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Can the Waves Generated by Fast Ferries be a Physical Model of Tsunami?

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Abstract—The potential of long ship-induced waves to serve as a physical model for tsunami waves (called simply tsunami below) is examined. Such waves (wavelengths more than 200 m at depths down to 10–20 m) are induced by high-speed ferries sailing at near-critical speeds in semisheltered, relatively shallow areas. It is shown based on experience from Tallinn Bay, Baltic Sea, that for many aspects these waves can model nearshore dynamics and runup of tsunami caused by landslides, including processes of wave refraction, diffraction, and sea-bottom interaction in bays and harbors. Many governing nondimensional parameters (such as the nonlinearity, dispersion, Reynolds and Ursell numbers, surf similarity parameter, breaking parameter, etc.) of the largest ship waves and landslide tsunamis have the same order of magnitude. It is especially important that use of ship waves for wave propagation and runup studies allows their spatial structure to be accounted for adequately. Near-critical ship waves can therefore be used as a natural substitute for tsunami, for study under controlled and safe conditions.

Key words: Tsunami, landslides, long waves, induced by high-speed ferries, physical modeling, Tallinn Bay, Baltic Sea.

1. Introduction

At the present time, existing tsunami warning systems record many tsunamis instrumentally in the open ocean. Additionally, the properties of tsunamis in harbors are registered by local tide gages. The extended observation network allowed, for example, worldwide recording of the catastrophic 2004 tsunami in the Indian Ocean (TITOV *et al*., 2005; RABINOVICH and THOMSON, 2007). The recorded data are widely used for testing and calibrating basic numerical models of tsunami propagation, which are applied in operational practice (WEI *et al*., 2008). Nevertheless, tsunami behavior in coastal areas is a very complicated process, depending on many factors, such as strong nonlinearity, bottom friction, wave dispersion, diffraction, and scattering above complicated bottom topography, and still remains a problem. While considerable progress towards solving the problem has been made for earthquake-generated tsunamis, the problems are even more complicated for tsunamis caused by landslides.

Landslides are the second most frequent tsunami source after earthquakes, responsible for about 10% of all tsunamis (GUSIAKOV, 2009). The resulting events are frequently "surprise tsunamis" (WARD, 2001), initiated far outside the epicentral area of an earthquake, or much larger than expected given the earthquake size. In many cases, a tsunami generated by a spontaneous submarine landslide arrives without any precursory seismic warning at all (WARD, 2001). The resulting waves generally have smaller periods and wavelengths than earthquake tsunamis. Usually, landslide tsunamis do not propagate over long distances in the open ocean but can have extremely strong local effects (BARDET *et al*., 2003; MURTY, 2003; FRITZ *et al*., 2009). For example, an underwater landslide caused the destructive Papua New Guinea tsunami (July 17, 1998; maximum runup 15 m), which devastated three villages and took more than 2,200 lives at the coast around Sissano Lagoon (MCSAVENEY *et al*., 2000; SYNOLAKIS *et al*., 2002; TAPPIN *et al*., 2001, 2008). On August 17, 1999 an earthquake of magnitude 7.4 caused a shore slump in Izmit Bay (Turkey), which generated a 2.5-m-high tsunami (ALTINOK *et al*., 2001). Four weeks later (September 13, 1999) a slump of a high cliff generated a 5-m-high tsunami near Fatu Island (French Polynesia) (HÉBERT *et al*., 2002; OKAL *et al*., 2002). On November 18, 1929, a $M = 7.2$ earthquake occurred at the southern edge of the Grand Banks,

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Canada. It triggered a large submarine slope failure that caused the most catastrophic tsunami in Canadian history. Waves generated by this failure had amplitudes of 3–8 m and runup of up to 13 m (Fine *et al.*, 2005). All these events demonstrate that tsunamis of landslide origin can be very dangerous in coastal areas.

Numerical models of tsunami dynamics in the near-shore region and runup require testing on natural and laboratory data. Progress in this direction has mostly been achieved through use of physical modeling of tsunami in laboratory flumes and basins. Such experiments have been conducted for the wave runup problem (Synolakis, 1987; Lara *et al.*, 2006; Baldock *et al.*, 2008; Madsen and Fuhrman, 2008; Synolakis *et al.*, 2008), wave interactions with coastal constructions (Xiao and Huang, 2008), forest and mangrove protection against tsunami (Ba Thuy *et al.*, 2009; Irtem *et al.*, 2009), etc. A major shortcoming of this approach is that tsunami properties cannot be fully reproduced in laboratory tanks due to the "scale effects." As a result, the physical models developed so far are only conditionally valid, and there is an acute need for better understanding of tsunami dynamics by means of their modeling in natural basins under controlled conditions of wave generation.

