BOREAL ENVIRONMENT RESEARCH 16 (suppl. A): 138–148
ISSN 1239-6095 (print) ISSN 1797-2469 (online) Helsinki 31 March 2011

Shapes of freak waves in the coastal zone of the Baltic Sea (Tallinn Bay)

Ira Didenkulova

Laboratory of Wave Engineering, Institute of Cybernetics at Tallinn University of Technology, Akadeemia tee 21, Tallinn 12618, Estonia; and Department of Nonlinear Geophysical Processes, Institute of Applied Physics, Uljanov Street 46, Nizhny Novgorod 603950, Russia

Received 19 Nov. 2009, accepted 23 Aug. 2010 (Editor in charge of this article: Kai Myrberg)

Didenkulova, I. 2011: Shapes of freak waves in the coastal zone of the Baltic Sea (Tallinn Bay). *Boreal Env. Res.* 16 (suppl. A): 138–148.

The properties of extreme sea surface waves (freak waves) in shallow water and, particularly, their shape are analysed based on the high-resolution records of sea surface elevation in Tallinn Bay, the Baltic Sea, measured at the water depth 2.7 m from 21 June to 20 July 2008. The data set contains 97 freak waves, which occur in both calm and relatively rough weather conditions. It is shown that typical shapes of freak waves in the nearshore differ from those which are known for the deep sea. No groups of subsequent extreme waves, like the famous “three sisters” usually reported by eyewitnesses and measured instrumentally in the open sea, are found for the coastal zone. All freak waves in the records are single waves: 63% of them have positive, 19.5% sign-variable and 17.5% negative shape. It is shown that both the frequency of occurrence and the wave height of positive freak waves are correlated with the significant wave height. The height of sign-variable freak waves, which are observed only in relatively calm weather conditions, also changes in accordance with the significant wave height, while the height of negative freak waves shows no explicit dependence on the background wave height. It is found that 90% of all recorded freak waves have the height in the range from 2.0 to 2.3 times the significant wave height. About 10% of freak waves with the largest amplification (from 2.3 to 3.2 times the significant wave height) have a negative shape and their amplification factor decreases with an increase in the significant wave height.

Introduction

The problem of frequent occurrence of freak waves (rogue waves) received much attention in scientific literature during the last decades. It has been realised that, in many situations, extreme single waves can cause significant damage to or even failure of a marine structure. A great number of ship accidents in open ocean apparently have been caused by freak waves (Toffoli *et al*. 2005). That is why most attention has been paid to a freak wave occurrence in the deep part of the ocean, with the aim to prevent ship accidents and damages of ocean platforms. A large number of accidents have been reported from the North Sea that has become a place of intense studies (Magnusson *et al*. 1999, Guades Soares *et al*. 2004, Walker *et al*. 2004, Stansell 2005, Petrova *et al*. 2006). An extreme wave data analysis has been also performed for the Mediterranean (Prevosto

Fig. 1. Freak waves in Mavericks Beach (California, USA) on 14 February 2010 (©Scott Anderson; reproduced with permission from the copyrigh owner).

et al. 2000), Japan Sea (Mori and Yasuda 2002), Gulf of Mexico (Al-Humoud *et al*. 2002), Black Sea (Cherneva *et al*. 2005) and Kuwaiti territorial waters (Neelamani *et al*. 2007).

Freak waves are also observed and measured in the Baltic Sea (Paprota *et al*. 2003, Sulisz and Paprota 2005). Probably, the latest dramatic example was the case of sinking of a 25-meter Latvian fishing vessel in Danish territorial waters near the island of Bornholm on 17 February 2009, where two people died. The crew said that the ship was struck by a heavy wave, after which it capsized and sank.

Similar freak wave events are also observed in nearshore regions (Chien *et al*. 2002, Cherneva *et al*. 2005, Didenkulova *et al*. 2006). They frequently lead to damage of coastal structures and loss of lives. Chien *et al*. (2002) reported about 140 freak wave events in the coastal zone of Taiwan in the past 50 years (1949–1999). Some of coastal freak wave events described by eyewitnesses in 2005 are presented in Didenkulova *et al*. (2006). One of those occurred on 16 October 2005 in Trinidad and Tobago, when "a series of towering waves, many over 7 m high according to eyewitnesses, sent sunbathers, vendors and lifeguards running for their lives". Similar waves attacked Mavericks Beach in California, USA, on 14 February 2010, when two unexpected 6-m-high waves washed off 13 people standing on the parapet at the coast (Fig. 1). Observations of such events become more frequent, and they broaden the area of possible freak wave occurrence.

Usually freak wave events occurring onshore result in a short-time sudden flooding of the coast (Fig. 1), or strong impact upon a steep bank or a coastal structure. Descriptions of such accidents are also given by Dean and Dalrymple (2002) and Kharif *et al*. (2009). Similar impacts on coastal structures are also observed during strong storms (*see* Fig. 2).

