ANTHROPOGENIC STORMS IN THE BALTIC SEA AND THE COASTAL RESPONSE

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1. INTRODUCTION

The Baltic Sea is nearly tideless (amplitudes of M2 and K1 waves are 0.01–0.02 m in the Baltic Proper, e.g. Suursaar et al, 2003), a large brackish inland sea, located in north-eastern Europe (Fig. 1). 16 million people in 9 countries residue near the Baltic Sea coast, therefore making the sea an important area for food, recreation and transport. Due to the complex geometry with straits, sills, archipelagos and open sea areas, the Baltic Sea can be regarded as a number of natural sub-basins (Omstedt and Axell, 2003). The Gulf of Finland is a sub-basin in eastern part of the Baltic Sea (Fig. 1). It is an elongated estuarine sea with an open boundary to the west.

Two capital cities lie at the opposite coasts of the Gulf of Finland: Helsinki in the north and Tallinn in the south. Between these cities, vessel traffic has rapidly increased after the collapse of the Soviet Union. Waves generated by high speed crafts (HSC) in the vicinity of ship lanes have become a problem of growing concern in many countries (Kofoed-Hansen and Mikkelsen, 1997; Parnell and Kofoed-Hansen, 2001; Velegrakis et al, 2007), among them Estonia, and particularly in Tallinn Bay. High-speed vessels (monohulls, hydrofoils and catamarans) with cruising speeds up to 40 knots (kn) were operating the Tallinn–Helsinki route between 1999 and 2008, whereas the most intense traffic occurred in 2005 (Erm et al, 2008), when 45 crossings per day was counted. Tallinn Bay is a small sea area located in the southern Gulf of Finland (Fig. 2). It is a confined bay protected from waves due to the shallows and islands, whereas only certain wind conditions can lead to a high wave activity in the bay interior (Soomere, 2005). Intense traffic of high speed crafts has led to a situation, where ship wakes form an essential component of the hydrodynamic activity on some sections of the coast of Tallinn Bay.

From 2009, the fleet of vessels which induce high wakes are characterized by long (~ 200 m), highly powered crafts with service speeds of up to 27.5 knots (Table 1). Nowadays, these vessels make 16 crossings daily, almost every day (sometimes, on Sundays they rest). With the use of wave measurements, underwater light field measurements and numerical modelling, it is the purpose of this study to characterize the unique properties of the wakes from high speed crafts and interactions with the sea bed in the coastal regions of Tallinn Bay. The paper is structured as follows: an overview of the ship park and the theory of generation of vessel wakes, together with the measurements of waves and optics, modelling, are presented in Section 2. Section 3 demonstrates the properties of the waves both of anthropogenic and natural origin, and the impact of the wakes on the sediment resuspension and underwater light field. The results are discussed in Section 4 together with methods minimizing the hazardous effects of fast ferry wakes. The work is concluded in Section 5.

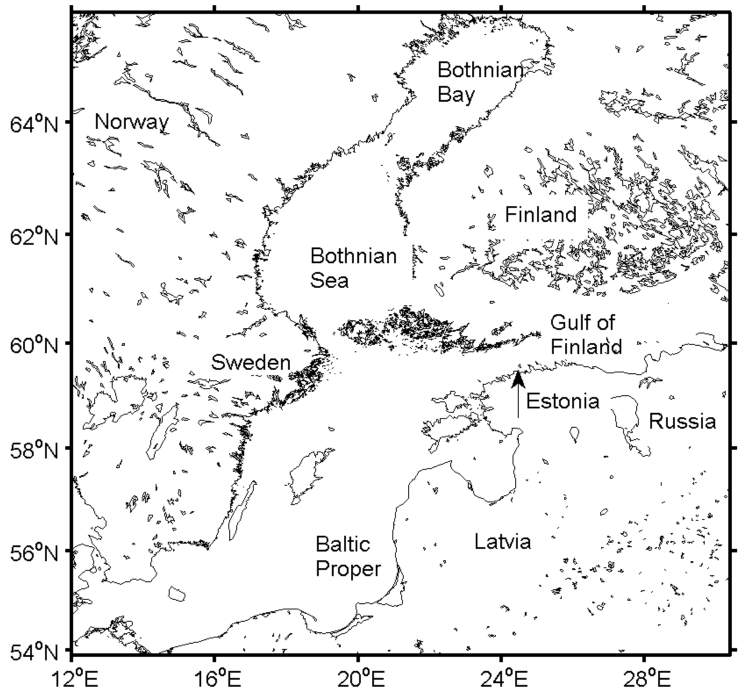

Figure 1. The Baltic Sea and the approximate location of Tallinn Bay (black arrow).

Table 1. The vessels and their characteristics. F_h and F_l denote the depth and length Froude numbers, respectively. *the vessels are no longer in service.

