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BALTICA Volume 19 Number 1 June 2006 : 20-29

Peculiarities of sea wave propagation in the Klaipėda Strait, Lithuania

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Kriaučiūnienė, J., Gailiušis, B., Kovalenkovienė, M., 2006. Peculiarities of sea wave propagation in the Klaipėda Strait, Lithuania. *Baltica, Vol. 19 (1), 20–29.* Vilnius. ISSN 0067-3064.

Abstract During rough weather, navigation in Klaipėda port is risky because of the high wave penetration into the Klaipėda Strait from the Baltic Sea. Objectives of the present paper are to study wind and wave regimes in Klaipėda port water area and to develop the short wave propagation model at wind speeds of 15, 20 and 25 m/s and varying directions. The modelled wave parameters are significant wave height and wave disturbance coefficient. The software MIKE 21 BW (Boussinesq Wave Module) is used for the development of wave propagation model in the Klaipėda Strait.

Keywords *Wind–wave, wind, Klaipėda Strait, modelling, MIKE 21 BW, wave height.*

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INTRODUCTION

Klaipėda State Seaport is the main port of Lithuania. It is located on the southeast coast of the Baltic Sea at the Klaipėda Strait, which joins the Baltic Sea and the Curonian Lagoon (Fig. 1a). Under rough weather, navigation in Klaipėda port is risky due to the high wave penetration into the Klaipėda Strait from the Baltic Sea. A short–wave and long–wave climate originates in the Strait. The incident short wave field is associated with bound long waves (Kirlys, Šičkus 1981). Long waves can have periods between 30 and 500 seconds and can penetrate into the harbour. The long waves may cause resonant motions in surge for moored ships. The short wave penetration in the Strait is more common. These waves depend mainly on the wind climate.

In the Lithuanian territorial waters and the Klaipėda Strait wave regime has been poorly investigated. Researches done till now in Sweden, Russia and Lithuania cover the offshore part of the Baltic Sea (Blomgren *et al.* 2001; Mažeika 2001; Atlas 1965). Surge regime of Lithuanian nearshore has been discussed by Kirlys and Lazauskas (1993). In the monograph (Gudelis 1998) regularities of waves of the Baltic Sea nearshore are presented; relating them to key factors causing the swell, i.e. wind speed and duration, wavelength, and water depth. In the near-shore area of the Baltic Sea and the Klaipėda Strait wave elements were measured from ships. Instrumental measurements of waves are not sufficient to describe the swell process during storm conditions. The only way to create an atlas of extreme wave parameters is modelling on the basis of wind parameters. In such way, wave atlases of the Baltic Sea, relevant for the offshore sea part, have been formed.

Different mathematical modelling methods, which describe wave propagation in the sea or in the harbour areas, have been used lately. Most frequently used models may be of two types: modelling of wave climate in the open sea and modelling of wave penetration in the harbour structures. Numerical modelling of wave climate with software packages WAVAD, STWAVE, MIKE 21 EMS, MIKE 21 NSW is used by many scientists (Blomgren *et al.* 2003; Thompson *et al.* 2004; Maa *et al.* 2000; Johnson 1998; Karambas, Tozer 2003). Results of offshore wave models are applied as boundary conditions for the modelling of wave penetration in the harbour areas. Boussinesq wave models are common for calculation of wave penetration in the harbour structures (Johnson 2006; Johnson *et al.* 2005; Bredmose 2004). The software MIKE 21 BW created

Table 1. Prevailing wind directions in Klaipėda from 1993 to 2004 (data from the Klaipėda Meteorological Station).

Wind direction	NE	E	SE	S	SW	W	NW	N
Number of cases, %	12.4	16.8	11.2	7.7	15.7	12.7	13.3	9.3

Table 2. Distribution of strong winds (%) according to direction and speed from 1996 to 2004 (Klaipėda Meteorological station data).

Wind speed, m/s	14–17	18–22	23–27	28–32	>33	Total
N	1.8	0.3	–	–	–	2.1
NE	–	–	–	–	–	–
E	1.4	0.4	–	–	–	1.8
SE	3.7	1.2	0.4	–	–	5.3
S	11.0	5.3	1.2	0.2	–	17.7
SW	21.6	10.1	2.8	0.7	0.4	35.6
W	13.6	7.9	1.8	0.5	0.5	24.3
NW	8.9	4.3	–	–	–	13.2
	62.0	29.5	6.2	1.4	0.9	100.0

by Denmark Hydraulic Institute is widely applied for calculations of wave propagation in the harbour area (MIKE 21, 2002).