A feasible substitute for some types of tsunami are long waves of large amplitude generated by high-speed ferries under certain conditions in natural basins. As shown below, the leading components of such vessel wave wakes have similar dynamics and properties to tsunamis of landslide origin. This partial similarity can be used to model tsunami under natural conditions using high-speed ferries as "generators" of artificial tsunami. A promising study in this direction of properties of long nonlinear vessel waves and their effect on the coast was recently performed in Tallinn Bay (Estonia, Baltic Sea) (Parnell *et al.*, 2008; Didenkulova *et al.*, 2009; Torsvik *et al.*, 2009; Soomere *et al.*, 2009).

In this paper we explore the potential of long ship waves as a physical model of tsunamis from the viewpoint of the basic dynamic parameters of these two wave classes. The paper is organized as follows. The properties of waves induced by high-speed ferries and certain similarities of ship wakes and tsunamis are described in Sect. 2. The possibility of modeling tsunami propagation using ship waves is analyzed in Sect. 3 by means of comparing the most important parameters for wave propagation. The perspectives of physical modeling of tsunami runup at the coast are discussed in Sect. 4. The main results are summarized in Sect. 5. It is concluded that ship waves can be used as an adequate physical model for shoaling and runup of tsunamis caused by landslides, while the high frequency of high-speed traffic allows for collection of a wide range of experimental data each day.

2. *Waves Induced by High-Speed Ferries and Tsunamis*

Tallinn Bay, a semi-enclosed body of water, approximately 10 × 20 km^2 in size in the Baltic Sea (Fig. 1), is one of a few places in the world where high-speed ferries operate at service speeds near the shoreline, with up to 22–25 sailings per day (Parnell *et al.*, 2008; Torsvik *et al.*, 2009).

Significant lengths of the ship tracks in Tallinn Bay are in water depths ranging from 20 to 40 m, where ships sail in the near-critical regime (Torsvik *et al.*, 2009) and generate packets of large, very long, long-crested waves. Under calm conditions, vessel-generated waves of up to 1.5 m, with periods of 10–13 s, frequently occur in the near-shore region, about 3 km from the sailing line at water depth of

Figure 1
Location of Tallinn Bay, Baltic Sea; the *solid line* in the right bottom box indicates the Tallinn–Helsinki track of high-speed ferries

$\sim$2 m. Such packets of long waves, resembling tsunamis, occur 15–20 times a day in Tallinn Bay during the high navigation season. This allows numerous repetitions of experiments in a short period of time in this natural laboratory for study of tsunami dynamics.

The distribution of maximum wave heights in wakes from different ships based on 1 month of experimental data is shown in Fig. 2 (KURENNOY *et al.*, 2009). Some high-speed ferries such as the Superstar produce large-amplitude waves with little variation in their height, while other vessels such as the Viking XPRS and Super Sea Cat have a wider distribution of maximum wave heights (see PARNELL *et al.*, 2008 for a detailed description of the vessels). The typical daily highest ship wave is approximately 1.2–1.3 m, while typical wind wave heights in summertime are about 10–20 cm and may reach 50 cm during moderate wind conditions. Therefore ship waves can be easily extracted from sea level records.

The periods of ship-generated waves also vary for different vessels, depending on their size and operating speeds (KURENNOY *et al.*, 2009). The periods of the highest vessel waves reach up to 15 s, much longer than the wave periods of 2–4 s typically found for wind-generated waves in this sheltered body of water. This feature enables ship waves to be distinguished even in relatively rough seas. The longest waves are usually induced by the faster and smaller vessels such as the Super Sea Cat and Nordic/Baltic Jet (average periods about 12.3 s), while larger and slower ships such as the Star and Superstar produce waves of smaller periods (average periods about 9.2 s). The largest ship wakes are frequently preceded by relatively low waves (typically below 5 cm) with very long periods (25–30 s). This part of the wake may be associated with the precursor solitons (long solitary waves propagating ahead of high-speed ships) that are typical of near-critical speeds (ERTEKIN *et al.*, 1986). As water depths are mostly below 20 m between the ship lane and the coast, many vessel waves are effectively long waves.