Vessel	Type	Length (m)	Width (m)	Draught (m)	Speed (kn)	F_h 30 m	F_h 40 m	F_h 50 m	F_h 60 m	F_l, max speed
*HSC SuperSeaCat (SSC)**	Monohull	100,3	17,5	2,6	35	1,05	0,91	0,81	0,74	0,57
*HSC Nordic Jet (NJL)**	Catamaran	60	16,5	2,22	36	1,08	0,93	0,84	0,76	0,76
HSC Merilin	Twin hull hydrofoil	52	13	1,51	40	1,20	1,04	0,93	0,85	0,91
M/S Star	Monohull	186	27,7	6,8	27,5	0,82	0,71	0,64	0,58	0,33
M/S SuperStar	Monohull	177	27,6	7,1	27,5	0,82	0,71	0,64	0,58	0,34
M/S Viking XPRS	Monohull	185	27,7	6,5	25	0,75	0,65	0,58	0,53	0,30
M/S Superfast	Monohull	203	25	6,5	25	0,75	0,65	0,58	0,53	0,29

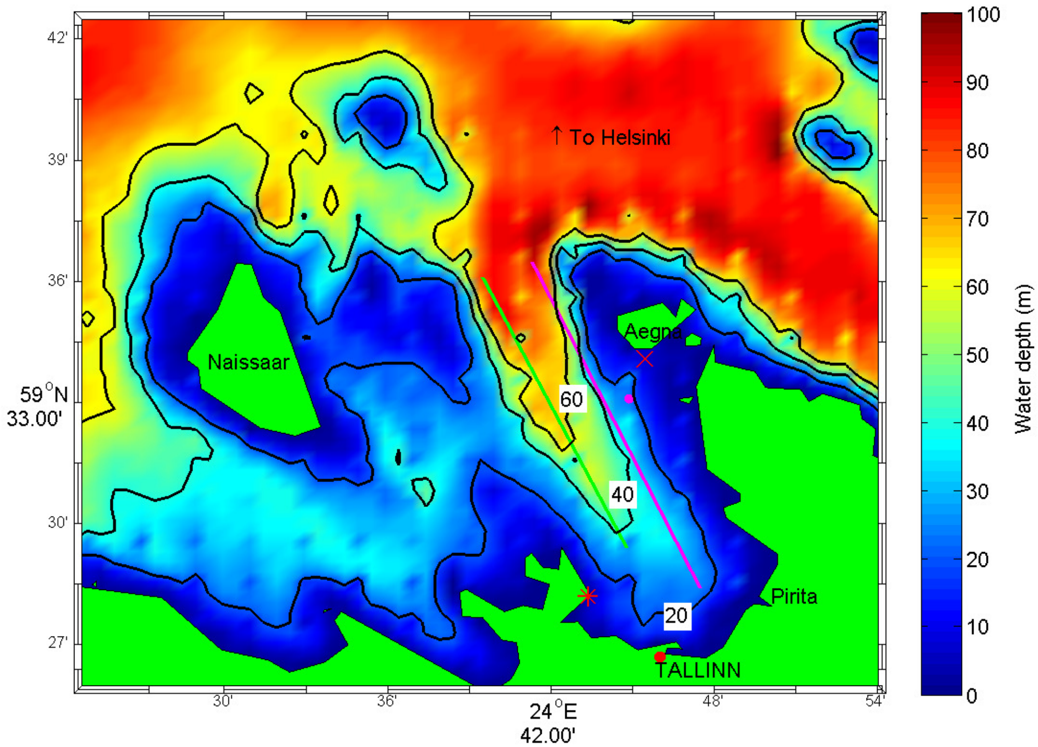

Figure 2. Tallinn Bay. The magenta line represents the outgoing fairway and the green line the incoming fairway. (•) is the Vanasadam harbour, (*) the Katariina Jetty, (x) the measurement site near Aegna Island and (•) the place where wind wave statistics is extracted.

2. DATA AND METHODS

2.1 GENERATION OF WAKE WAVES. THE FLEET

Every vessel making way generates perturbations in the bow and stearn region. The physical mechanism behind the generation of vessel wakes is as follows. The distribution of the hydrodynamic forces along the hull is not constant. A high pressure region exists in the bow and at the aft, whereas a low pressure system is aligned at midship. This results in the curving of the free water surface. Where the flux of the pressure is greater than the atmospheric pressure, wave crests form. Where it is lower than air pressure, wave through appear. Water particles, which are forced away from their equilibrium state, now try to reach their original position due to inertial and gravity forces. This result a floating process, which is seen for a naked eye as vessel wakes (diverging and transverse), forming on the relaxed water surface.

Thousands of vessels are sailing in the coastal region at every time moment. But not all of them generate wakes, which are potentially hazardous to coasts and other vessels, as well as for humans. The generation of high, long-crested asymmetrical waves, need special preconditions. These preconditions are usually described in the literature with the depth and length Froude numbers. For example, high speed vessel can be interpreted as a vessel, which has a regular sailing regime of depth Froude number over 0.6 (this is the limit where the normal Kelvin-Havelock wave pattern is modified and special non-linear features may appear) and the length Froude number between 0.4-0.6. The dimensionless length and depth Froude numbers are defined, respectively:

$$F_L = \frac{U}{\sqrt{gL}}$$

$$F_H = \frac{U}{\sqrt{gh}},$$

where U is the ships speed, g is the acceleration due to gravity, L is the ship length and h is the water depth.

