the shoreline, thus permitting measurement of the unbroken wave forms (including their shape and asymmetry) close to shore. The site also allows comparison of the runup with the unbroken wave characteristics, which is difficult on beaches where both broken and unbroken waves meet the beach face. Experiments performed in 2002–2006 used sub-surface pressure sensors, which were 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 be estimated only approximately. In the present study, approaching waves were measured by tracking sea-surface elevations of unbroken waves using an ultrasonic echosounder. We used a LOG_aLevel® device (General Acoustics), designed as a complete, stand-alone remote sensing water level gauge. The standard configuration was modified by adding a standard car battery and larger memory card, so that the system was able to operate without attention or external connections 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. According to the manufacturers, the systems needs no calibration or on-site maintenance. The typical time scale of factors, potentially affecting the reading of the device caused by changes of the local air density (such as temperature, humidity, barometric pressure, and salinity), are usually much longer (a few hours) than the duration of a single wake (15–20 min). Moreover, such changes in atmospheric conditions are accounted for internally using sound velocity compensation. The device was mounted on top of a heavy tripod (Fig. 6d), constructed and manufactured by AS Dimentio, Tallinn, at a location about 100 m from the shore and the southern end of the jetty (59°34.259′N, 24°45.363′E). The tripod legs were made of 60.3 × 2.6 mm zinc-coated steel tube. The total weight of the structure is about 150 kg. The legs were equipped with 20 cm long spikes that penetrate into the seabed sediments and prevent horizontal shift of the entire structure. Plates with a diameter of about 25 cm prevented the tripod’s legs from sinking deeper into soft sediments. The tripod was made more rigid by horizontal braces halfway up the legs. The device was mounted in an area with gently sloping gravel bottom so that the water depth at the location of the sensor (Fig. 6b) was approximately 2.6–2.7 m with respect to the long-term average sea level. In the essentially tideless Tallinn Bay, maximum water level variation over the experimental period was 37 cm (+30 cm on 25 June and –7 cm on 7 July).

During the first few days of measurements at Aegna, the ultrasonic transducer was mounted directly at the tripod apex at a distance of about 1.5 m from the calm water surface. The combined effect of relatively high water level at the end of June, intense ship waves and considerable wind wave background resulted in a too low clearance to the water surface. The system failed to adequately measure distances less than about 60 cm from the sensor, which led to underestimation of the largest elevations in measurements. This was corrected on 7 July by increasing the clearance between the sensor and the water surface by adding a 1 m high extension to the platform at the tripod apex.

The vessel(s) associated with a wake event were determined either from the operating schedules (Fig. 3) or by observation. When possible, a Newcon LRB 3000PRO Laser Range Finder was used to estimate the vessel speed and distance to the track. This binocular device is equipped with an eye-safe laser and FMC optics enabling ranging targets up to a distance of 3 km with a measurement accuracy of 1 m in good visibility. The distance and bearing to a fixed point on the vessel was measured on at least two occasions from the most landward tetrapod of the sea wall (59°34.301′N, 24°45.431′E) and from these data, speed and track were calculated. At times, due primarily to atmospheric conditions, the range finder did not operate.

Besides providing data to measure and understand the far-field wake events, and to fix the changes that have occurred since previous studies [5,14], a number of other experiments were conducted, the results of which will be reported elsewhere. These include (i) measurement of wave runup and its correlation with measurements made at the tripod, in order to empirically test the semi-analytical solutions derived in [39–42] and to identify a relationship between wave shape (primarily the asymmetry) and wave runup in realistic conditions of partially breaking waves, (ii) examination of the effect of wakes on bottom sediments using optical methods, extending the work described in [5,43], (iii) studies detailing the effect of the wave events on shoreline geomorphology [6,17,25], and (iv) numerical simulations of wave properties for typical ship tracks and the spatial variability of the ship wave patterns [34,37].

## 4. WAVE RECORDINGS

The surface water elevation data were collected almost continuously over 30 days during the period from 21 June to 20 July 2008 at a recording frequency of 5 Hz. The recording was only stopped for short time intervals (typically a few tens of minutes) for maintenance reasons on 26 June and on 2, 7 and 15 July. The total record contains more that 650 outbound wake events from fast ferries, about 400 of which can be adequately separated from the wind wave background and attributed to particular vessels, and several hundred distinguishable smaller wakes from other ships and vessels sailing to Tallinn.