The properties of coastal freak waves differ from their sisters occurring in deep waters and need special analysis. One of the important characteristics of freak waves is their shape. Freak waves in deep waters are usually individual waves of exceptional height or a group of extreme waves (for example, so called "three sisters"). Single deep-water freak waves are characterized by both vertical and horizontal asymmetry. Their crests are usually high and sharp, whereas troughs are much shallower and wider (Guades Soares *et al*. 2004, Walker *et al*. 2004). These features are not necessarily the same in shallow waters or sea areas of intermediate depth. However, the shape of a freak wave is especially important in the coastal zone, since it may cause death of people on the shore or in the nearshore region, and this topic has not been studied yet. This paper focuses on the identification of possible changes in the freak wave shape in shallow water. This issue is studied based on the wind-wave data recorded in the coastal zone of the Baltic Sea.

Study site and wave measurements

The measurements of waves were carried out in

Fig. 2. The wave hitting the lighthouse during the storm in Porthcawl, South Wales (©Nick Russill; reproduced with permission from the copyrigh owner).

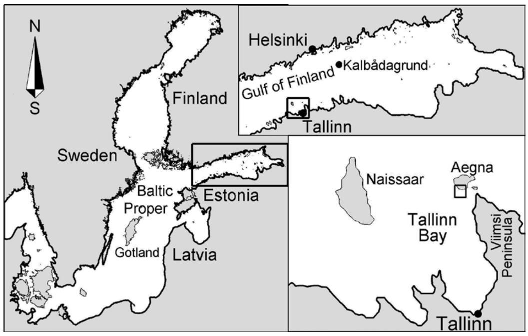

Fig. 3. The study site on the SW coast of Aegna (lower right-hand-side panel).

the Tallinn Bay, the Baltic Sea (Fig. 3). The overall setup of the experiment is described in detail in Parnell *et al*. (2008).

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. 3), 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 2.42 m. Since very high (more than 1 m above the mean sea level) water level events are rare, the wind wave impact is concentrated within a relatively narrow range in the coastal zone.

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

As a result of these factors, the local wave climate is relatively mild in Tallinn Bay as compared with that in the adjacent sea areas. The significant wave height exceeds 0.5–0.75 m in the Bay with a probability of 10% and 1.0–1.5 m with a probability of 1% (Soomere 2005). 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 the central part of the Bay during extreme NNW storms.

The wind-wave measurements were performed by the SW coast of Aegna in Tallinn Bay (Fig. 3). The island, about 1.5 × 2 km in size, is located at the northern entrance to 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 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. 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 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 W–SW end of Aegna, Fig. 3) and even if they reach the SW coast owing to refraction, they impact the coast in a similar way to waves approaching from the west. The western side of the jetty is protected by tetrapods.

High-resolution time series of water surface elevations were collected using an ultrasonic echosounder LOG_aLevel® from General Acoustics, designed as a complete, stand-alone remote-sensing water-level gauge, which was mounted on top of a heavy tripod at a location about 100 m from an effectively non-reflecting shore of the island of Aegna and the southern end of the jetty (59°34.259´N, 24°45.363´E) at a depth of ~2.7 m. The measurement range of the sensor was 0.5–10 m to the water surface with the accuracy of ±1 mm. Looking down and reflecting from the water surface it gives a good representation of waves of the negative shape. It is also proved by our measurements experience that measurement errors are very visible in the record and can always be detected and eliminated.

The surface water elevation data were collected continuously over 30 days (21 June–20 July 2008) at a recording frequency of 5 Hz. A large part of the experiment was performed in calm conditions (significant wave height H_s below 0.1 m). It also reached 0.6 m during short time intervals.

Recorded freak waves

Although overall waves in the study region are relatively low, freak wave events occur also there. Freak waves were identified as those, whose height was at least twice as large as the significant wave height ($H \geq 2H_s$). The threshold for a single wave to be identified as a freak wave obviously varies with the height of the background from calm to stormy days. We analyzed all measured freak waves, which satisfied this criterion, to get the full picture of the potential of occurrence of unusually high waves in the coastal zone.

Here we present the analysis of shapes of the recorded freak waves in Tallinn Bay, the Baltic Sea. Since this region has a very intense ship traffic during the daytime (Parnell *et al.* 2008), we processed only pure wind-wave data recorded during nights (from 00:00 to 07:00). The heights of all waves, which occured from 00:00 to 07:00 every day were calculated using the down-crossing method. The approximate significant wave height was estimated as an average height of 1/3 of the highest waves. This quantity was calculated for every 20-min interval, during which wave conditions apparently did not change. This interval is usually used for finding H_s in both deep water (for example, Stansell 2005) and a coastal zone (Cherneva *et al.* 2005). A total of 609 such 20-minute intervals during 29 days of measurements were studied. These intervals contained ~400 000 single wind waves, only 97 of which were identified as freak waves. The Raileigh distribution (if the wind wave field has narrow-band Gaussian statistics) predicts the occurrence of a freak wave ($H_f \geq 2H_s$) once in 3000 wave events (Kharif *et al.* 2009). It corresponds to 130 freak wave events for our number of waves, which is close to the number we recorded. However, among the 97 freak waves recorded in the experiment there were 3 waves with a wave height greater than 3 ($H_f \geq 3H_s$), while the Raileigh distribution gives very small probability (<< 1) for waves of this height.