The vessel fairway is located in the central part of Tallinn Bay and passenger ships depart and arrive in the Vanasadam harbour (Fig. 2). The outgoing vessels use eastern part of Tallinn Bay and incoming vessels use western part of the Tallinn Bay. While the incoming leg moves with the bottom slope, the outgoing leg is rather parallel to the coastal slope of eastern part of Tallinn Bay. Quite long section of this is aligned with the 40 m isobaths. As the aim of this study is to describe the impact of wakes from crafts capable of moving with high depth Froude numbers, the conventional ferries with sailing speeds of order 20 kn is not listed in table 1. The conventional ferries sail at moderate depth Froude numbers (≤ 0.5) and do not generate waves higher than 30 cm and periods 4 s in Tallinn Bay.

2.2 MEASUREMENTS OF WAVES AND UNDERWATER LIGHT FIELD

Although the ship wakes cross Tallinn Bay and could reach even the Naissaar Island, which is some 8 km west of the incoming fairway, the effect of wakes there is negligible, as the wakes are dissipated on the shallows east of Naissaar. The northbound sailing vessels posses a threat to eastern part of Tallinn Bay and on southern coasts of the Aegna Island (as the apex angle of Kelvin wedge is about 30^{o} for the diverging wakes which hit Aegna Island; Torsvik et al, 2009). The vessels sailing southbound generate waves, which affect the ports located in southern part of Tallinn Bay (especially the Lennusadam harbour, where the wake induced harbour resonance tears loose ships lines) and a famous recreational area the Pirita beach.

Extensive measurement campaigns have been made at southern coast of Aegna Island during recent years. The wave measurements were usually conducted with pressure based sensors with a sampling frequency of 4 Hz. When the background of wind waves was necessary, the signal was corrected with the frequency dependent attenuation coefficient. Simultaneously with the wave measurements, an optical sonde was also located in the bottom in order to quantify the impact of waves on sediment resuspension. The parameter that describes the worsening of light conditions is the diffuse attenuation coefficient of irradiation.

In this study the main attention is on the measurements conducted in July 2008 near Aegna coast, as that recording gives us six days of wind-wave free environment (mean wind speed was ~3 m s^{-1} during this period) with a high prevalence of ship wakes. A two day long measurement campaign was also conducted in 2009 near the Katariina Jetty (Fig. 2), along with the measurements of underwater light conditions. This record is not affected by waves from HSC *SSC* and HSC *NJL*, as they were not operating anymore in 2009. A record from 2006 is also used to show, how immense a non-breaking wake wave can be in 5 m of depth.

2.3 WAVE MODELLING

As the wake waves are highly asymmetrical, the near bottom-orbital speeds would be higher than calculated with the linear wave theory. Therefore, the spatial evolution of wake wave is modelled with COULWAVE and compared with the measurements. Once the modelled time-series matches the measured one in shape and high, the near bottom velocities are extracted. The model allows for the evolution of fully nonlinear and weakly dispersive long and intermediate waves over variable bathymetry (Lynnet, 2002).

In order to compare the wakes waves with natural wind wave background, the SWAN model is used to model the wave fields of Tallinn Bay in different forcing conditions. The SWAN model is a third-generation shallow-water spectral wave model that includes wave propagation, refractions due to currents and depth, generation by wind, dissipation (whitecapping, bottom friction, depth-induced breaking) and non-linear wave-wave interactions (Booij et al, 1999).

3. RESULTS

3.1. WAKES FROM FAST FERRIES

The wake system is usually characterized by two-or three distinct groups of waves with variable heights and periods. The leading group has the highest waves and is the best to distinguish, while the second and third group sometimes may be left unsighted. An important feature of these waves is the crest-through asymmetry, where the wave resembles a cnoidal wave or even solitonic shape. Different ships generate wakes with different heights and periods. The waves have a pronounced temporal variability (Fig. 3) and a large scatter in height-period distributions (Fig. 4). A definite relation between wave height and period is not obvious. This apparently reflects the different nature of origin (different ships) and other aspects. However, some general notes can be established.

The daily maximum wave heights reach 1 m and the periods of the highest waves are over 12 s. The highest periods (14 s and more), however, are related to wave heights less than 0.4 m, but some deviations occur: for example, on 29 July, a 0.83 m wave has a period of 15 s. The scatter-plot somewhat has twofold feature after the wave height has reached 0.6 m. The lower group represents waves with periods around 8 s and the upper group represent waves with periods around 11-12 s. Erm et al (2009) found during measurements conducted in autumn 2007, that the vessel M/S *Star* generates usually waves with periods of 8 s near Aegna Island. Therefore, it is suggested that the lower group represent the slower vessels (M/S *Star*, M/S *SuperStar*, M/S *Superfast* and M/S *Viking XPRS*) and the upper group faster vessels (HSC *SSC* and HSC *NJL*). The two day long measurements made near the Katariina Jetty in July 2009 also support the latter.