The raw record from the water level gauge (Fig. 7) 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.

Single wakes (or groups of wakes) were separated manually from a spectrally filtered record (in which the long components of wakes from fast ferries were usually easily identifiable) and related to particular ships with the use of the timetable and visually recorded data. An attempt was made to separate each single wake and to specify a section of the record of pure background wind waves with a duration of 10–20 min adjacent to the wake in the record, if possible, 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.

A low-pass spectral filter (an elliptical filter in the Matlab environment) was adjusted as the occasion required in order to remove the wind wave background and to adequately define the start and end of the wake event. The wake event data were then adjusted to a mean of 0 and detrended. Approximately 6–10 waves in each wake were very high and long, with periods about 10 s or larger. Their shape was usually asymmetric (Fig. 8a).

A Matlab low-pass elliptic filter of 9th order with at most 0.1 dB passband ripple, 60 dB stopband attenuation, ±10% width of the cutoff band and 2.5 s cutoff frequency was used to remove most of the wind wave components from the recorded signal. As the proportion of wave components from fast ferries with periods less than 2.5 s is very small [14], such a filtering almost exactly conserves the energy of the wake. On the other hand, the majority of wind wave components on relatively calm days have periods below 2 s and are effectively removed from the signal.

The filtering process caused a certain phase shift of the wave forms and frequently led to unrealistic wave shapes with deep troughs and moderate elevations (Fig. 8b). This distortion is not unexpected, because similar effects are

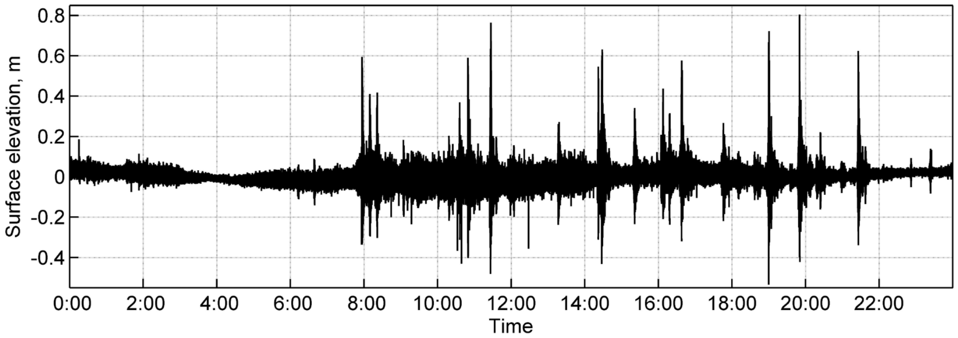

**Fig. 7.** The record of water level elevation on 8 July 2008 after adjustment of the transducer to a higher position (2.55 m above the mean water level of this day).

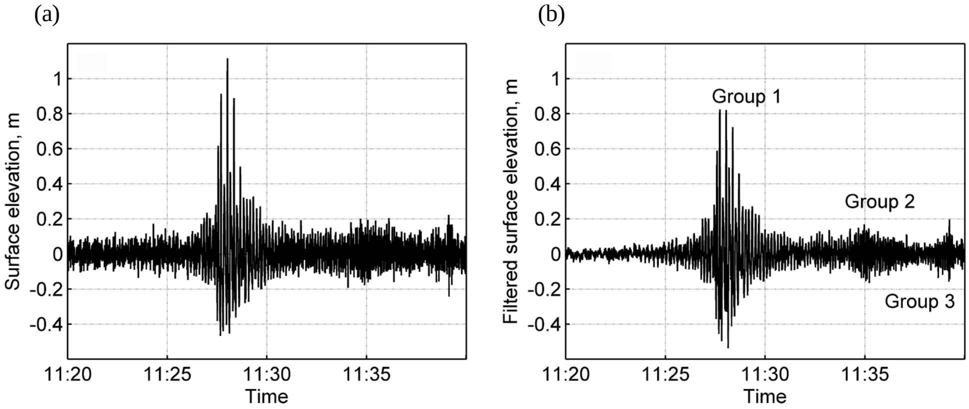

**Fig. 8.** The wake, created by *Star*/*Superstar* on 9 July 2008: (a) original recording; (b) low-pass filtered water level data with cut-off frequency 2.5 s.

customary in filtering of elevation data, derived from narrow wave groups, where the use of high-order filters result 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 the large phase shifts may cause substantial changes of the wave shape and (for phase shifts of the order of $\pi$) even an inversion of the wave shape. While 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 frequently gives 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 allows more exact determination of the end of the wake.