The time series of water surface elevation in wave wakes from high-speed vessels at a long distance from the sailing line possesses a striking similarity to

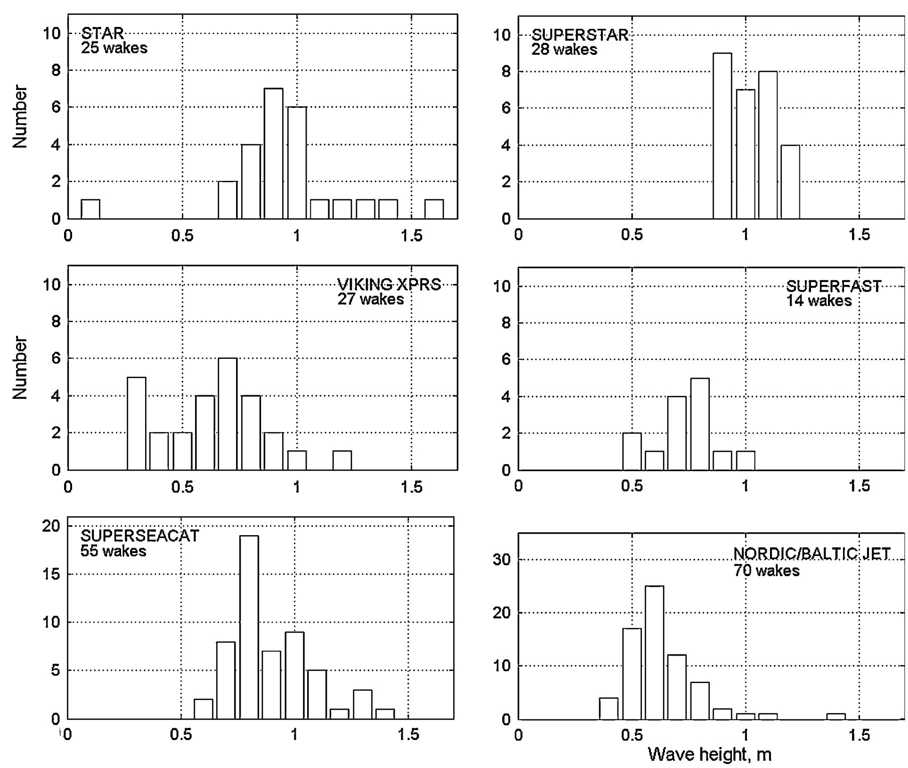

Figure 2
Recorded maximum wave heights in wakes from different ships (KURENNOY *et al.*, 2009)

many classic records of tsunamis in coastal areas. The wake has a pronounced group structure at a distance of a few kilometers from the ship lane (Fig. 3). Typically it contains at least four wave groups, where the first groups usually have the highest amplitudes and very long periods. The longest waves are concentrated at the beginning of the signal, whereas the largest waves usually arrive 1–2 min later. After the highest waves have passed, both the length and height of single wave components gradually decrease, yet there may be some groups of relatively high waves in the tail of the signal (Soomere, 2005).

A very similar signal is typical for tsunamis of landslide origin, especially in cases when the characteristic horizontal scale of the disturbance and the length of the generated waves are relatively small. This is not very surprising, because an underwater landslide that propagates approximately with the maximum celerity of linear waves for the given depth has an impact on the water mass equivalent to that of a high-speed vessel. A similar impact may result from a pyroclastic flow that propagates with a similar speed, which is why many tsunamis of volcanic origin have the same group properties. For example, Fig. 4 demonstrates tsunami from the 1883 Krakatau eruption in Port Elizabeth, South Africa (Pelinovsky *et al.*, 2005). Such events frequently have a group structure, and very often the first wave is not the largest one. What is interesting is that similar features become evident in the signal of earthquake tsunamis at large distances (see examples from the 2004 Indian Ocean tsunami, Rabinovich and Thomson, 2007), but

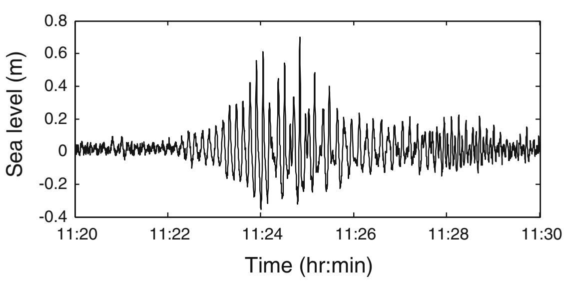

Figure 3
Waves from the basically conventional but strongly powered ferry *Star* (length 186 m, 36,250 GRT, cruise speed 27.5 knots) at water depth of 2.7 m and a distance of 2.7 km from the sailing line on 6 July 2008 in Tallinn Bay