Only the great powered vessels M/S *Star*, M/S *SuperStar* and M/S *Viking XPRS* were sailing that time. The periods of the highest waves (0.6-0.85 m) were between 7-8 s.

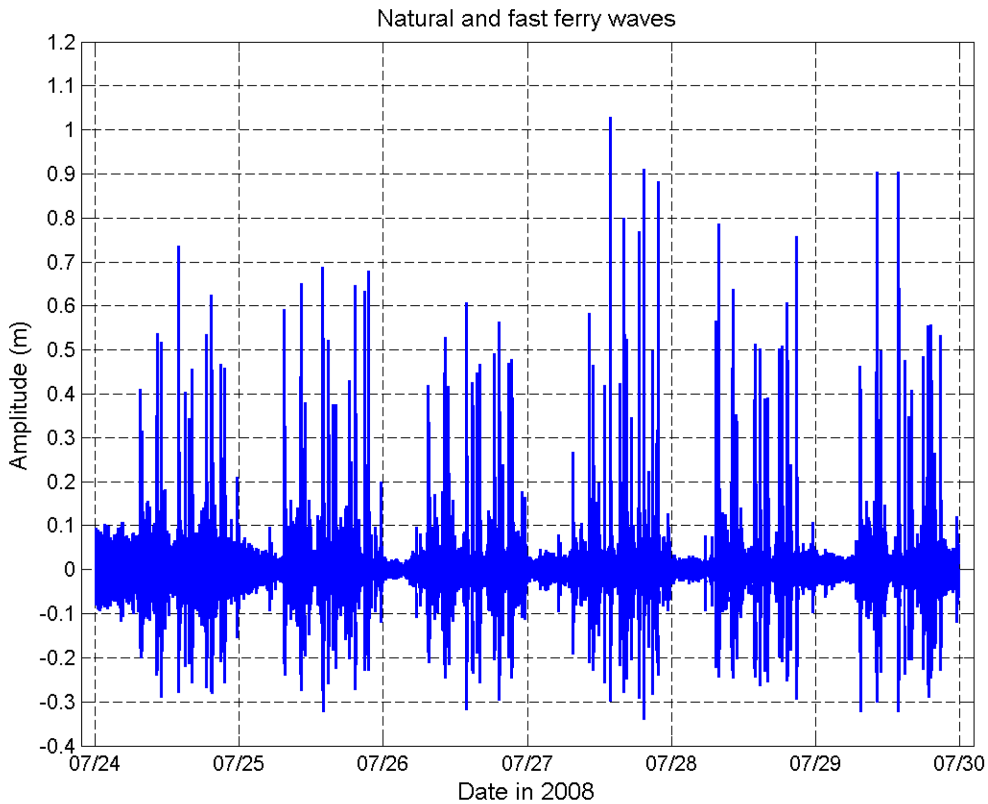

Figure 3. Near the Aegna jetty.

During the measurements of ship wakes near the coast of Aegna, the wave heights usually were below 1.5 m. However, on one occasion in 2006, the wave height of a non-breaking wave reached 1.75 m and the associating period waves 10 s (Fig. 5). As the corresponding water depth was about 5 m, the wave-length was 70 m and the near bottom orbital velocity was nearly 1.2 m s^{-1} according to linear wave theory, but may exceed over 1.5 m s^{-1} in the framework on non-linear wave theory. This wake corresponded to HSC *SSC*.