For the listed reasons, further analysis of each wake event was performed in parallel for the original recording and for the filtered signal. Single waves and their properties in each wake were extracted with the use of both zero-upcrossing and zero-downcrossing methods. To the first approximation, the maximum wave height is defined as the maximum of wave heights obtained by the zero-upcrossing and zero-downcrossing method. For the largest waves in each wake, this quantity almost always coincides with the maximum variation of the water surface within a 30 s interval.

The largest ship waves have, as expected, an asymmetric shape: the magnitude of the increase in water level above the mean at their crests considerably (in extreme cases up to three times) exceeds the magnitude of the decrease in the trough area (Fig. 9). This feature is probably caused by non-linear effects, the influence of which usually tends to reshape the wave profile so that it resembles a cnoidal wave [44]. In many cases, the high, asymmetric waves were interspersed with much lower waves of the same period, as noted in [45].

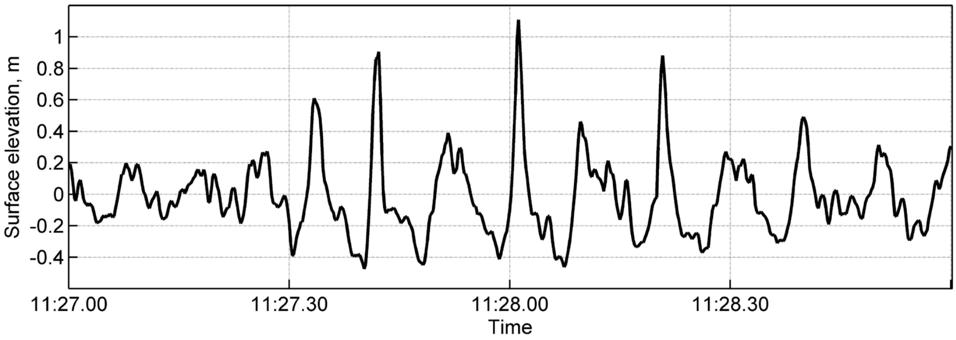

**Fig. 9.** The shape of water surface for relatively large waves created by *SuperStar* on 9 July 2008. The dominant period is about 10 s, as is typical for this ship. The significant wave height of the wind wave background is below 10 cm.

The shape of the largest waves was frequently strongly asymmetric in another sense also. The front of the wave was much steeper than the back. This is also an expected feature, however, in our experiment it was not clear beforehand whether it simply reflected the effects of shoaling in the shallow nearshore, or whether it was partially caused by the process of non-linear steepening of long waves over a horizontal bottom. The observed asymmetry is almost certainly one of the reasons why waves within ship wake events produce higher runup than one might expect based on the wave height data alone. This feature of long waves has been predicted in [41,42].

The energy of each wake was also calculated from both the original and filtered water level data. The difference between the results was compared with the energy of the background waves in order to estimate the adequacy of the method of separation of the wake events. Finally, the wave power was calculated for each wake by means of summing the power, carried by each wave for the given water depth.

As during most of the measurements there was considerable wind-wave background, the wake separation process usually allowed adequate identification of the first two wave groups (out of a characteristic three in near-critical wakes [14,24,32]) in each wake event (Fig. 8b), the typical periods of which were much larger (>5 s) than the periods of wind waves in weak and moderate wind conditions (2–4 s). This is acceptable from the viewpoint of wake energy and power, because the third group of almost monochromatic waves with periods close to 3 s is present only occasionally and usually contains only a few per cent of the energy and power of a wake event [14].

The typical durations of the identified single wake events varied from 15 to 20 min, depending on the particular ship (Table 2). Events containing waves from two or more ships were even longer. Such complex wakes usually happened two times a day at 14:00 and 19:30 (Fig. 3) and sometimes at 08:00, when some ferries were delayed. The largest duration (25–30 min) was usually from those

