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Measurements of Long Waves in Port of Klaipėda, Lithuania

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ABSTRACT

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Port of Klaipėda is in Klaipėda Strait that connects the Curonian Lagoon with the south-eastern Baltic Sea. Its quays are well sheltered from open sea waves but the port area still hosts dangerous water level oscillations that are apparently generated in the system consisting of the Curonian Lagoon and a strait that connects the lagoon with the Baltic Sea proper. The analysis of spectral composition of these oscillations is based on continuous pressure recordings with a frequency of 4 Hz in Port of Klaipėda during the stormy season December 2016–January 2017. The majority of the energy of oscillations is concentrated in three frequencies bands. Considerable water level changes occurred owing to infragravity motions with periods >30 s (<0.03 Hz) and disturbances with the typical periods of wind waves at the Lithuanian coast with periods of 3–10 s (0.1–0.3 Hz). The highest peak in the wind wave frequency band corresponds to typical storm conditions in the Baltic Sea with periods 9–5 s. While the typical amplitudes of oscillations in this range were modest, particularly hazardous changes in the water level, with amplitudes >0.5 m, were created at lower frequencies. The recording reveals the presence of harbor oscillations with periods 30–200 s (0.005–0.03 Hz) and seiches of the Curonian Lagoon with periods >1200 s (<0.0008 Hz).

ADDITIONAL INDEX WORDS: *water level, harbor oscillations, wind waves, long waves, shipping safety, Klaipėda Strait, Baltic Sea*.

INTRODUCTION

The most dangerous situations in semi-enclosed water bodies and harbors mainly occur due the unexpected and rapid water level changes. Such situations are often induced by the impact of long waves or by resonance of the water motions in small basins such as harbors or marinas excited by shorter waves. The resulting water level fluctuations and extensive seiches can cause excessive movements of vessels, compromise harbor operations, create danger to vessels, harbor constructions and in extreme cases even loss of lives (Brázdil *et al.,* 2010; Chen and Mei, 2006; de Jong and Battjes, 2004; Dragani *et al.*, 2009; Rabinovich, 2009; Thotagamuwage and Pattiaratchi, 2014). For many harbors, the most important natural modes oscillation have rather long periods, from several minutes to an hour (Rabinovich, 2009).

Even though Port of Klaipėda is a small port, strategically and geographically, it has several specific and unique features among the ports in the Eastern Europe. The port is located on the south-east coast of the Baltic Sea, in Klaipėda Strait. The port is located in the middle of the 12 km long and up to 1.5 km wide inlet where the width of the free-flowing part of Klaipėda Strait is only 0.4 km (Figure 1). The entire strait is not only the basis of the port aquatorium and a vital navigational artery from the Baltic Sea proper to the Curonian Lagoon, but also a complex water system. It connects two water basins of with large different size, depth and properties (incl. substantially contrasting salinity and density). The waters of the Curonian Lagoon are almost fresh whereas the salinity of the Baltic Sea in the Lithuanian nearshore is about 3-4 ‰ (Leppäranta and Myrberg, 2009). The two basins also have greatly different scales and properties of their physical and biological processes (Jakštas *et al*., 2003; Žaromskis, 2008).

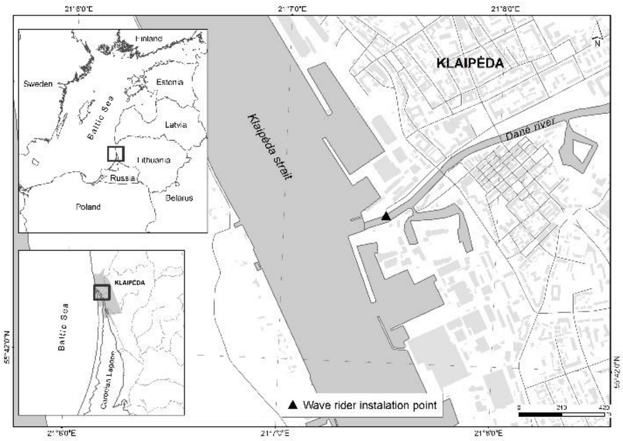

Figure 1. Study site.