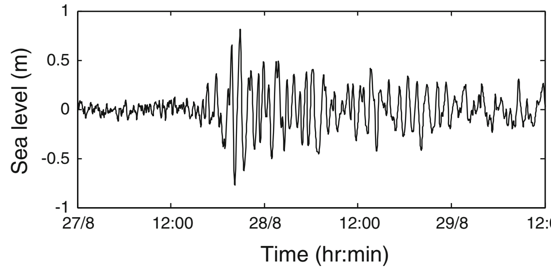

Figure 4
Tsunami from the 1883 Krakatau eruption in Port Elizabeth

the typical periods of oscillations are much longer, from a few minutes up to a few tens of minutes. The oscillations observed during the 2004 tsunami have a typical period of 40–50 min, while some locations, such as Réunion Island, display shorter periods (Rabinovich and Thomson, 2007). Probably, the longer periods are due to reflections and refraction, while the shorter periods may correspond to eigenfrequencies of semiconfined basins. Similar effects (albeit of slightly different physical background, for example, caused by geometrical defocusing of the leading waves accompanied with an increase in wave periods at longer distances from the sailing line) can also be manifested for ferry waves in Tallinn Bay.

We would like to emphasize here that the above-described group structure of ship wave packets is a natural property of the near-critical vessel wave field, reproduction of which in laboratory conditions for tsunami studies is a very complicated task.

The periods of the highest vessel waves reach 15 s, and the time intervals between the precursor solitons are up to 30–40 s (Soomere, 2005; Parnell *et al.*, 2008). These periods are quite close to (and in many occasions belong to) the range in periods of tsunamis caused by landslides; for example, during the tsunamis of 30 December 2002 (that were generated by landslides and caused severe damage at Stromboli), periods of $\sim$40 s were observed at Ustica Island (Maramai *et al.*, 2005). Eye witnesses reported a sequence of sudden rises and falls of sea level. These strong and powerful wave events caused a continuous surge superimposed by periodic inundation and retreat of water. The phenomenon went on without interruption for about 2 h, with a typical period of 20 s between the inflow and outflow of water. A ferry moored in the harbor was forced to departure because the anchors and mooring lines were at risk of breakage (MARAMAI *et al.*, 2005).

A numerical simulation of these events showed that the main tsunami signal had a dominant period of about 1 min, although higher-frequency oscillations were also seen, corresponding especially to the large positive waves (TINTI *et al.*, 2006). A numerical simulation of one of the most famous tsunami of landslide origin [Papua New Guinea (PNG) tsunami of 17 July 1998, with 15 m wave height] also showed periods of tsunami of $\sim$40 s (TAPPIN *et al.*, 2008). Oscillations with comparable periods (about 1 min) occurred during the 1597 landslide tsunami in Nizhny Novgorod (Russia), when the whole Pechersky Monastery with all its buildings slid down into the Volga River (DIDENKULOVA AND PELINOVSKY, 2002; 2006) and during landslide tsunamis in the Italian artificial Vajont Reservoir in 1960 and 1963 (PANIZZO *et al.*, 2005). Tsunami of 2 min period and 2 m wave amplitude were observed in Saint Laurent du Var (France) on 16 October 1979, when a part of the Nice new harbor extension, close to Nice International Airport, slumped into the Mediterranean during landfilling operations (ASSIER-RZADKIEWICZ *et al.*, 2000). The tide gage in Skagway Harbor (Alaska) recorded waves with periods of 3 min following an underwater landslide formed during the collapse of a cruise ship wharf undergoing construction at the head of Taiya Inlet on 3 November 1994 (KULIKOV *et al.*, 1996). Thus, many landslide-generated tsunamis have characteristic periods from 20 s to a few minutes, which roughly correspond to ship wave periods or insignificantly exceed them.

The frequent presence of wakes from high-speed vessels, the similarity of their internal structure to that of many tsunami events, and the partially overlapping temporal scales of the two wave classes suggests that ship wakes can be used as a dynamically similar input allowing modeling and measurements of the shoaling and runup properties of certain types of extreme, long, large-scale ocean waves and tsunamis under safe and controlled conditions. Moreover, the natural variability of the properties of waves produced by different ships provides the variability of wave parameters important for the experiment.

Sea areas such as Tallinn Bay, hosting intense fast ferry traffic, therefore can be used as a natural laboratory for such waves. A prerequisite for successful application of this idea is the feasibility of basin-wide numerical simulations of long ship waves in Tallinn Bay by models that are also used to model tsunamis in other basins. Various numerical models are applied for description of tsunamis of landslide origin. One of them is the Coulwave model, based on Boussinesq equations, and developed at Cornell University (LYNETT AND LIU, 2002; LYNETT *et al.*, 2002). This model was modified and adapted for description of waves induced by high-speed ferries in Tallinn Bay. Simulated results are in a good agreement with measurements made in the bay (TORSVIK *et al.*, 2009). This gives hope that the experimental data from areas hosting intense fast ferry traffic can be used for direct testing of such models applied for studies of large-scale natural phenomena in other basins. This research is very important for proving the validity of numerical simulations of real tsunami events.