**Table 2.** Properties of wakes from single ships and double wakes during days with comparatively low wind wave background (1–9, 12, 13 and 20 July 2008). Wake energy and power reflect the total energy and power of the signal, integrated over the duration of the wake. Unidentified wakes belong to smaller or slower ships sailing to Helsinki, or to incoming ships

| Vessel | No. of identified wakes | Minimum, maximum and average properties | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | Wake duration, min | | | Wake energy, $10^4$ J · s/m$^2$ | | | Wake power, $10^4$ W · s/m | | |
| | | Min | Max | Av | Min | Max | Av | Min | Max | Av |
| *Star* | 21 | 12.1 | 25.8 | 19.1 | 2.92 | 9.66 | 4.92 | 13.1 | 50.4 | 23.8 |
| *Superstar* | 25 | 13 | 26.8 | 19.1 | 4.07 | 9.1 | 6.58 | 18.3 | 45 | 30.5 |
| *SuperSeaCat* | 48 | 5.8 | 28 | 16.2 | 2.96 | 10.9 | 5.37 | 14.5 | 54.2 | 27.3 |
| *Viking XPRS* | 21 | 8.4 | 20.4 | 15.8 | 0.41 | 3.41 | 1.84 | 1.73 | 15.6 | 7.83 |
| *Nordic/Baltic Jet* | 59 | 9 | 26.4 | 16.6 | 1.48 | 8.06 | 2.86 | 7.04 | 42 | 13.9 |
| *Superfast* | 11 | 6.5 | 32.3 | 19.2 | 0.82 | 4.92 | 3.22 | 3.49 | 22.8 | 14.6 |
| Unidentified wakes | 126 | 4.2 | 28 | 12.4 | 0.05 | 4.42 | 0.78 | 0.18 | 17.5 | 3.25 |
| *SuperSeaCat* + *Star* | 4 | 19.5 | 27.8 | 22.9 | 11.1 | 13 | 12.2 | 58.2 | 65.4 | 61.7 |
| *SuperSeaCat* + *SuperStar* | 3 | 18.5 | 29.3 | 22.8 | 6.77 | 12.5 | 9.48 | 30.7 | 60.6 | 46.3 |
| *SuperSeaCat* + *Nordic Jet* | 7 | 18.8 | 27 | 22.4 | 5.95 | 8.6 | 7.82 | 28.1 | 45.6 | 40.5 |

wakes in which the third group was identifiable. The largest duration in these cases had the second wave group (that consisted of waves that generally are attached to the classical Kelvin wake) with typical periods of 5–7 s. A part of these waves may represent transverse elements of the Kelvin wake. Such a long duration of wake events is remarkable, given the small size of the water body and the distance of the study site from the sailing line. Wakes with such a long duration evidently have been created not only at a relatively large distance from the study site (as is expected), but also at speeds close to critical[2].

The distance between the source of the waves and the measurement site can be roughly estimated based on the difference in group speeds of different components of the wake and a reasonable assumption that all the wake components have been excited in a small sea area adjacent to the ship. For example, the highest waves of a typical wake from *SuperSeaCat* have typical periods ~13 s whereas the usual period of components of the third group is about 3 s. For an average water depth about 20 m along the wave rays from the sailing line to the measurement site, the wake must have propagated over a distance of 6–8 km. The nearshore, shallow area adds very little to the duration of the wake, because the difference of the group speed of different components is small.

An analogous estimate for many wakes of relatively small height and duration (6–7 min) corresponds to the propagation distance of about 2 km over a water depth of about 20 m. This estimate matches well with the theoretical properties of propagation of the classical Kelvin wake with an apex half-angle close to 20°.

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[2] A small duration wake may occur in two cases: when the ship is sailing close to the measurement site or when the ship is sailing at an almost critical speed. In this case the wake energy is concentrated in a few high waves.

The ships mostly follow the same sailing line (Fig. 2). The typical distance from the study site to the sailing line (measured by the rangefinder as the distance to the ships in the direction of the southern end of Naissaar) was 2.5–3 km. The apex half-angle of the Kelvin wedge under these conditions apparently was much larger. This means that ships were frequently sailing in the near-critical regime over extensive sections of the route (Fig. 2). In reality, different wake components propagate in different directions whereas the crests of the longest, long-crested waves of the first group form the largest angle with the sailing line. Therefore, the longest wake components have covered the longest distance to the study site.