The layout of Port of Klaipėda is designed as a semi-open interior basin. The entrance to Klaipėda Strait is protected from

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*Corresponding author: loreta.kelpsaite-rimkiene@ku.lt the hydrodynamic drivers of the open Baltic Sea by two jetties. The gateway to the landing quays is only partially protected by jetties and several quays are widely open to the main body of the strait. Such a port gateway design does not completely protect the inland port waters from the effects of waves (Kirlys, 2000). This solution assumes that the marine area adjacent to the harbor is perfectly sheltered against high waves. This assumption is only conditionally valid for Port of Klaipėda. Firstly, large wind waves created in the Baltic Sea proper by north-western winds may enter Klaipėda Strait from a specific direction. The strait serves as a wave guide for such waves. North-western winds are one of the strongest in the northern Baltic Sea (Soomere, 2003). Moreover, large vessels sailing in such long, narrow and relatively shallow straits may generate strong wave wakes (see Soomere, 2005 for an overview of the related processes) and dangerous water level dropdowns (Parnell *et al.*, 2014).

The depicted features of Port of Klaipeda give rise to hazardous situations of different kind. Some of them have led to major accidents. The most significant incident happened on 22 November 1981 when the UK tanker *Globe Asimi* sank in Klaipėda Strait. This event led to the dumping of 16,493 tons of fuel oil into the sea. The outflowing current transported the oil slick to into the Baltic Sea proper and stormy winds carried it by more than 80 km along the seashore so that oil reached even the Latvian shores.

The onset of this disaster was triggered by harsh meteorological conditions (wind speed >22 m/s). It was well known that waters in Port of Klaipėda are prone to experience hazardous oscillations under such conditions. *Globe Asimi* made an attempt to leave the port to mitigate the risk of snapping of the mooring ropes and collisions with other vessels within the port area. The attempt was unsuccessful, the ship was thrown to the port jetties and sank to the north of Port of Klaipėda (Butkus, 2016).

The jetties protecting the landing quays were reconstructed and prolonged, and underwent certain changes in their configuration in 2002. However, situations when hazardous oscillations snap the mooring ropes and render ships unmanageable still occur in the port (Aleksėjūnaitė, 2017).

The aim of this study is to identify the occurrence of large amplitude (>0.5 m) oscillations with typical periods from a few minutes to almost half hour and to establish their characteristics in Port of Klaipėda.

METHODS AND DATA

The measurements of local water level fluctuations were performed using an autonomous water level recorder LM2 constructed and manufactured by PTR Group (Tallinn, Estonia). The device (basically a pressure gauge based on a Keller pressure sensor) was mounted according to the classical scheme (*e.g.* Soomere, 2005) in the water column about 2 m below water surface to reliably measure the displacements of the water surface with periods starting from about 2 s.

Time series of water level was measured during 31 days from 22 December 2016 till 21 January 2017. The continuous pressure times series was recorded with a frequency of 4 Hz. To exclude high-frequency components (short waves) and noise, and to reduce the size of the record we averaged the entries over 4 subsequent samples. Further, the record was de-meaned and de-trended, and converted into time series of water level using linear wave theory.

Spectral analysis was applied to the resulting water level data to identify the predominant frequencies and periods of recorded oscillations. The classic Fourier transform was used to construct time-frequency plots from the auto-spectra and to identify the temporal changes in the spectral energy distribution (STFT). The time series were split into sections of 1024 points (covering about 17 min). The power spectrum (Bendat and Piersol, 1986) in each section was evaluated using the "Welch" method and Cooley-Turkey Fast Fourier Transform (FFT) algorithm (Little and Shure, 1988). A 50 % overlap (*i.e.*, 512 points from a section) was used to calculate subsequent auto-spectra. Band pass filters were applied to water level time series to extract oscillation bands with the highest energy. Cut off frequencies were set to $0.1 < f < 0.3$ Hz; $0.03 < f < 0.01$ Hz and $0.001 < f < 0.0006$ Hz.

RESULTS

A predominant feature of the course of water level form short term, aperiodic water level fluctuations in Klaipėda Strait with an amplitude of about 0.3 m and periods of 20–30 min (Table 1). Hazardous situations in Port of Klaipėda occur when the water level undulations have the period of 0.5–3 min and their amplitude reaches about 50 cm (Gailiušis *et.al.*, 2010). These threshold values were compared with the properties of the predominant frequencies in the recorded signal.

Table 1. *Typical characteristics of long wavelike oscillations in Port of Klaipėda (according Gailiušis et.al., 2010).*

Type	Amplitude (m)	Period (min)	Frequency (mHz)
Seiche	0.3	20–30	0.8–0.5
Harbor oscillation	>0.5	0.5–3	30–5

Power density of spectra

The time series of unfiltered water levels measured in the port of Klaipeda show the water level variation during the entire measurement interval (Figure 2). The water level varies by more than 1.5 m. An abrupt drop in the water level by about 0.5 m occurred on the 5th measurement day and an even larger (about 0.8 m) but much gentler decrease occurred on the 21st day. In both case substantial water level changes occurred in less than 16 hours.