All the selected 97 freak events were single waves. No groups of freak waves consisting of two or three (so-called “three sisters”) subsequent freak waves (*see*, for example, Kharif *et al.* 2009) were recorded. The recorded freak waves had either positive, negative or sign-variable shapes. The positive shape means that the wave-crest amplitude with respect to the mean sea level is at least 50% greater than the wave-trough amplitude (Fig. 4). Opposite is true for waves having a negative shape (Fig. 5). The rest of freak waves are called sign-variable (Fig. 6).

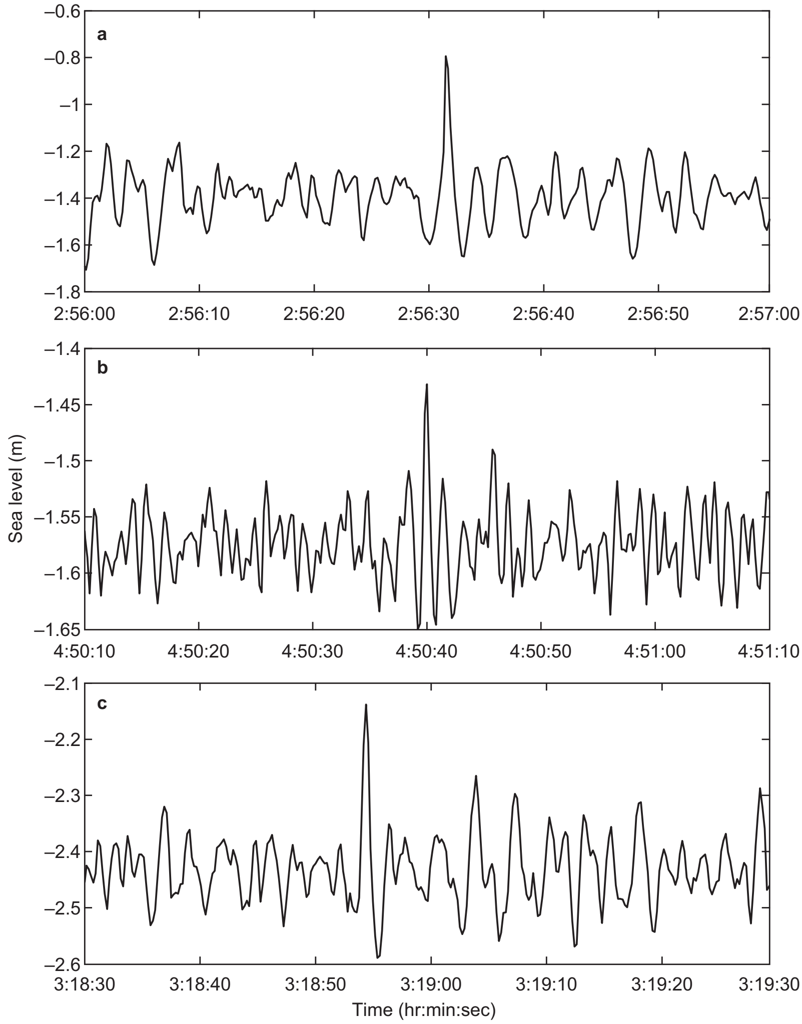

Fig. 4. Freak waves of a positive shape in Tallinn Bay on (**a**) 26 June, (**b**) 7 July and (**c**) 15 July 2008. The sea level is measured as a distance from the echosounder to the water surface.

The wave periods varied from 1 to 6 s depending on weather conditions and wind direction. This difference can be well seen in Fig. 6. Note that the threshold for freak waves and, consequently, the height of such waves follows the significant wave height and varies from several centimeters up to more than one meter.

Most of the freak waves (61 events or 63% of waves) had a positive shape. The numbers of waves having sign-variable and negative shapes were substantially smaller: 19 events (19.5%) and 17 events (17.5%), respectively.