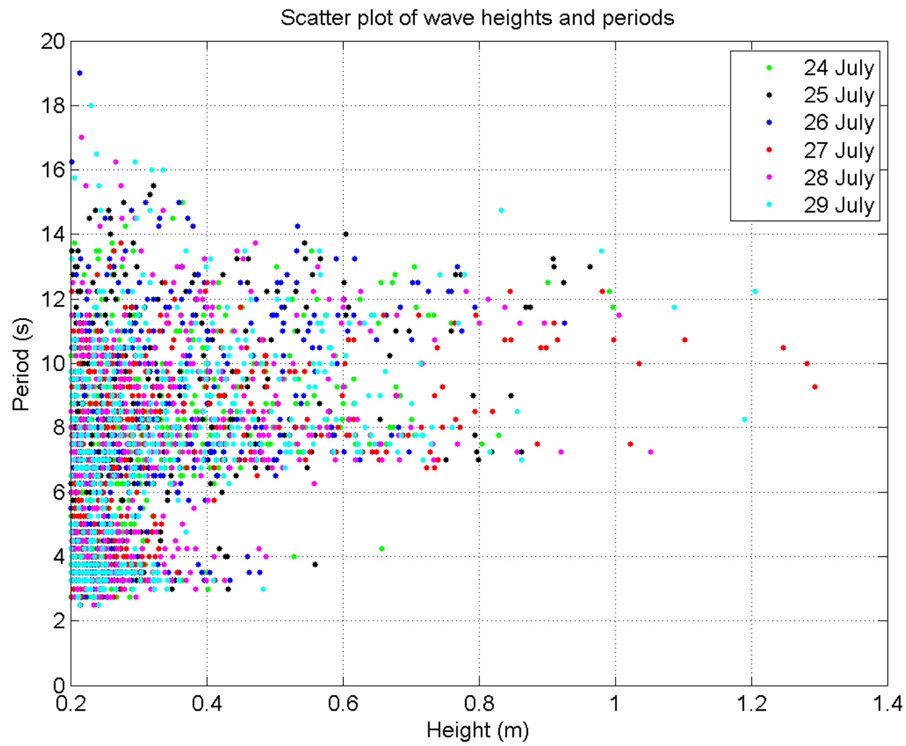

Figure 4. The waves from fig 3.

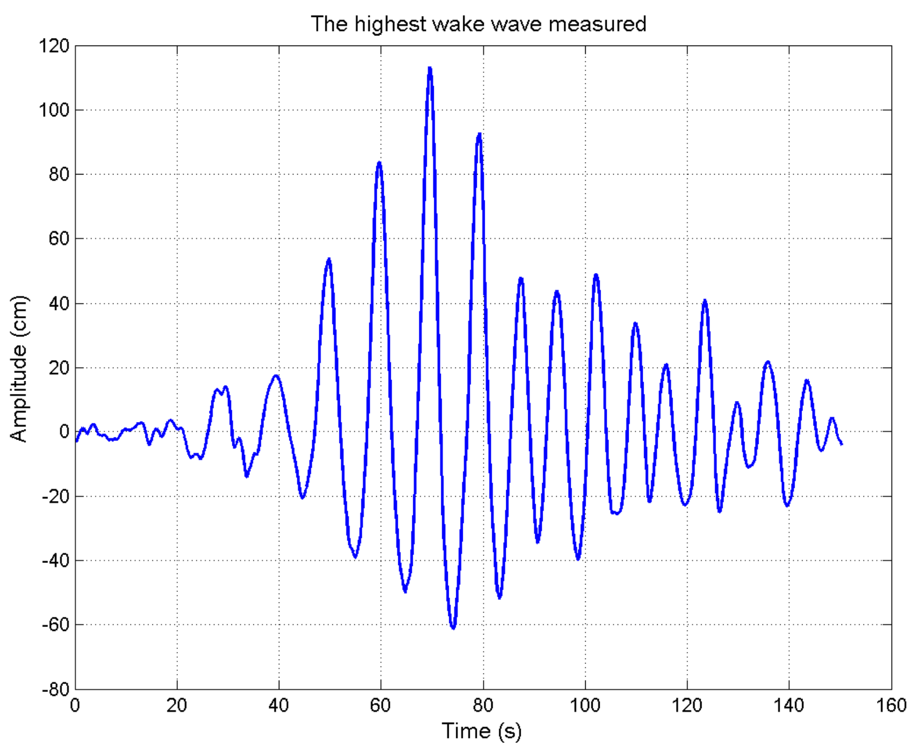

Figure 5. Near Aegna jetty in 5 m of water depth.

3.2 WIND WAVES

Wind wave fields of Tallinn Bay were calculated with wind speeds of 6 m s^{-1}, 12 m s^{-1} and 18 m s^{-1}. While the first value may represent the typical state of the Tallinn Bay in autumn and winter (usually in summer, the background of wind waves is really negligible as the mean wind speed in Tallinn Bay during summer months is 3-4 m s^{-1}), the second value is not exceeded by 6.4 % and the third value by 0.1 % according to the HIRLAM wind fields between years 2006-2009.

We choose a point near the Aegna Island in 25 m of water depth (see Fig. 2) for the description of wind waves. When the wind speed is 6 m s^{-1}, the significant wave height does not exceed 0.45 m and the peak period remains below 3 s (Fig. 6). As seen, the highest values for significant wave height and peak periods occur with NW and NNW winds (the bay is open for this direction).