3. Modeling of Tsunami Propagation

The above discussion suggests that waves induced by high-speed ferries are similar to certain tsunamis and can be considered as their physical model in coastal areas. For quantitative comparisons, however, it is necessary to compare all parameters characterizing the wave processes.

First of all, scaling effects should be studied. Linear wave motion in a basin of constant depth is characterized by two length scales: vertical (water depth, h) and horizontal (wavelength, λ). They should both be changed with the same scaling factor in the modeling process. Temporal scaling in the case of long waves can be determined through the wave period, T

$$T = \lambda / \sqrt{gh}, \qquad (1)$$

where g is the gravity acceleration. As tsunamis are usually characterized by their spatial scales, this approach has clear physical interpretation. The characteristic scales of tsunamis, which can be modeled by ship waves in Tallinn Bay for different geometrical scaling coefficients, are presented in Table 1. The results indicate that the geometrical

Table 1

Scales of tsunamis in terms of geometrical similarity

	Depth, h	Wavelength, λ	Period, T
Ship waves	20 m	200 m	15 s
Tsunami	200 m	2 km	50 s
	300 m	3 km	1 min
	1 km	10 km	2 min
	2 km	20 km	2.5 min
	4 km	40 km	3.5 min

scaling is adequate for relatively short tsunamis with periods up to 3 min in both shallow and deep water. As mentioned above, such periods are typical for tsunamis of landslide origin.

An important characteristic of wave modeling is the Reynolds number

$$\mathrm{Re} = uD/\nu, \tag{2}$$

where u is the characteristic velocity, D is the characteristic scale, and ν is the kinematic viscosity, which we take to be $\nu = 10^{-6}$ m^2/s. As the critical value of the Reynolds parameter is quite small (we use the critical shear Reynolds number of 420 for a semi-infinite plane boundary layer), it is convenient to use the water depth, rather than the wavelength in Eq. (2). The characteristic velocity of water particles can be estimated from the linear shallow-water equation:

$$u \sim A\sqrt{g/h}, \tag{3}$$

where A is a wave amplitude. As a result, the Reynolds number can be estimated as

$$\mathrm{Re} = \frac{A\sqrt{gh}}{\nu}. \tag{4}$$

For the typical amplitude of the largest vessel waves at depth of 20 m in Tallinn Bay conditions (0.7 m, Torsvik and Soomere, 2008), the Reynolds number for ship waves can be estimated as being on the order of 10^7. Reynolds numbers calculated for different tsunami events of landslide origin are in the range of 10^7–10^9 for the 1960 tsunami in the artificial Vajont Reservoir (Panizzo *et al.*, 2005), for the 2002 Stromboli tsunami (Tinti *et al.*, 2006), for the 1998 tsunami in Papua New Guinea (Tappin *et al.*, 2008), and even for the Tafjord 1934 event (Harbitz *et al.*, 1993), which represents a catastrophic tsunami caused by a huge rock slide (Table 2). As mentioned above, the approach of tsunami modeling using vessel waves is the most appropriate for landslides of moderate volume and associated tsunamis of moderate magnitude. The 1934 Tafjord tsunami was induced by a huge 1.5×10^6 m^3 rock slide, which presumably released another 1.5×10^6 m^3 of submerged mass (Harbitz *et al.*, 1993). Tsunamis induced by such large landslides are more similar to earthquake-generated tsunamis and, as will be demonstrated below, have very little similarity with vessel waves.

For comparison, we also present data from a laboratory experiment of wave generation by landslides (Sælevik *et al.*, 2009) in Table 2. The associated Reynolds number ($\sim 10^5$) is two orders of magnitude less than in the case of tsunamis in nature but still significantly larger than the critical value. Thus, in both tsunami-induced and ship-wave-generated flows, the Reynolds number obviously exceeds the critical value by several orders of magnitude and indicates turbulent wave motion. An important consequence is that the dissipation of wave energy apparently follows the same rules for both tsunamis and ship waves.

It is also important to compare the nonlinear and dispersive characteristics of tsunamis and ship waves. The nonlinearity coefficient is defined here as the ratio (Whitham, 1974; Murty, 1977; Pelinovsky, 1982, 2006)

$$\mathrm{Nl} = A/h. \tag{5}$$

Its values are about 0.03 for vessel waves at 20 m depth and vary from 0.005 to 0.03 for landslide tsunamis (Table 2). As for both tsunami and ship wave cases this parameter is $\sim 10^{-2}$, linear or weakly nonlinear wave theory can be applied for their description. The nonlinearity coefficient for the Tafjord tsunami is one order of magnitude larger than for all other events (Table 2). This demonstrates that events of such a large scale cannot be modeled by ship-induced waves. However, waves in the laboratory experiment correspond to the same level of nonlinearity as ship waves recorded in Tallinn Bay.