As several wake events come in groups (due to the sailing times of various ships) (Table 1, Fig. 3), each day usually has about 15 strong wake-wave events. These events, which occur at almost exactly the same time each day, are clearly distinguishable not only in the record of the water surface, but also in the record of optical properties of near-bottom water that to some extent reflects the reaction of bottom sediments. This reaction was estimated by means of measurements of the changes of the diffuse attenuation coefficient $K_d$ in the near-bottom water column at the tripod, located at a distance of 0.25–0.75 m from the bottom. Although the values of $K_d$ also contain some noise (created, for example, by changing clouds and small-scale light reflection by waves), it usually characterizes quite well the optical properties of sea water and their (at times drastic) reaction to ship waves in terms of an increase in the amount of (re)suspended matter [5,43]. An important consequence of intense vessel traffic is that over the course of a day, the values of $K_d$ gradually increase, commonly by 0.2–0.4 1/m, which corresponds to an increase in the suspended matter concentration of about 4–8 g/m$^3$ [5].

Wake events have even more clearly discernible impact on the shoreline. An attempt to quantify this impact was made through recording of the runup of individual ship-induced waves on the beach face using survey staff (Fig. 6c) and a video recorder. Wind waves with the height of <0.5 m produced runup events up to 20–30 cm above the still water level. As expected, the largest ship waves produced substantial runup heights that commonly exceeded the height of measured non-broken waves (Fig. 10). Typically, the highest and longest ship waves from the first group reached over 1 m above the still water level with several examples going over the berm crest, over 1.5 m above the still water level. Waves from the second group, however, in many cases produced runups equivalent to those of wind-waves.

An attempt was also made to quantify the reaction of the beach to the joint influence of wind and ship waves in terms of changes of the dry beach profile. The beach at the study site was stable under moderate wind wave conditions that gradually refilled the study site with sand and gravel overnight, after sediment was removed by vessel wakes during the day. Typically a small gravel berm of 15–30 cm height formed overnight under the impact of wind waves. This berm was usually completely removed by the first ship waves the following morning.

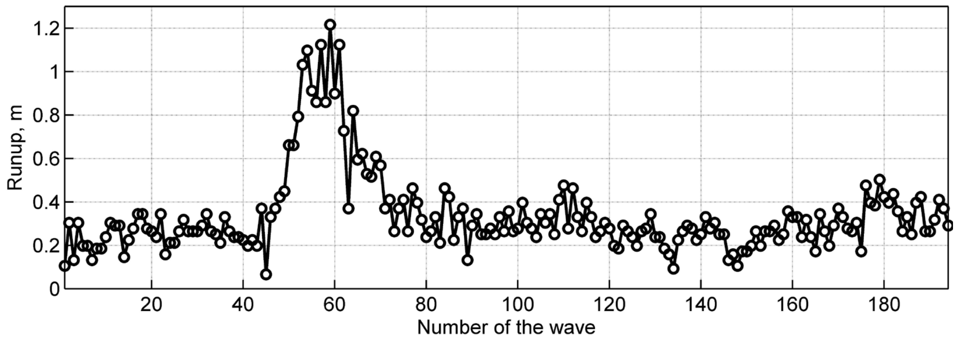

**Fig. 10.** Runup height associated with ship waves from *Star* on 14 July. The maximum non-broken wave height was below 1 m.

On several calm days when ship-generated waves dominated, we observed very rapid loss of sediment (see Fig. 6c). A more detailed description of the procedure and results of runup measurements, and details of the evolution of the beach profile will be reported elsewhere.

## 5. WAKE HEIGHT, SPECTRUM, ENERGY AND POWER

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 non-filtered data, all exceeded 1 m and were typically approximately 1.2 m (Fig. 11). The largest ship wave heights in more or less calm conditions were 1.5 m. The combined ship and wind wave heights reached 1.7 m on a few days, with the significant height of the background about 0.3–0.4 m. The maxima extracted from the spectrally filtered signal are typically about 15% smaller, but on many days these values almost coincide (Fig. 11). The lowest daily maxima correspond to weekends (Sunday, 6 July, and the weekend 19–20 July) when the number of ships is somewhat smaller and the loadings are 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.