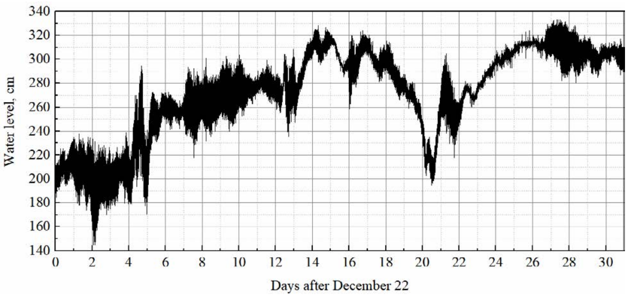

Figure 2. The course of recorded water level in the Danges river mouth.

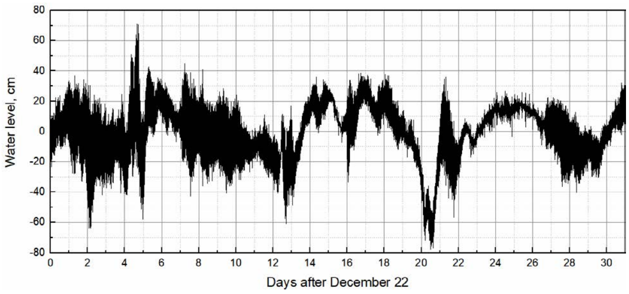

Figure 3. Detrended water level times series in Port of Klaipėda.

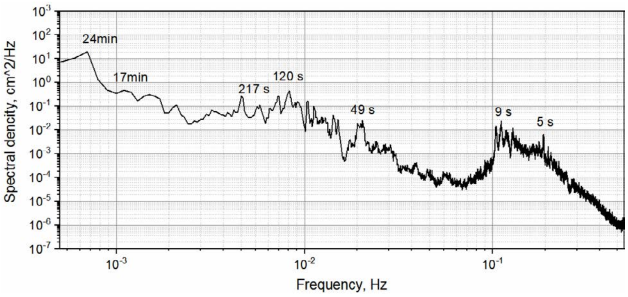

Figure 4. Power density spectra showing the dominant frequency peaks in the recorded data.

After removing the linear trend that apparently reflects an increase in the water volume of the entire Baltic Sea (Soomere *et al.,* 2015) (Figure 3), the STFT time frequency analysis can be used to identify and separate time intervals with high wave energy and comparatively calm conditions. The total detrended water level variations reach up to 160 cm, during a stormy period. During comparatively calm periods on 23th–26th observation days, the amplitude of water level oscillations was just 0.2 m.

The power density spectra for the recorded signal includes several distinct frequency peaks (Figure 4). Firstly, comparatively high peaks appears at periods of 5 s and 9 s. These peaks apparently indicate the penetration of storm waves or swells from the Baltic Sea proper into the harbor.

The infragravity frequency band (0.004–0.03 Hz) contains several marked narrow-banded relatively high peaks. A significant peak at 24 min and a less distinct one at 17 min likely reflect the presence of long waves in the system. These periods roughly match the known periods of 20–30 min of seiche oscillations in Klaipėda Strait (Gailiušis et. al., 2010).

Three distinct peaks exist at 217 s, 120 s and 49 s (Figure 4). They correspond to infragravity motions with periods of 0.8–3.6 min and can be associated with relatively energetic natural harbor oscillations with frequencies of 30–5 mHz. Such oscillations are evidently common for Port of Klaipėda and are generally admitted as a potential source of hazards (Gailiušis *et. al.*, 2010). Short-time spectrogram technique was employed to identify the predominant frequency in the signal during different instants of the recording time. The time-frequency plot (Figure 5) indicates a concentration of spectral energy in certain time intervals. Continuous high energy oscillations were recorded in three frequency bands: (i) $0.1 < f < 0.3$ Hz; (ii) $0.03 < f < 0.005$ Hz and (iii) $0.001 < f < 0.0006$ Hz. For the further analysis we separated oscillations in these frequency bands.