The dispersion coefficient for waves can be defined as (Whitham, 1974; Murty, 1977; Pelinovsky, 1982, 2006)

Table 2

Wave motion parameters for ship waves and tsunamis

	Wavelength, λ	Depth, h	Wave amplitude, A	Re	Nl	Disp	Ur
Ship waves	200 m	20 m	0.7 m	10^7	0.035	0.01	3.9
Vajont 1960 tsunami	2.5 km	200 m	1 m	4×10^7	0.005	0.006	0.8
Stromboli 2002 tsunami	5 km	500 m	15 m	10^9	0.03	0.01	3.0
PNG 1998 tsunami	4.4 km	1.4 km	13 m	10^9	0.01	0.1	0.1
Tafjord 1934 tsunami	8 km	200 m	45 m	2×10^9	0.2	0.0006	360
Laboratory experiment	3 m	0.6 m	0.17 m	4×10^5	0.3	0.04	7.5

$$\text{Disp} = h^2/\lambda^2. \qquad (6)$$

The calculated dispersion coefficients for ship waves and tsunamis of landslide origin are $O(10^{-2})$ for both ship-induced waves and landslide tsunamis (Table 2). Therefore, both ship waves and tsunamis can be described by shallow-water or weakly dispersive theory. The large-scale Tafjord tsunami corresponds to a much smaller value of the dispersion coefficient of $O(10^{-4})$. This result suggests that events of such a large scale as the largest earthquake tsunamis can be described by nondispersive theory.

The character of the wave process in a basin of constant depth is usually characterized by the Ursell number (Whitham, 1974; Murty, 1977; Pelinovsky, 1982, 2006)

$$\text{Ur} = A\lambda^2/h^3, \qquad (7)$$

which is the ratio of the typical magnitudes of nonlinearity and dispersion. It has comparable values for ship waves and several tsunamis. As it frequently is O(1), both nonlinear and dispersive effects are excepted to affect the propagation of ship waves and tsunamis. Therefore, long-term evolution of both wave classes may result in the formation of solitary waves or solitons (Table 2). The Ursell number for Tafjord tsunami is significantly larger and lies outside of the range of values for vessel waves.

The scale analysis that was performed and the data summarized in Table 2 suggest that high-speed vessel waves in semi-enclosed sea areas can be used as an appropriate natural model of tsunamis caused by landslides of moderate size. The dimensions of Tallinn Bay correspond to a tsunami path of 200 km in real conditions. A match of all the significant scales indicates that physical modeling of realistic tsunami dynamics in the coastal zone (including wave refraction, diffraction, and sea-bottom interaction) by means of vessel-induced waves is possible by means of the relevant down- or upscaling. A favorable feature of Tallinn Bay is that the wind wave background is very low during a large part of the high navigation season: significant wind wave heights are in the range of 10–20 cm and reach 50–70 cm during short wind events, with periods of 2–4 s. Thus, Tallinn Bay can be considered an ideal natural laboratory for modeling of dynamics of tsunamis caused by landslides, in the coastal zone.

4. *Modeling of Tsunami Runup*

Frequently, vessel waves substantially increase in height in the near-shore region (Hamer, 1999) and may have a destructive impact even on remote coasts (Parnell *et al.*, 2008; Soomere, 2005). Their runup height on a beach may reach 2 m, whereas typical runup of wind waves is about 30–40 cm height in Tallinn Bay (Didenkulova *et al.*, 2009).

Tsunamis are known to be catastrophic and destructive at the coast. In general, vessel waves can also be dangerous for people in shallow water and on the shore. The first adequately documented fatal accident caused by a wake from a fast ship was in 1912 (Soomere, 2007). Four people are believed to have been killed directly or indirectly by waves from high-speed ferries in Tallinn Bay since they started operation in the late 1990s (Soomere *et al.*, 2002; Jõevere, 2003).

Ship waves may also dramatically increase coastal erosion and disturb marine habitats. Several features of ship wakes (such as their longer length and/or different propagation direction) may lead to substantial changes to the nature of the local erosion–

accretion system. For example, on Aegna Island in Tallinn Bay, four early-morning ship wakes reduced the beach volume by about 1 m^3 of mixed sand and gravel sediment per meter of coastline. A single ship wake was observed to move up coast or wash away (by 1–2 m) heavy boulders about 40 cm in diameter (Soomere *et al*., 2009).