One of the largest challenges in the analysis of ship wakes in open sea areas is the separation of ship waves from the wind wave background. A benchmark can be obtained through the analysis of wave records on calm 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). The anthropogenic contribution to the wave field almost totally dominated on these days (Fig. 12). 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

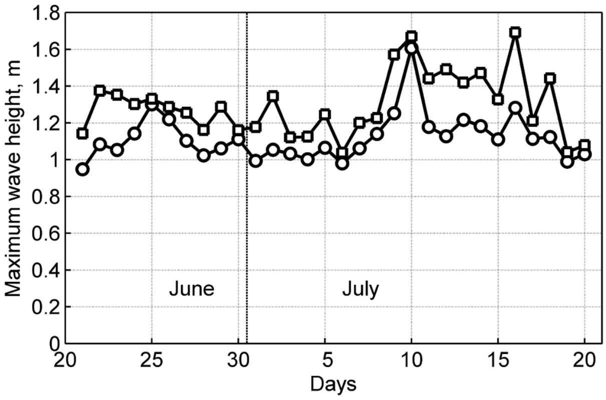

**Fig. 11.** Daily maximum ship wave heights. Squares reflect unfiltered data and circles – data filtered using a low-pass filter with a cut-off frequency at 0.4 Hz.

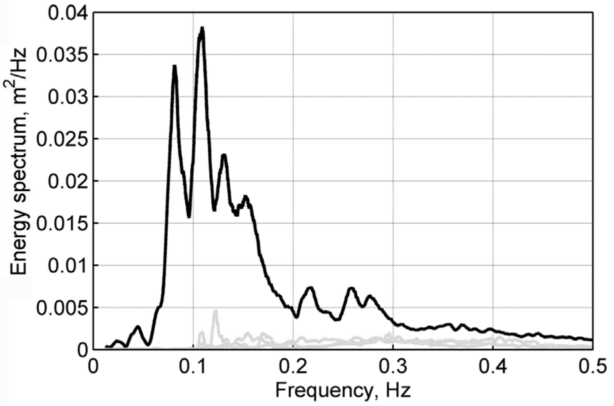

**Fig. 12.** Total wave energy density on 4–6 July (solid line) and the energy density of wind wave fields at 00:30–07:30 on the same days (grey lines).

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, a 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, the major component (about 70%) of ship wave energy is concentrated in the frequency range of 0.06–0.2 Hz (periods $T = 5$–16 s). 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 [14]. 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, 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 1) suggests that *SuperSeaCat*, *Nordic* and *Baltic Jet*, and possibly the twin hull hydrofoil *Merilin* (the wakes of which were not always separable from other wake events, but which is expected to contribute some very long wave energy) belong to the faster group, the wakes of which mostly form the peak at $T = 12.3$. Ships sailing at 25–30 knots (~45–55 km/h) are apparently responsible for the other, slightly higher peak. Note that the numbers of departures of ships of both groups are approximately equal each day.

The largest ship wakes were frequently preceded by relatively small amplitude waves (typically below 5 cm) with very long periods (20–30 s). 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 [46]. 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 *Viking XPRS* and *Superfast* and in unidentified wakes they occurred in very few cases (about 10%). Typically, 1–2 such structures were present, but in some cases up to five were observed. A small peak at $T \cong 20$ s in the spectrum in Fig. 12 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, a 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 portion 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 of different ship wave components is 0.125 Hz. On the one hand, 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 share is almost constant over these days although the number of departures varies. 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 [28].

The variation of daily average ship wake energy at the study site (Fig. 13) shows that the overall mean ship wake energy is about 16 J/m$^2$. This estimate shows that the annual mean of the ship-induced wave energy at this site, estimated as 15.8 J/m$^2$ in [14], has remained basically the same. Although one may expect some increase of the nearshore wave heights and energy due to the shoaling process, given the relatively uneven seabed and considerable attack angle of ship waves with respect to the isobaths in the experiment area, the effects of shoaling are apparently balanced by the wave energy damping and spreading due to refraction. More reliable estimates of the potential changes can be made based on the analysis of the set of single waves. As mentioned above, the variations of the water level were typically about 10–15 cm (the full range within the measurement period was 37 cm). This variation insignificantly alters the shoaling and breaking properties of waves at the site, where the water depth mostly varied between 2.6 and 2.7 m and reached 2.8 m for a short period.

While the daily average ship wave energy varies insignificantly, the energy contained in a single wake of a particular ship may vary considerably (Table 2). In general, the most energetic wakes are those from *SuperSeaCat*, *Superstar*, and *Star*. 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 *Nordic Jet*, *Baltic Jet* and *Superfast* are (by about 50%) less energetic than wakes of *Superstar* (Table 2). The wakes from *Viking XPRS* are usually much smaller than wakes from the above ships. The total energy of wakes from a specific ship typically varies by factors up to 6 times, but even larger variability (up to an order of magnitude) exists for wakes from *Viking XPRS* and *Superfast*.