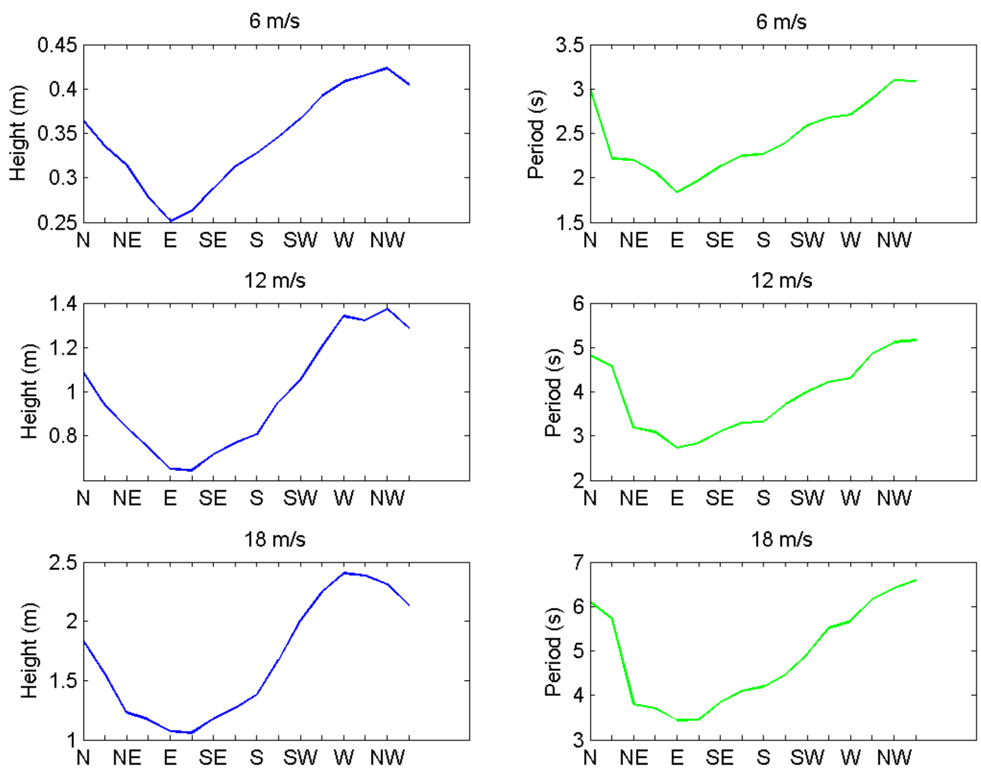

Figure 6. Wind wave statistics of Tallinn Bay.

With 12 m s^{-1} winds, significant wave height grows to 1.4 m and peak periods stay around 5 s maximally (Fig. 6). The shape of the rose is again similar to previous.
When wind speed grows to 18 m s^{-1}, the significant wave height reaches 2.4 m and peak period grows to 6.5 s.

It is evident that in severe storms the peak periods are never as high as the daily average ship wave periods. This well defines that the ship wakes can be a substantial driving force of the near bottom sediments resuspension. This feature is examined in the following section.

3.3 SEDIMENT RESUSPENSION

A wake measured on 27 July in the leading group had a 1.3 m s^{-1} flow maximum (Fig. 7), when the wave height was 0.9-0-95 m and the period about 10 s. According to linear wave theory, the near bottom orbital speed should not exceed 1 m s^{-1}. This wake represents the wake that had a maximal value in height during measurement campaign in July 2008. However, similarly, many waves during the measurement campaign could resuspend sediments (Fig. 8). About 85 % of seabed near southern coast of Aegna Island is sand with grain size between 0.063-2 mm. The corresponding critical shear velocities are 1.1 and 3.5 cm s^{-1}, respectively.

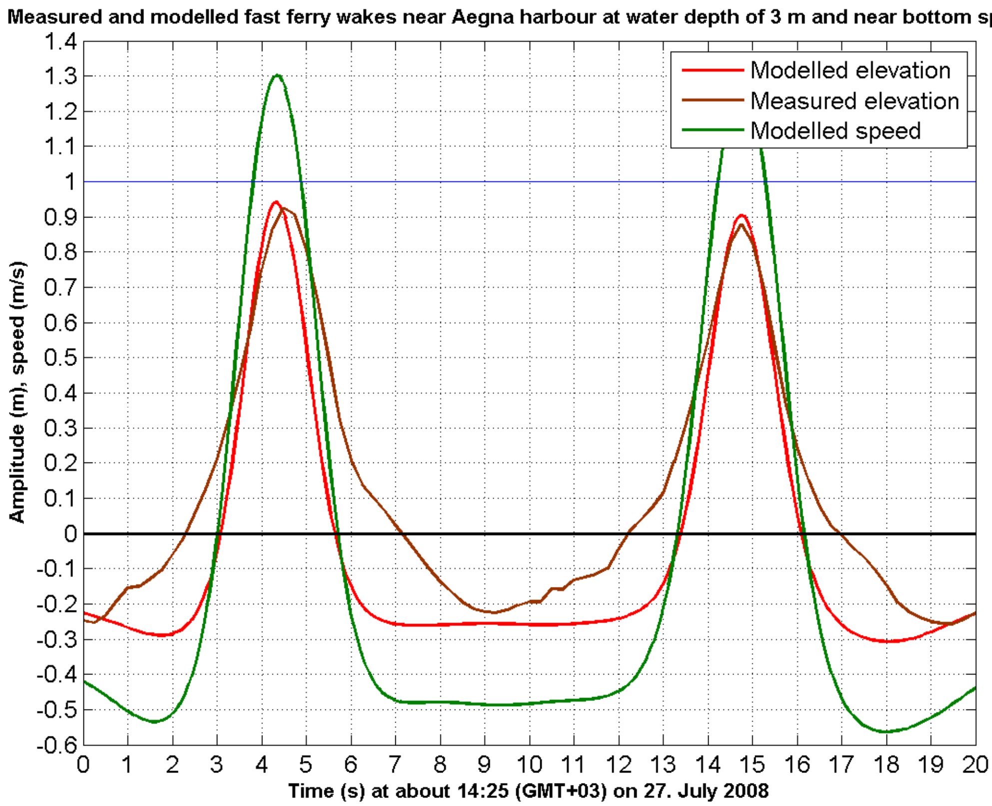

Figure 7.