Mastronuzzi and Sanso (2000) report that boulders more than 70 cm in diameter were moved by tsunami 30 m inland and 1–2 m uphill. It is known that the characteristic distance of boulder transport does not exceed the tsunami wavelength (due to friction). Given that the length for ship waves is 10–20 times smaller than for tsunamis (Table 2), the expected distance of boulder transport for ship waves is 1.5–3 m, which corresponds to our observations (Parnell *et al*., 2008).

The excess water brought to the coast by strongly nonlinear wave motions is one of the factors leading to the destructive behavior of tsunamis in the coastal zone (Fig. 5). A landslide-induced tsunami is usually associated with a large initial displacement of a certain amount of water in relatively shallow water. This disturbance in many cases initially has a much more nonlinear character than, for example, earthquake-generated tsunamis in the deep ocean or swell waves even in the near-shore region. As a result, a landslide-induced tsunami often carries a significant amount of water with it. This is (to a first approximation) evident, for example, in the framework of the Korteweg-de Vries equation, where shallow-water solitons not only are located above the still water level but also create substantial displacement of water in their direction of propagation. This is very different from water transport under almost linear wave groups in the near-shore region, which generally results in pushing water back offshore (as demonstrated by Longuet-Higgins and Stewart, 1962) with setup being observed only in the surf zone. At large distance from the landslide tsunami source, such displacement usually is not evident (cf. Table 1) because of dispersion.

Unexpectedly large devastation by moderate-height tsunami may be, at least heuristically, associated with this sort of displacement of large amounts of water in the near field of several tsunamis. For example, the 1998 Papua New Guinea tsunami, caused by a submarine landslide, devastated three villages with the loss of over 2,200 lives (Tappin *et al*., 2008). A landslide in Skagway, Alaska, caused a tsunami that destroyed the southern 300 m of the railway dock and claimed the life of one construction worker (Kulikov *et al*., 1996). Unusually strong impact on the coast, however, also occurred for several earthquake tsunamis of moderate amplitude. During the 1992 Flores tsunami (Indonesia), the estimated wave runup on the southern coast of Babi Island (Moslem Village) was 3.6 m, which is quite moderate for tsunamis. However, this place sustained severe damage, so that only bare land was left and Moslem Village was devastated. All houses were completely destroyed, with 263 lives lost out of a population of 1,100. This is explained by the powerful water flow (Imamura *et al*., 1995), which is also a reason why vessel wakes of height less than 2 m can cause significant impacts.

Quite similar (but based on different physics) water transport has recently been observed in the field

Figure 5
Ship waves in Tallinn Bay (*left*) and waves from the 2004 Indian Ocean tsunami (*right*) near the coast

of transcritical ship waves (SOOMERE *et al.*, 2010). Namely, at relatively large distances from the sailing line (about 2.5–3 km), a small-amplitude (a few centimeters) but extremely long-lasting (up to 5 min) event of water elevation carries a substantial amount of water (up to 6 m^3 per each meter of coastline) towards the coast just before the highest ship waves arrive. The nature of this feature is not yet clear. It is possibly an almost degenerate undular bore (that has been extensively discussed in the Korteweg-de Vries framework). Alternatively, recent research into a forced Kadomtsev–Petviashvili equation for steady transcritical flows shows that an extremely long and long-crested elevation feature may extend very far from the source (ESLER *et al.*, 2007).

In many cases the devastation power of tsunamis may be enhanced by the presence of trapped waves. ISHII AND ABE (1980) suggested that the manifestation of the catastrophic 1952 Kamchatka tsunami on the Japanese coast is related to trapped waves. About 70% of the tsunami wave energy propagated along the Kurile Islands in the Pacific Ocean as trapped waves (FINE *et al.*, 1983). Landslide tsunamis are also known to directly generate shore-trapped, edge wave modes. This has already been observed in experimental testing (DI RISIO *et al.*, 2009) and numerical simulation of landslide tsunamis (TINTI *et al.*, 1999; SAMMARCO AND RENZI, 2008).

Waves induced by high-speed ferries approaching the coast at a certain angle are also able to generate trapped waves. Usually, the impact of trapped waves becomes evident in the form of beach cusps, such as those observed during the experiment in Tallinn Bay in summer 2009 (Fig. 6). The study of vessel-wave-induced trapped waves is an independent and interesting problem that is beyond the scope of this paper.