A large part of the variability of wave patterns occurred owing to the simultaneous arrival of waves from two vessels that leave Tallinn at the same time (Fig. 3, 14:00 *Star* and *SuperSeaCat*, and 19:30 *SuperSeaCat* and *Baltic Jet*

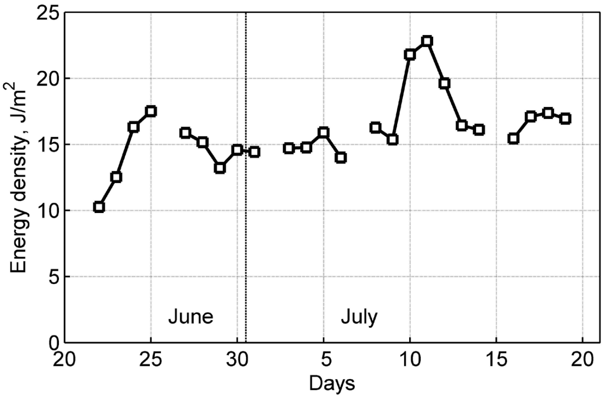

**Fig. 13.** Daily average energy density of ship wakes, estimated from the energy in long components with periods >8 s. Days with missing data due to maintenance are not represented.

or *Nordic Jet*). Usually energy of such a “double” wave pattern was approximately equal to the sum of typical wave energies of single wakes from these ships. In many cases such combined wave systems resulted in the highest waves of the day.

The variability of the non-broken wave heights and wake energy is not necessarily correlated with the associated variability of breaking waves, wave runup and the impact of waves on the coast. The observers at the coast noted that, as a rule, waves from *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 non-broken wave parameters recorded for this case were not exceptional and these waves were not even the highest of the day.

An estimate of the daily mean wake power has been also made 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 distance from the sensor to the water surface varied from 1.49 to 1.54 m. Given the full height of the tripod (without the leg spikes) was 4.1 m and the height of the mounting point of the sensor at the body of the LOG_aLevel® device about 20 cm from the tripod apex, it is safe to say that the mean water depth (taken as the basis for calculation of group velocity) was 2.7 m on these days.

The properties of the very low wind wave background (significant wave height between 6–8 cm) were almost unchanged during the night and day within these days. This allowed the estimation of the ship-induced wave power as the difference between the daily average wave power and the mean wave power during the night (from midnight to 07:30). As the waves produced by ships sailing at night were much shorter than the leading waves from high-speed ships, the share of ship wakes in the night-time wave power can be neglected. This procedure resulted in the estimate of the daily average ship wake power for 4–6 July as 78, 45, and 57 W/m, respectively. The night-time average wave power was 17, 8, and 8.6 W/m on these days. As 5–6 July were weekend days, with fewer departures of ships, the weekly average of ship wave power is probably close to 70 W/m. These results suggest that the average ship wave energy (Fig. 13) is not necessarily correlated with the ship wave power on the same day.

## 6. DISCUSSION AND FURTHER STUDIES

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 our knowledge of the wave-making potential of new, high-powered ships operating on the Tallinn to Helsinki route. Both direct measurements of speed made onboard several vessels [37] 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 [14] are no longer in service, the maxima of ship wave heights have not decreased. Assuming no loss or spreading of wave energy, a 1.08 m high wave with a period of 11 s, detected at Aegna in 2002 with the use of a pressure sensor at the depth of 6.7 m [14], would evolve to about a 1.3 m high wave at the location of the water surface profiler used in this experiment at the depth of 2.7 m. In this light, several recorded wave heights close to 1.5 m suggest that the maximum ship wave heights have, instead, increased.

The continuous recordings also led to much more reliable estimates of the contribution of ship wakes to the total wave energy and power. Earlier estimates have been based on a few hours of recordings a day at each site in the burst mode and extended to the annual scale, based on the assumption that the rest of the ship wakes of these days are equivalent to the average of measured wakes [14]. The estimates presented in this study rely on weeks of continuous recordings of hundreds of ship wakes; among them many on almost perfectly calm days. The central result of this study is that the overall amount of ship wave energy received by the coast of north-eastern Tallinn Bay has not decreased since 2002 (when the annual mean energy was estimated as 15.8 J/m$^2$ [14]), although the ships that produced the largest and longest waves in the past are no longer in service. As the wind wave activity has decreased during the last decade [47,48], the relative share of ship wave energy with respect to wind wave energy (5%–8% in 2002 [15]) may have even increased since then.