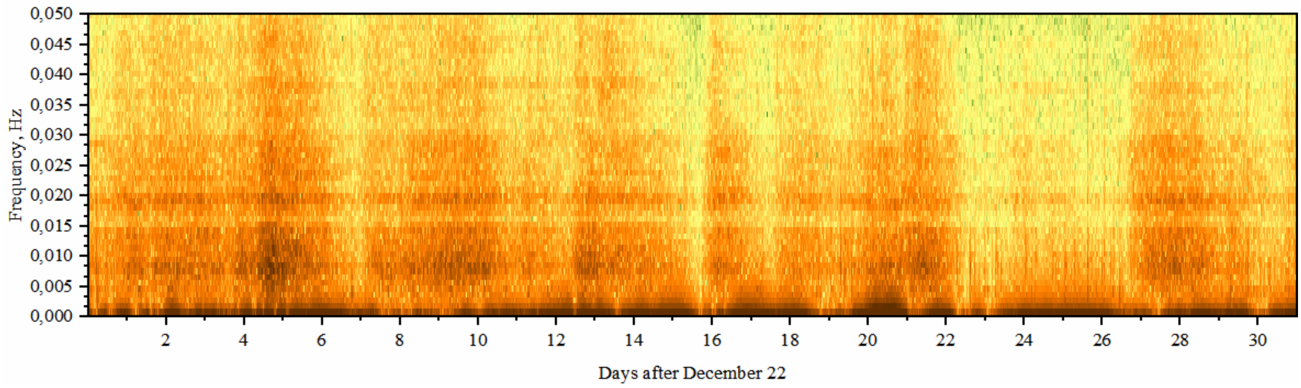

Figure 5. Spectrogram of the water level record. Horizontal bands indicate continuous oscillations, vertical bands are associated with periods of increased wave energy. Brown: high energy, green: low energy.

Time series analysis in different bands

The first frequency band ($0.1 < f < 0.3$ Hz) reflects motions with periods of 3–10 s. These periods often occur in the fields of wind generated waves in the Baltic Sea proper (Kelpšaite *et al.*, 2011; Räämet and Soomere, 2010; Räämet and Soomere, 2011; Räämet and Soomere, 2011; Soomere, 2003, 2005; Zaitseva-Pärnaste *et al.*, 2011). The amplitude of oscillations with such periods in Port of Klaipėda varies from several centimeters (as on the 23rd–26th observation days) till almost 50 cm as on the 2nd observation day.

Oscillations of the second frequency band ($0.03 < f < 0.005$ Hz) reflect the rapid SWL changes by up to 50 cm (Figure 6). Differently from the strong evidence of wind waves, higher amplitudes of motions in this band occur on the 4th–5th recording days. It is likely that long waves of this frequency band produced rapid, high amplitude (>50 cm) changes to the water level Port of Klaipėda on the 5th, 21st and 28th recording days.

Motions in the third frequency band ($0.001 < f < 0.0006$ Hz) cause much smaller changes in the water level. The relevant amplitudes are below 5 cm. The associated long waves have a cyclic recurrence with low amplitudes <3 cm. Only in specific situations (e.g., on the 4th observation day) the relevant amplitude reached 4.3 cm. Notice that oscillations from frequency band (ii) simultaneously reach their maximum amplitudes of 25 cm whereas wind waves did not notably contribute to the water level variations during this event.

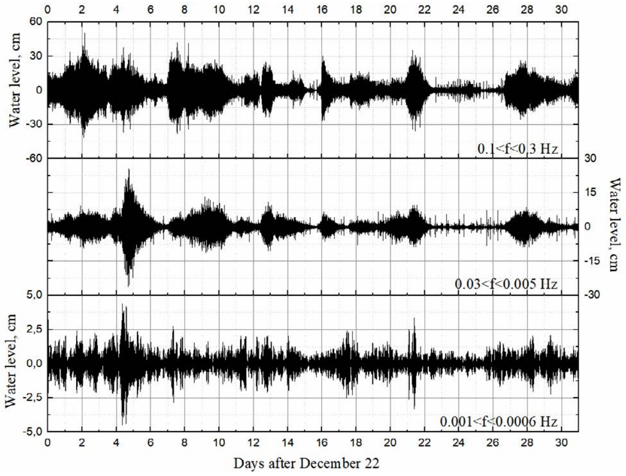

Figure 6. Variations in the water level driven by motions with typical periods of wind waves.

A comparison of the spectral density during the calm (days 23–24) and stormy intervals (days 4–5) shows a distinct difference in the location of energy peaks. The relevant periods differ by 2 min in the long-wave frequency band (Figure 7). This feature may be interpreted as showing the possibility of the existence of different natural seiche regimes in Klaipėda Strait that are excited by different types of external drivers. The presence of comparably high spectral energy peaks at 24–28 min during both calm and stormy days together with the time-frequency (spectrogram) plot signals that oscillations with periods >10 min were present continuously in Klaipėda Strait. This indicates the presence of a continuous external energy source that is able to energize these oscillations within the strait. As there exist strong density gradients in the strait, the typical outflowing current may develop a shear similarly to an approaching tide (Vlasenko *et al.,* 2005), become unstable and generate, e.g., Kelvin-Helmholtz instability and pump energy into internal waves and related basin-scale oscillations.