Importantly, all measured freak waves were also asymmetric in terms of front–back asymmetry. In general, negative-shape waves were more asymmetric than the positive and sign-variable waves. This distribution is in acordance with the nonlinear shallow-water wave theory stating that the wave asymmetry and wave breaking affect the wave trough more than the wave crest: the back slope of negative waves is steeper than the front; while in the case of positive and sign-variable waves, the front slope is steeper than the back (Didenkulova *et al*. 2007, Zahibo *et al*. 2008). The fact that waves of a sign-variable shape are less asymmetric than freak waves of positive and negative shapes, can be explained by the wave nonlinearity. As such, sign-variable waves have smaller deviation from the mean water level, hence their propagation is less affected by nonlinear effects than that of positive or negative waves of the same height. This also

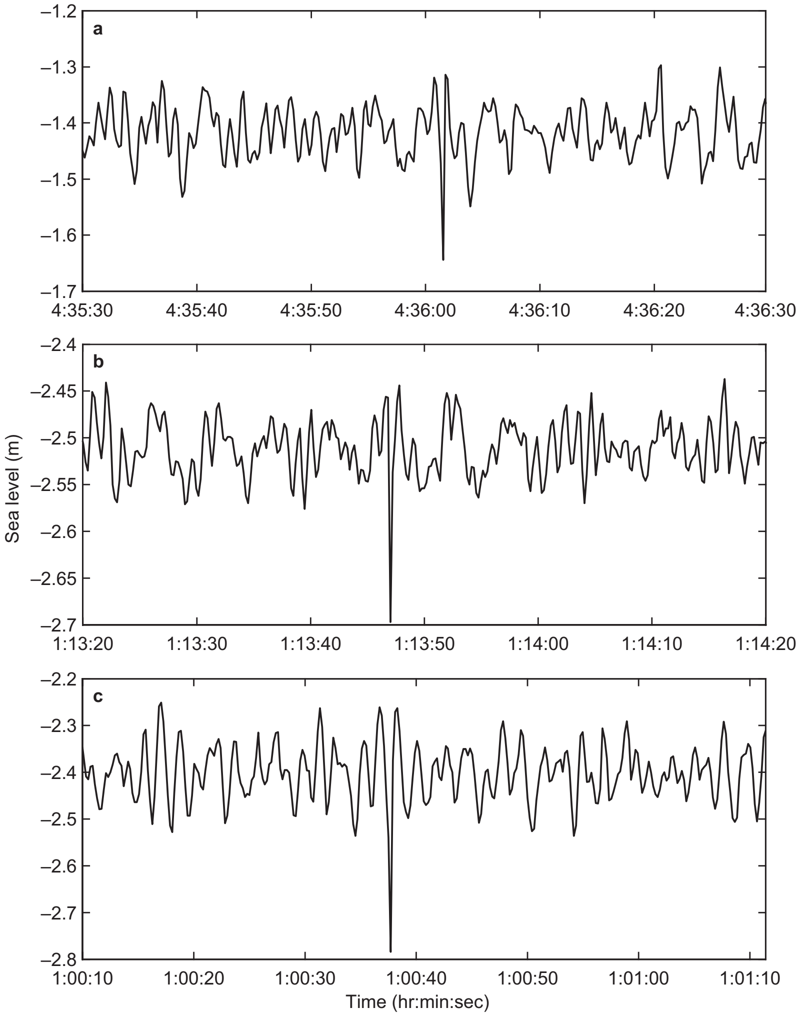

Fig. 5. Freak waves of a negative shape in Tallinn Bay on (**a**) 28 June, (**b**) 13 July and (**c**) 19 July 2008. The sea level is measured relatively to the location of the echosounder.

explains why freak waves of a smaller height are generally less asymmetric.

The frequency of occurrence of freak waves of different shapes changed during the month (Fig. 7). The total number of freak waves was relatively high in the beginning of measurements. Altogether 8 freak waves were recorded on 24 June. The number of freak-wave events per day decreases monotonically until 5–9 July. A strong peak was observed on 7 July (8 freak waves). This day also contains the largest number of sign-variable freak waves. Further on, the number of freak waves monotonically increased until the end of the month when it reaches its absolute maximum (9 freak waves on 20 July).

The frequency of occurrence of positive freak waves during the month has mostly a similar variation as for the total number of freak waves. The only difference is that the peak for positive freak waves on 7 July is small and almost negligible. The number of sign-variable freak waves is usually quite small: no more than one per night until 7 July. On this day, the maximum number of five sign-variable freak waves occured. Further on, the number of such events decreased and did not exceed two until the end of the measurement period. The frequency of occurrence of negative freak waves had its maximum on 13 July.