The estimate obtained for the average wake power is clearly smaller than the one derived in 2002 (110 W/m [14]). A part of this difference may result from the changes of the fleet with increasing share of large conventional ships with increased cruise speed tending to generate shorter waves than the classical high-speed ships, and thus contributing less to the wave power. On the other hand, the loss of wave energy and spreading due to refraction when waves propagated from the measurement site, used in 2002, to the current measurement site could cause an equivalent decrease in the observed wave parameters. Moreover, the measurement site in 2008 was very well sheltered from wakes generated by incoming ships, while the measurement site in 2002 received an appreciable amount of incoming ship wave energy. Although the magnitude of these changes cannot be adequately estimated based on the existing data, it is clear that despite the introduction of new classes of vessels and reduced sailing frequency, ship wave generated wave energy and power has not been significantly reduced, and the adverse effects of ship waves on coastal processes have almost certainly not been mitigated.

Many ship wakes are effectively long waves over large parts of the bay. Tallinn Bay thus appears to be an ideal “natural laboratory” to study the behaviour and impact of long waves. The regular presence of such wave trains, generated by high-speed ferries, although with varying properties from departure to departure, but still with remarkable intensity and asymmetry, can be used to develop and validate calculation methods for runup characteristics of long, potentially hazardous (tsunami, surge, sneaker etc.) waves. The location, geometry, and motion of their sources are known and thus incident (offshore) wave parameters can be modelled with great accuracy. The resulting data set can be used to test and calibrate both numerical and semi-analytical models, and may contribute to optimal methodologies for the forecast of all kinds of long-wave-induced marine natural hazards in the coastal zone, and to estimate limitations of the models.

The continuing high level of ship wave activity means that there remains a concern about the potential impact of ship wakes on vulnerable coasts. On many sea coasts the presence of such high and steep, soliton-like waves, which are accompanied by significant beach run-up is believed to be an additional agent of coastal erosion even if they have periods of only about 7 s and occur only twice a day [7]. In addition, the regular presence of such high wakes, occasionally containing strongly asymmetric components, may be used to understand the sediment transport induced by transient wave trains, which is an important driver of the morphology and evolution of the coastline. Most research in this field is focused on the net transport due to a large number of waves. Much less is known about sediment transport due to a single wave or a short wave group. Since the long-wave components of the ship waves arrive at the shore as a group of a few waves, this approach enables the study of the impact of virtually single waves on sediment transport processes (including net and bulk bedload transport of sediments by single wakes) in the coastal zone.

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## Laevalainete kaugmõjust Tallinna lahel

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On analüüsitud klassikaliste kiirlaevade ja hiljuti kasutusele võetud kiirekäiguliste parvlaevade käigulainete omadusi Tallinna lahes laevateest 3 km ning lainete tekkimiskohast kuni 8 km kaugusel paiknevas piirkonnas Aegna saare edelarannikul veepinna asendi aegjada kõrglahutusega salvestuse alusel enam kui 650 laeva käigulaine jaoks ajavahemikus 21. juunist 20. juulini 2008. Kiirekäigulised parvlaevad sõidavad kriitilisele lähedase kiirusega (25–30 sõlme, 45–55 km/t) piki Tallinna lahe idarannikut, tekitades kiirlaevade käigulainetele analoogilisi laineid perioodidega 10–13 s. Päeva kõrgeimad laevalained 2,5–2,8 m sügavuses vees on tavaliselt ligikaudu 1,2 m kõrgused. Kõrgeimad registreeritud laevalained ulatusid üle 1,5 meetri tuulevaiksel merel ja koos mõõduka tuulelainetusega 1,7 meetrini. On näidatud, et laevalainete mõjul suureneb järk-järgult heljumi kontsentratsioon põhjalähedases veekihis ja et laevalained modifitseerivad tugevasti ka kuiva ranna kujunemist. Pikkade ja kõrgete laevalainete uhtekõrgus ületab lainete endi kõrguse. Kõrgeimad laevalained on asümmeetrilised keskmise veetaseme suhtes ja nende esinõlv on taganõlvast märksa järsem. Laevalainete summaarne intensiivsus on jäänud ligikaudu sajandivahetuse tasemele, kuigi tollal kõrgeimaid laineid tekitanud laevad ei ole enam käigus.