In the near-shore region, effects of wave shoaling and breaking become important. These processes can be characterized by the nondimensional surf similarity parameter, also known as the Iribarren number (MADSEN AND FUHRMAN, 2008):

$$\xi_\infty = \frac{\alpha}{\sqrt{H_\infty/\lambda_\infty}} = \sqrt{\frac{g\alpha^2T^2}{2\pi H_\infty}}, \qquad (8)$$

where λ_∞ and H_∞ are the wavelength and wave height in deep water, respectively, and α is the bottom slope. The breaker types on plane impermeable beaches can be classified in terms of this parameter, with $\xi_\infty < 0.5$ indicating spilling, $0.5 < \xi_\infty < 3.3$ plunging, and $\xi_\infty > 3.3$ surging breakers. Ship waves in Tallinn Bay are principally generated in shallow water, and we cannot use wave characteristics in the deep water for them. That is why we use a current value of ξ in Eq. (8) which corresponds to the local wave height H at or near the toe of the slope (MADSEN AND FUHRMAN, 2008). In this case parameter ξ varies in the range $0.2 \le \xi \le 5$ and includes all types of wave breaking. The largest ship waves (their parameters are discussed in the previous section), which cause the most significant damage at coasts, have $\xi \approx 0.5$. If waves with similar parameters at the sailing line had approached from deep water and only experienced the shoaling process, the relevant values of ξ would be even smaller. The surf similarity parameter for tsunamis caused by landslides has values within the range of ξ for ship waves (Table 3).

Figure 6
An indication of shore-trapped waves generated by ship waves in Tallinn Bay

Table 3

Properties of tsunamis at the coast

	Period, T	Wave height, H	ξ
Ship waves	up to 30 s	up to 2 m	0.2–5
Vajont 1960 tsunami	1 min	1 m	1.5
Stromboli 2002 tsunami	40 s	15 m	0.3
PNG 1998 tsunami	40 s	13 m	0.3
Tafjord 1934 tsunami	3 min	45 m	9.5
Laboratory experiment	0.6 s	0.17 m	0.8

The only exception is the Tafjord 1934 tsunami, which has a ξ value outside the range of the relevant values for ship waves or moderate landslide-induced tsunamis.

Another important parameter characterizing the process of wave runup is the wave breaking parameter (Didenkulova *et al.*, 2007, 2008)

$$\mathrm{Br} = \frac{4\pi^2 R}{g\alpha^2 T^2}, \tag{9}$$

where R is the runup height. The parameter defined by Eq. (9) has been introduced in the theory of nonlinear long-wave runup as the mathematical criterion of wave breaking with an increase in the wave height for a hyperbolic shallow-water system. Using the relation $\mathrm{Br} \sim 1/\xi^2$ (Didenkulova *et al.*, 2009), this parameter of essentially mathematical origin can be related to the basically empirical surf similarity parameter ξ. Owing to the nonlinear nature of this relationship, the analysis of the breaking parameter apparently gives some additional information about the behavior of essentially nonlinear long waves before breaking. Landslide-generated tsunamis have relatively short lengths in comparison with tsunamis of earthquake origin and often attack the coast as breaking waves with $\mathrm{Br} > 1$. The wave breaking parameter for ship waves of large amplitude is also $\mathrm{Br} > 1$ (Didenkulova *et al.*, 2009), and therefore, the process of runup and breaking of landslide tsunamis apparently can be reproduced in natural conditions by means of ship waves.

5. Conclusions

The problem of finding a dynamically similar substitute for tsunamis in safe, natural or laboratory conditions is discussed from the viewpoint of the potential use of some other frequently occurring wave types. It is demonstrated that virtually all the characteristic parameters governing propagation, transformation, and runup of a certain class of ship-induced waves match similar parameters of many landslide-generated tsunamis. Although this match is not universal and in many cases the lack of relevant data in the international literature does not allow the nondimensional parameters to be determined, use of certain types of vessel waves seems to be feasible for suitably downscaled properties and the impact of landslide tsunamis with the use of high-resolution measurement techniques normally only applied in laboratory situations. Note that this dynamical similarity is generally restricted to landslides of moderate size. Catastrophic tsunamis caused by large-scale slides are more similar to earthquake tsunamis and represent a different category of wave events.

Specifically, groups of long and high waves generated by high-speed ferries sailing at near-critical speeds in relatively large, semisheltered basins can be considered as a prospective model for physical modeling of tsunamis of landslide origin. The similarity is best for vessel waves in the immediate near-shore region and for modeling of coastal zone dynamics and runup of landslide-induced tsunamis. A promising site is Tallinn Bay in the northeastern part of the Baltic Sea. The very intense ship traffic in Tallinn Bay (up to 25 sailings a day) combined with the intrinsic variability of the parameters of vessel waves provides not only the possibility to collect experimental data of large-scale sea waves in a short time under safe and controlled conditions but also the option of considering a multitude of events with largely different properties.

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