These fluctuations of occurrence of freak waves can be related to variations of the significant wave height during the measurements

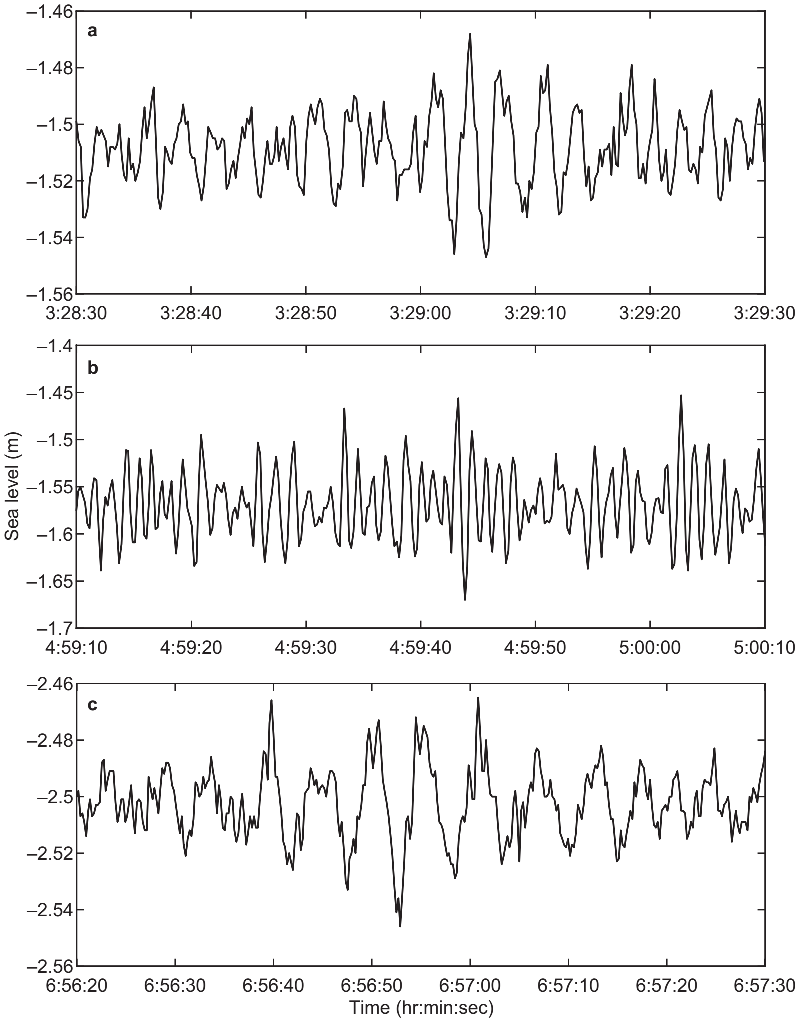

Fig. 6. Freak waves of a sign-variable shape in Tallinn Bay on (**a**) 5 July, (**b**) 7 July and (**c**) 20 July 2008. The sea level is measured relatively to the location of the echosounder.

(Fig. 8). There is a strong correlation between the total number of freak waves and H_s, which becomes clearly evident for the 5-day average number of freak waves $\bar{N}$ and an averaged significant wave height $\bar{H}_s$ ($\bar{N} = 15.07\bar{H}_s$ correlation coeff. 0.9, *see* Fig. 9). The number of positive freak waves is correlated with the significant wave height in a similar way as the total number of freak waves. The variations of the frequency of occurrence of negative and sign-variable freak waves, however, have no clear correlations with variations of the significant wave height. For instance, H_s is relatively low and even decreases, when the maximum number of negative and sign-variable freak waves occurs.

The distribution of freak wave heights and the corresponding distribution of local significant wave heights (for those 20-minute intervals when freak waves occur) for different wave shapes are presented in Figs. 10 and 11. The vertical resolution in Figs. 10 and 11 is 0.1 m and 0.05 m, respectively.

It is hard to see any regularity in the distribution of the total number of freak wave heights in Fig. 10. The distribution is almost uniform, except for only one strong peak at 0.5 m. There is no evidence of a correlation between it and the corresponding distribution of local significant wave heights in Fig. 11. However there is a correlation between the heights of positive freak waves and the significant wave height for both total number of waves and for positive freak waves only. It also

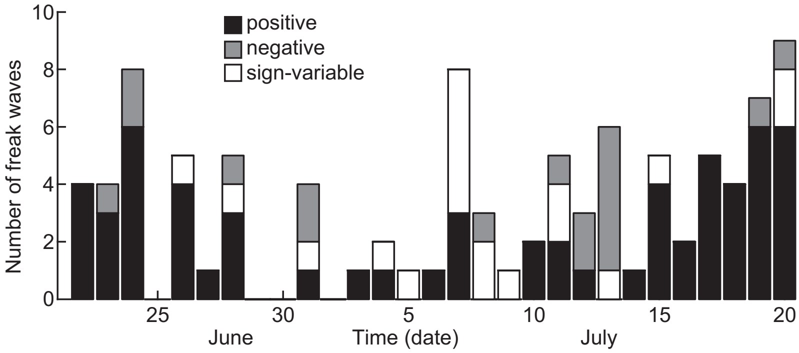

Fig. 7. Wave occurrence during measurements (00:00 to 07:00).