Objectives of the present paper are: (i) to study wind and wave regime in Klaipėda port water area; and (ii) to develop the short wave propagation model in the Klaipėda Strait at wind speed of 15, 20 and 25 m/s and different directions. The modelled wave parameters are significant wave heights and wave disturbance coefficients. MIKE 21 BW (Boussinesq Wave Module) is used for the development of wave propagation model in the Klaipėda Strait.

METEOROLOGICAL REGIME

Wind regime of the Klaipėda region, determining wave penetration in the Klaipėda Strait, is defined for its significant variation during the year as well as during multi-year period. The long–term wind climate in Klaipėda is based on measurements made at the Klaipėda Meteorological station between 1947 and 2004 (Bukantis 1994; Manual 1996). When analysing wind regime at Klaipėda harbour area, more attention is given to the analysis of strong winds during the last decade since only strong winds cause high waves. The dominant wind direction at Klaipėda depends on atmosphere circulation processes and fluctuates significantly during the multi-year period. In the period of 1946–1965 southwest winds prevailed. During the later period till 1990 southeast winds prevailed, whereas in the last decade the winds from E and SW–NW sectors were more frequent (Table 1). In individual years sometimes one wind direction dominated, for example, in 1993, 1998 and 2000 this was the case with SW winds, whereas in 1994 and 2004 – W winds, and in 1996 – E winds.

Depending on the prevailing wind direction, stormy winds differ from the average ones. S–NW winds are distinguished among strong winds. SW winds comprise 35.6%, W winds – 24.3%, S winds – 17.7% (Table 2). Among strong winds, according to all directions, speeds of 14–17 m/s prevail.

Significant seasonal character is typical of strong winds – they are usually observed during the autumn–winter months. Comparing wind speeds from 1999 to 2004 with the data of 1961–1990, we should note that the average wind speed has changed insignificantly; however, variation of gradation distribution of different wind speeds is rather significant. In the period of 1999-2003 mild winds reduced significantly (9.1% instead of the previous 15.1%) and wind speeds of 6–7 m/s (29.8% instead of 21.3%) were observed more frequently. Wind speeds of 14–15 m/s and 21–25 m/s prevailed as well.

According to multi-year period observations at Klaipėda, a typical year was notable for winds stronger than 15 m/s observed during 67–73 days, whereas winds stronger than 20 m/s were fixed during 15–20 days. The year 1990 was very special, when winds stronger than 15 m/s and 20 m/s were observed, respectively, during 99 and 32 days.

An exclusive case was observed on 04 12 1999, during hurricane *Anatoly*, when for 17 hours without interruption the average wind speed ranged in 17–25 m/s, whereas gusts of wind reached 38 m/s. Very strong winds prevailed before *Anatoly* with their total duration making 106 hours.

Recurrence of storms agreeably to duration is presented in Table 3.

During the multi-year period (1947–2004) no regularities, tendencies or cycles were determined in recurrences of the storms. Depending on the course of circulation processes in some years strong winds prevail, whereas in other years they do not.

Table 3. Recurrence of storms (%) according to their duration from 1995 to 2004.

Duration, hour	0–6	6–12	12–24	24–48	48–72	72–96	>96
Recurrence, %	18.8	22.0	31.0	18.8	5.8	3.1	0.5

Annual course of swell repeats the wind regime, therefore, while calculating wave parameters, one of primary data are wind regime characteristics. On the basis of the performed wind regime analysis, it was determined that calculations of wave propagation of the Klaipėda Strait should be performed at the following wind parameters:
(1) wind speed – 15, 20 and 25 m/s;
(2) wind directions – 225º, 247º, 270º, 292º and 315º.

INVESTIGATION OF WAVES

Simulating wave propagation in the Klaipėda Strait it is important to carry out the analysis of wave parameters both in the Lithuanian Baltic near-shore area and the Klaipėda Strait. Heights of the Baltic Sea waves are used as boundary conditions for the simulation of wave propagation in the Strait. The highest waves are observed during autumn and winter times, whereas the smallest waves are observed in summer. Direction of wave propagation is close to the prevailing wind direction.