Oscillations with frequencies from band (ii) $0.03 < f < 0.005$ Hz have much lower energy density. This band does not contain any distinct spectral peak and the water level record reveals no well-expressed repeatability in time of motions with such periods. Consequently, it is likely that both natural and anthropogenic energy sources do not produce motions with notable amplitudes within this frequency band.

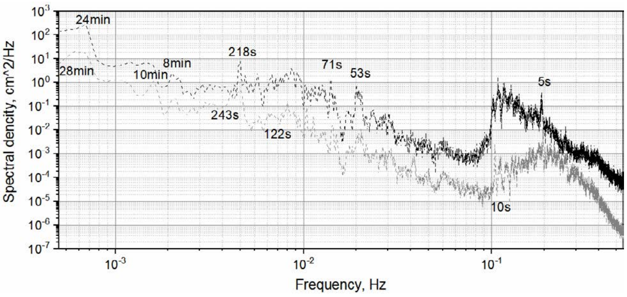

Figure 7. Power density spectra showing the dominant frequency peaks on days 4–5 (black line) and days 23–24 (grey line).

Oscillations with the frequency matching the frequencies of wind waves (band (i)) have the lowest spectral energy density in both windy and calm conditions. There is, however, a clear difference in the location of spectral energy peaks for the two time intervals in Figure 8. The peak at the 10 s period evidently reflects the appearance of high and long (in the scale of wind waves) seas or swells at the entrance of Klaipėda Strait. The location of the spectral peak on calmer days matches typical periods 3–5 s of waves generated under moderate winds in the south-eastern part of the Baltic Sea.

DISCUSSIONS

The studies performed show that short term water level fluctuation in the Port of Klaipėda have different origin and magnitude. Changes in the water level with the period larger than 12 hours present in the recorded signal with the amplitude higher that 150 cm are not in our interest and was not analysed. However, this water level changes is a response of the internal sea-level variation in the Baltic Sea (Särkkä *et al.*, 2017).

The power density spectra for the total recoded signal and for the calm and for the stormy season shows the locations of the energy peaks in the major three groups of frequency bands: (i) $0.1 < f < 0.3$ Hz; (ii) $0.03 < f < 0.005$ Hz and (iii) $0.001 < f < 0.0006$ Hz. Differences in the wave periods that keeps largest energy peaks were observed in the $0.1 < f < 0.3$ Hz frequency band. In the stormy period largest energy spectra are concentrated at the 9 s period and during calm period – 5 s. These periods are representing main wind generated wave properties in the Baltic sea proper (Kelpšaite *et al.*, 2011; Räämet and Soomere, 2010; Räämet and Soomere, 2011; Räämet and Soomere, 2011; Soomere, 2003, 2005; Zaitseva-Pärnaste *et al.*, 2011).

Difference of the energy peaks in the power density spectra of the $0.03 < f < 0.005$ Hz and $0.001 < f < 0.0006$ Hz frequency bands stays similar in the calm and stormy period. Such oscillations are evidently common for Port of Klaipėda and reflect natural harbour oscillation frequencies $0.03 < f < 0.005$ Hz (Gailiušis et. al., 2010). Lowest oscillation amplitudes and highest energy density are concentrated in the $0.001 < f < 0.0006$ Hz frequency band what is responsible for the storm surges in the Baltic sea proper (Soomere and Pindsoo, 2016).

CONCLUSIONS

To obtain a better understanding of the occurrence, timing and main properties of water level variations in Port of Klaipėda, a field campaign was carried out in November 2016 – January 2017.

The recorded signal is separated into three frequency bands. High spectral density peaks occur in two of such bands. Wind waves that arrive to the entrance of Klaipėda Strait drive water level oscillations with fairly limited amplitude and with periods that match the expected periods of open sea waves in the Baltic Sea. Such disturbances, however, constitute a large part of energy in the records.

Oscillations with the frequencies in the range of 0.03–0.005 Hz have much lower energy density than those driven by wind waves. They have a wide frequency spectrum without any dominant frequencies that could trigger unexpectedly high water level fluctuations

The largest oscillations in Port of Klaipėda are created by infragravity motions with periods that roughly match the natural seiche periods of Klaipėda Strait. It is not clear what process feeds them with energy. A natural energy source is the Kelvin-Helmholtz instability of the outflowing shear current. Wind waves in combination with these motions are able to drive remarkable water level oscillations in Port of Klaipėda. Their joint effect can cause hazardous water level changes, with amplitudes exceeding 0.5 m. Such phenomena can break mooring systems and create damage for sizable vessels.

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