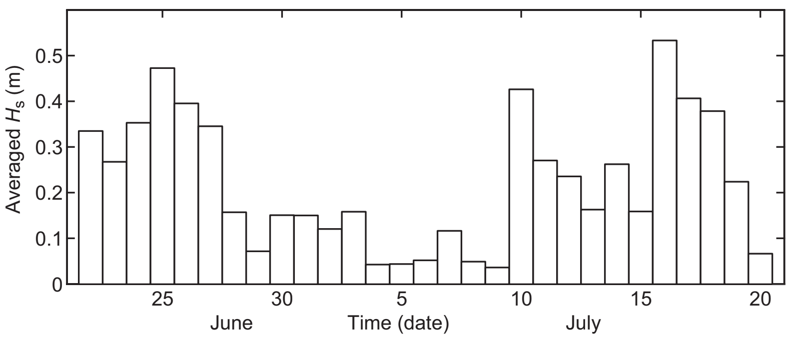

Fig. 8. Average significant wave height during the nights of 21 June–20 July 2008.

follows from Fig. 11 that positive freak waves occur for all the range of H_s observed in Tallinn Bay. The distribution of heights of sign-variable freak waves also more or less matches the distribution of the significant wave heights (again, both for total number of waves and for sign-variable freak waves only). Such freak waves occur, however, only in relatively calm weather conditions for values of H_s below 25 cm. Negative freak waves occur for significant wave heights from 0.1 m to 0.4 m and their frequency of occurrence does not show any clear correlation with H_s.

The amplification factor of the majority of freak waves (90%) is below 2.3. This range (2.0–2.3) includes freak waves of all different shapes (Fig. 12). A considerable amount (about 10%) of freak waves has a significant amplification ranging from 2.3 to 3.2, and almost all such waves have a negative shape. The described feature is illustrated in Fig. 13 where the amplification factor of the majority of freak waves reveals no clear dependence on the significant wave height, while for negative freak waves with a significant amplification (larger than 2.4) it decreases in average with an increase in H_s. This decrease

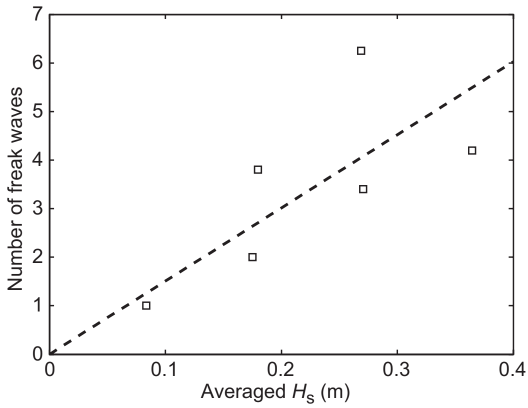

Fig. 9. Correlation between 5-day average number of freak waves and the significant wave height.

of the amplification factor with the significant wave height can be explained by the process of wave breaking, which more strongly affects nonlinear waves of larger amplitude. Although visual observations during the day time show that most of the waves do not break at the point of measurement, the largest of them, of course, should be affected by breaking. At the same time negative waves are more subject to the

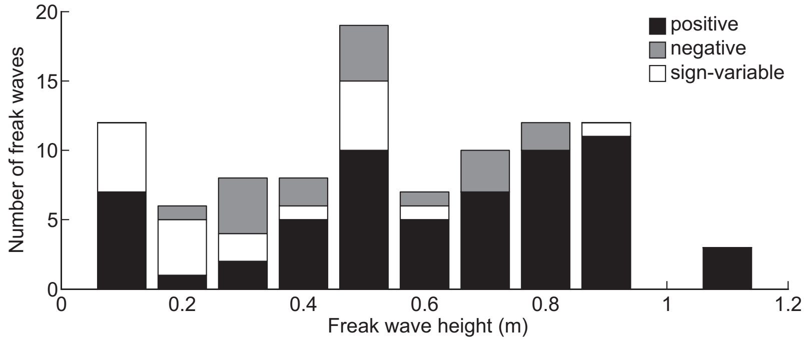

Fig. 10. The distribution of heights of freak waves of different shapes.

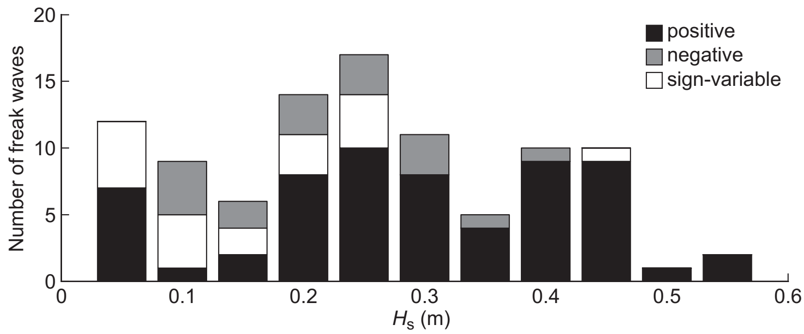

Fig. 11. The distribution of local significant wave heights, for which freak waves occur, for freak waves of different shapes.