The resuspended sediments manifest itself in lowered penetration of light (Fig. 9). The wave heights in that figure represent the average of maximum heights occurring between 24-29 July. The diffuse attenuation coefficient is also averaged so that a daily cycle appears. A quite good qualitative match appears between the measured waves and the fluctuation of the diffuse attenuation coefficient. Worsening of underwater light field is noticeable during the passage of M/S *Star* and HSC *SSC,* whereas their joint influence is the greatest after midday. An empirical relationship exists between the growth of the diffuse attenuation coefficient and the amount of resuspended sediments. Between 24-29 July 2009, the resuspension rate was 14 400 g s m^{-3} (Erm et al, 2009).

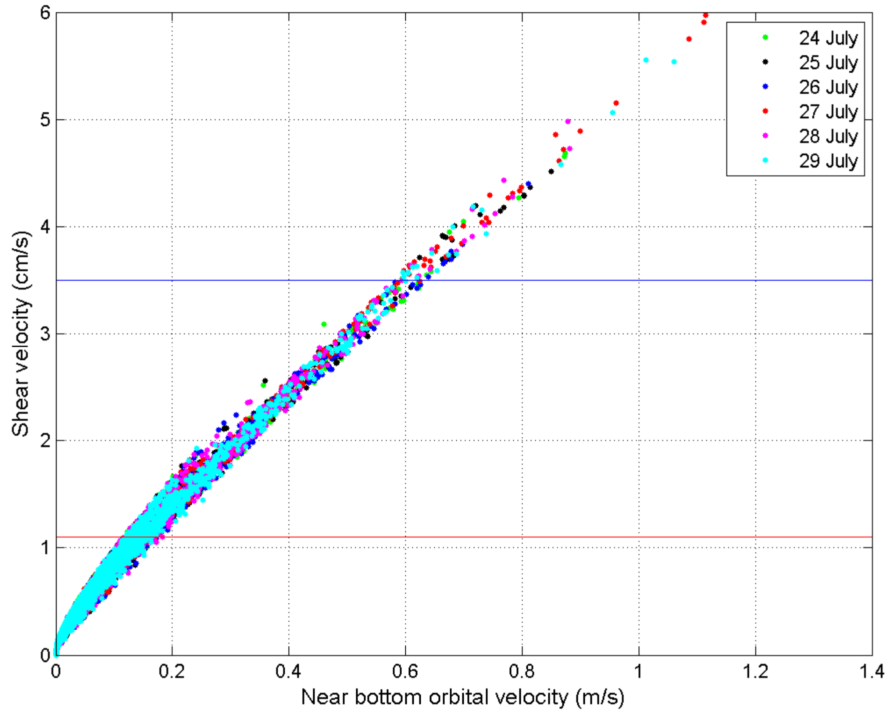

Figure 8. The impact of waves from fig 3 according to linear wave theory.