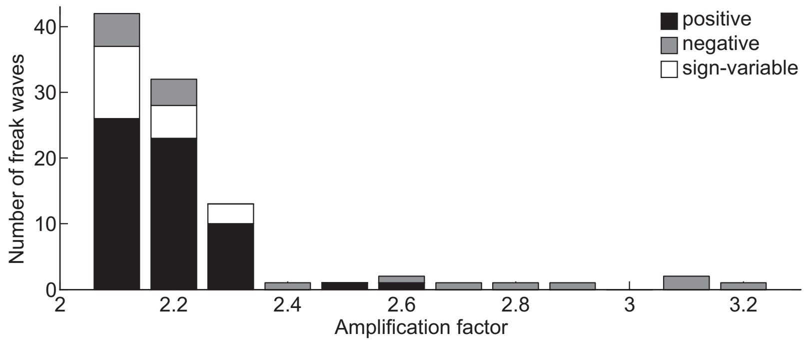

Fig. 12. The distribution of the amplification factor for freak waves of different shapes.

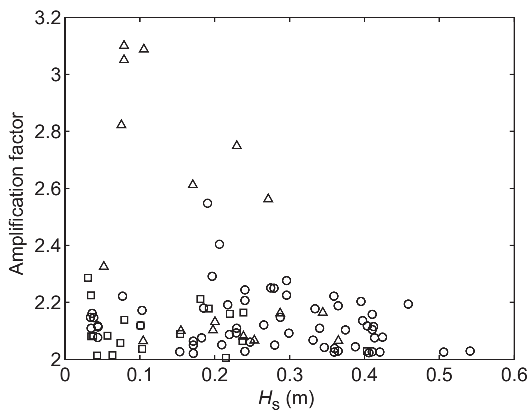

Fig. 13. Scatter diagram of amplification factors and significant wave heights for positive (circles), negative (triangles) and sign-variable (squares) freak waves.

breaking phenomenon: even in the case of sine wave propagation in the basin of constant slope, breaking usually occurs at the trough of the wave (Zahibo *et al*. 2008). This property is to some extent illustrated in Figs. 4 and 5: in contrast to the positive freak waves, the negative ones have a very sharp ending that can reflect the process of wave breaking.

Conclusion

The shape of freak waves in the coastal zone is analysed based on sea surface elevations recorded in the Baltic Sea at the water depth

2.7 m in June–July 2008. This dataset contains 97 freak waves, which occur in both calm and relatively rough weather conditions. No groups of subsequent freak waves have been recorded. All 97 freak waves are single waves of positive, negative or sign-variable shape. Most of the waves (63%) had positive shape, 19.5% had sign-variable and 17.5% had negative shape. All the waves are asymmetric in terms of front–back slope asymmetry, whereas the waves of negative shape are the most asymmetric.

It should be mentioned that the scale of wave heights that is dangerous in deep and shallow water is different. In deep waters it is mostly defined by the ship size and in coastal zone is defined by men's height. As it is known, even 0.5-meter wave flow on the coast can be hazardous. The typical velocity of such flow is about 2 m s^{-1} and it is strong enough to knock the person off his feet and to kill him. Such events were mentioned in our paper (Didenkulova *et al*. 2006). During our experiment in Tallinn Bay we measured 44 waves with the wave height exceeding 0.5 m and 3 waves with the height more than 1 m.

It is shown that frequency of occurrence of positive freak waves is correlated with the significant wave height and increases with an increase in H_s, while distributions of sign-variable and negative freak wave occurrence do not have such correlation.

Freak waves of a positive shape occur for all values of the significant wave height observed in Tallinn bay during the experimental period. Sign-variable freak waves are observed only in relatively calm weather conditions (H_s below 0.25 m) and negative freak waves occur for significant wave heights from 0.1 m to 0.4 m.

The distributions of heights of positive and sign-variable events change in accordance with the significant wave height, while the frequency of occurrence of negative freak waves does not depend on H_s.

The amplification factor of 90% of all recorded freak waves is in the range from 2.0 to 2.3, which includes freak waves of all different shapes, while 10% of freak waves with the largest amplification (from 2.3 to 3.2) have a negative shape and their amplification factor decreases with an increase in H_s. This dependence can be explained in terms of wave breaking.

Acknowledgements: This research was supported by targeted financing by the Estonian Ministry of Education and Research (grants SF0140077s08 and SF0140007s11), Marie Curie network SEAMOCS (MRTN-CT-2005-019374), Estonian Science Foundation grant (8870), EEA grant (EMP41), RFBR grant (11-05-00216) and also received funding from the European Community Seventh Framework Programme FP7-SST-2008-RTD-1 under grant agreement no. 234175.

References

Al-Humoud J., Tayfun M.A. & Askar H. 2002. Distribution of nonlinear wave crests. *Ocean Eng*. 29: 1929–1943.

Caliskan H. & Valle-Levinson A. 2008. Wind-wave transformations in an elongated bay. *Cont. Shelf Res*. 28: 1702–1710.

Cherneva Z., Petrova P., Andreeva N. & Guades Soares C. 2005. Probability distributions of peaks, troughs and heights of wind waves measured in the black sea coastal zone. *Coastal Eng*. 52: 599–615.

Chien H., Kao C.C. & Chuang L.Z.H. 2002. On the characteristics of observed coastal freak waves. *Coastal Eng. J*. 44: 301–319.

Dean R.G. & Dalrymple R.A. 2002. *Coastal processes with engineering applications*. Cambridge University Press, New York.

Didenkulova I., Pelinovsky E., Soomere T. & Zahibo N. 2007. Runup of nonlinear asymmetric waves on a plane beach. In: Kundu A. (ed.), *Tsunami and nonlinear waves*, Springer-Verlag, Berlin, Heidelberg, pp. 173–188.

Didenkulova I.I., Slunyaev A.V., Pelinovsky E.N. & Kharif Ch. 2006. Freak waves in 2005. *Nat. Hazards Earth Syst. Sci*. 6: 1007–1015.

Guades Soares C., Cherneva Z. & Antao E.M. 2004. Steepness and asymmetry of the largest waves in storm sea states. *Ocean Eng*. 31: 1147–1167.

Kharif Ch., Pelinovsky E. & Slunyaev A. 2009. *Rogue waves in the ocean*. Springer-Verlag, Berlin, Heidelberg.

Kurkin A. & Pelinovsky E. 2002. Focusing of edge waves above sloping beach. *European Journal of Mechanics B/Fluids* 21: 561–577.

Magnusson A.K., Donelan M.A. & Drennan W.M. 1999. On estimating extremes in an evolving wave field. *Coastal Eng*. 36: 147–163.

Mori N. & Yasuda T. 2002. A weakly non-gaussian model of wave height distribution for random wave train. *Ocean Eng*. 29: 1219–1231.

Neelamani S., Al-Salem K. & Rakha K. 2007. Extreme waves for Kuwaiti territorial waters. *Ocean Eng*. 34: 1496–1504.

Paprota M., Przewłócki J., Sulisz W. & Swerpel B.E. 2003. Extreme waves and wave events in the Baltic Sea. In: *Rogue waves: forecast and impact on marine structures*, GKSS Printing Office, Chapter 1.2.

Parnell K., Delpeche N., Didenkulova I., Dolphin T., Erm A., Kask A., Kelpšaite L., Kurennoy D., Quak E., Räämet A., Soomere T., Terentjeva A., Torsvik T. & Zaitseva-Pärnaste I. 2008. Far-field vessel wakes in Tallinn Bay.

Estonian J. Eng. 14: 273–302.

Petrova P., Cherneva Z. & Guades Soares C. 2006. Distribution of crest heights in sea states with abnormal waves. *Appl. Ocean Res*. 28: 235–245.

Prevosto M., Krogstad H.E. & Robin A. 2000. Probability distributions for maximum wave and crest heights. *Coastal Eng*. 40: 329–360.

Rabinovich A.B. & Monserrat S. 1998. Generation of meteorological tsunamis (large amplitude seiches) near the Balearic and Kuril Islands. *Natural Hazards* 18: 27–55.

Soomere T., Behrens A., Tuomi L. & Nielsen J.W. 2008. Wave conditions in the Baltic Proper and in the Gulf of Finland during windstorm Gudrun. *Nat. Hazards Earth Syst. Sci*. 8: 37–46.

Soomere T. 2005. Wind wave statistics in Tallinn Bay. *Boreal Env. Res*. 10: 103–118.

Stansell P. 2005. Distributions of extreme wave, crest and trough heights measured in the North Sea. *Ocean Eng*. 32: 1015–1036.

Sulisz W. & Paprota M. 2005. Analysis of wave parameters in extreme wave records. In: *Maritime Transportation and Exploitation of Ocean and Coastal Resources: Proceedings of the 12th International Congress of the IMAM*. Taylor and Francis Group, London, pp. 1153–1158.

Toffoli A., Lefevre J.M., Bitner-Gregersen E. & Monbaliu J. 2005. Towards the identification of warning criteria: analysis of a ship accident database. *Appl. Ocean Res*. 27: 281–291.

Walker D.A.G., Taylor P.H. & Eatock Taylor R. 2004. The shape of large surface waves on the open sea and the Draupner New Year wave. *Appl. Ocean Res*. 26: 73–83.

Zahibo N., Didenkulova I., Kurkin A. & Pelinovsky E. 2008. Steepness and spectrum of nonlinear deformed shallow water wave. *Ocean Eng*. 35: 47–52.