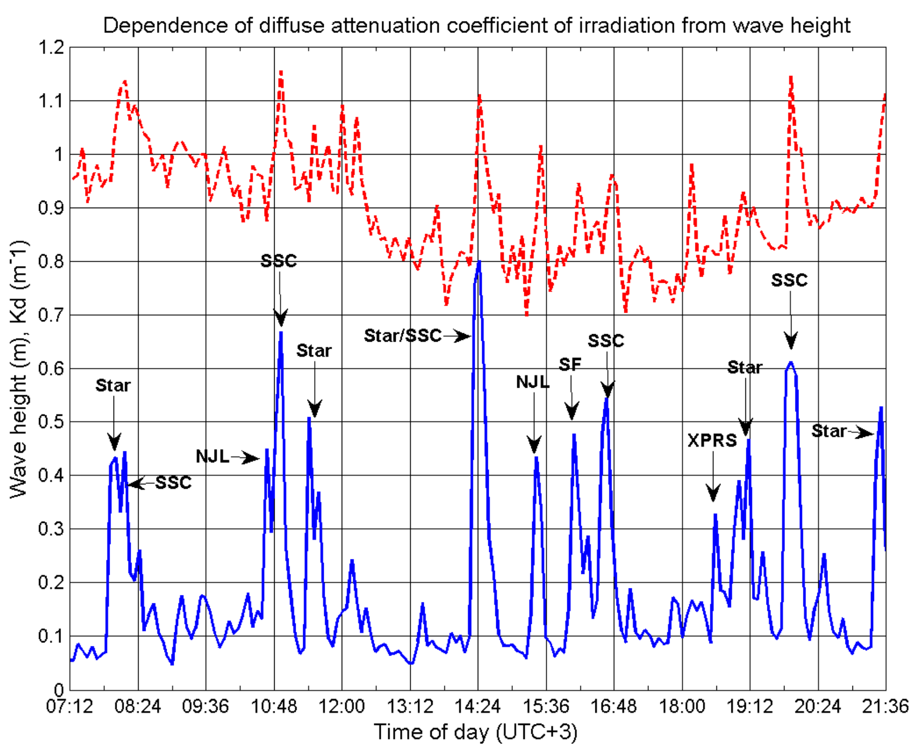

Figure 9. Near the Aegna harbour. Blue line represents the averaged maximum wave heights and the red line the averaged diffuse attenuation coefficient.

4. DISCUSSION

In 40 m of water depth, the depth Froude numbers are 0.9 for the HSC *NJL* and HSC *SSC* and about 0.65-0.7 for the conventional vessels with increased sailing speed (Table 1). In the outgoing leg, there exists an extensive section, when the vessels are sailing along the 40 m isobath. These numbers favour very well the excitation of high and long-crested waves. It has been shown, for example by Dam et al (2006), that the wave heights reach their maximal value on a sloping coast, when the depth Froude number reaches 0.95. To that limit, also the wave period increases, but thereafter gradually decreases. However, we have to recognize that the generation of dangerous wakes not only depends on these numbers, but depend on the width, draught and weight of the vessel also: for example, the twin hull hydrofoil *Merilin* travels at the greatest speed at all, but measurements do not show any significant impact of this ship. Also it is evident that HSC *NJL* generally makes lower waves than HSC *SSC* (see Fig. 9). The HSC *NJL* is a catamaran, it is shorter and has a lower draught compared to HSC *SSC*.

On 15 November 2001 a violent NNW storm with wind speeds 23 m s^{-1} occurred. It had a quite high impact on the beach processes on northern coast of Aegna Island and the water level rise flooded the Pirita harbour. However, the near bottom orbital speeds during that storm reached only 1 m s^{-1} in the coastal areas of Tallinn Bay and 0.5 m s^{-1} in southern coast of Aegna Island (not shown here). The storm lasted about 5-6 hours. As the wave period was 7 s in that storm, we should expect about 2500 waves, which could potentially resuspend sediments in the coastal areas. During the measurement period in July 2008, 225 wake waves had generated near bottom orbital velocities greater than 0.5 m s^{-1}. In that sense, passages of wake waves during a two month period adds a storm like described above, which statistically is a storm of a century in the area of interest

However, the behaviour of marine systems is not as simple. Basically, waves do resuspend sediments, but currents carry them away. A measurement campaign in 2006, when a current meter was deployed simultaneously with a wave gauge near southern coast of Aegna, showed flow of water towards the deeper parts of the Tallinn Bay entrance (Erm et al, 2008). This means, that during this event, the resuspended sediments were carried away to deeper areas, where they can never be resuspended again. When winds are blowing from the north, the sediments are carried towards the south etc.

The geometry of Tallinn Bay restricts the shifting of the fairway to more interior, as it is already in the deepest part as possible. In that sense, the impact of the wakes can be minimized only by reducing the speed of vessels (or by rising the speed over super-critical Froude number, which is not possible). Now the highly powered long vessels are cruising at a speed of 27.5 knots, which gives the depth Froude number in 30-40 m of depth 0.82 and 0.71, respectively. This is the average depth of the fairway in the northbound lane. In 60 m of depth the depth Froude number decreases below 0.6, when speed is 27.5 kn. Hence, if the ship increases it speed steadily and linearly till it has its maximum value in 60 m of water depth, the average time of travel increases only by 5 min (and had only increased by 10 min for the monohull *SSC*, HSC *AutoExpress* (a HSC saliling between 2000-2007) and HSC *NJL*).

If the vessels will not lower its speed, the resuspension of sediments and direct erosion of coastal areas of Tallinn Bay will persist. Also, the navigation of smaller vessels in harbours, water sporting (kayaking etc) and swimming will be continuously a dangerous act, especially during summer.

5. CONCLUSIONS

The profiles of wakes induced by fast ferries, worsening of underwater light climate and the resuspension of sediments in Tallinn Bay was shown. The ferries sailing at sub-critical and near-critical depth Froude numbers generate wakes that in natural conditions in Tallinn Bay do not occur. Frequently they are very long crested (periods of 10 s and more), are non-linear and have a distinguished shape resembling a cnoidal or even a solitary wave. The daily average heights of these wakes are nearly 1 m and they can generate near bottom orbital velocities over 1 m s^{-1} in areas, where wind waves would never be so intense. This intensifies the sediment resuspension and therefore the worsening of underwater light climate.

The reduction of the speed of vessels in Tallinn Bay would result in a lengthen travel time of 5-10 min, but will minimize the effects of wakes.

ACKNOWLEDGEMENTS

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