According to the data obtained (Hydrometeorological… 1983), in the south-eastern part of the Baltic Sea, the SW–W waves prevail: 0–2 m high waves evoked by the 4–9 m/s wind comprise ~ 70% of all cases, while 2–4 m high waves evoked by the 10–19 m/s wind comprise ~ 24%, whereas the storm winds in this part of the sea evoke 4–7 m high waves (~4%). The calm period is usually observed during time of summer and spring (~5%). A rather frequent swell of the Baltic Sea produces wave heights of 2–3 m. In the Baltic Sea wave periods range from 1 to 13 seconds, usually ~80% of waves with the period of 2–7 seconds are observed. Waves with a period less than 1 second comprise ~8%. In the Baltic Sea, depending on wind speed, direction stability, duration and water depth, and waves up to a length 130 m may be formed. Usually wavelengths of 20–70 m can be observed.

In the Lithuanian waters of the Baltic Sea the evaluation of waves is presented in many manuals, atlases and publications. Standard wind fields (Hydrometeorological… 1983) are used for the calculations of wave parameters, which are created employing 14600 synoptic maps. Probability characteristics of wave elements and wind regime of different seasons are presented. In the wave atlas (Atlas 1965), maps of standard wind fields are presented. For different wind speed gradations the maps of wave heights and periods are accordingly defined. The data published enabled to make a conclusion that waves excited by southwest, west and northwest winds prevail in the Lithuanian Baltic Sea near-shore, with their height reaching 3.0 m (~80%), whereas 4.0–7.0 m waves excited by stormy winds comprise only 2%.

Wave regime of the Klaipėda Strait is less analysed. Wave heights in the Strait were measured episodically, only during the implementation of a few projects. Some experiments were carried out preparing the project for reconstruction of Klaipėda harbour entrance channel and breakwaters. In the project *Improvement of Klaipėda Harbour Entrance* (WL/Delf Hydraulics, 1998), wave regime was simulated in the Klaipėda Strait at different constructions of harbour breakwaters. The long-term wind–wave climate is based on the statistics for winds and the use of hindcast techniques. The wave conditions are given at a water depth of 7 m. It is close to the location of the harbour, where waves from most directions have to pass over water of this depth to reach the harbour entrance. In order to assess the short wave height at the various harbour sections, computations for three different wave directions were carried out for waves originating from 240ºN, 270ºN and 300ºN. The computations were carried out with WL/Delf Hydraulics' software DIFFRAC.

Wave parameters calculated in the Baltic Sea area before Klaipėda harbour channel are also presented in the project *Mathematical Modelling of Wave Regime in the Entrance Channel and Port Water Area* (Sochi, 1998). Observation data of Klaipėda Meteorological station was used for the assessment of wind regime, wave elements were calculated in deep and shallow water (Table 4). Distribution of wave heights of various probability ($h_{1\%}$, $h_{3\%}$, $h_{5\%}$), average wave height $\bar{h}$, period $\bar{T}$ and wave length L were calculated employing software WAVE.

In order to calibrate the wave propagation model in the Klaipėda Strait, it was necessary to measure wave parameters. Constant measurements of wave parameters have been initiated since 2005 in an automatic wave and flow measurement station C, the coordinates of which are 55º43'40"N and 21º05'20"E (Fig. 1b). Meteorological parameters, i. e. wind speeds and directions, were measured in the automatic station E (Fig. 1b).

After performing the analysis of meteorological and wave parameters, it was determined that during the period of measurements (05 04 2005 – 11 08 2005) weak winds prevailed. Only waves caused by strong winds are significant for the model calibration. Meteorological data and wave parameters are presented in Table 5. Significant wind directions are coming from 225° up to 315º, as there are no high waves when winds of other directions blow in the Strait.

Table 4. Estimated wave parameters in the shallow water of the Baltic Sea (depth of 8 m) (according to the project *Mathematical Modelling of Wave Regime in the Entrance Channel and Port Water Area*).

Direction	Return period	Wave parameters					
		$\bar{h}$ (m)	$h_{1\%}$ (m)	$h_{3\%}$ (m)	$h_{5\%}$ (m)	$\bar{T}$ (s)	L (m)
NW	50 years	4.4	6.4	6.1	5.8	9.30	77
	10 years	2.5	5.3	4.9	4.4	8.70	72
	5 years	2.3	4.8	4.5	4.0	8.50	69
	1 year	1.9	4.1	3.8	3.4	8.00	65
W	50 years	4.4	6.4	6.1	5.8	9.30	78
	10 years	4.4	6.4	6.1	5.8	8.90	74
	5 years	4.4	6.4	6.1	5.8	8.70	71
	1 year	2.6	5.4	5.0	4.5	8.10	65
SW	50 years	4.4	6.4	6.1	5.8	8.50	70
	10 years	2.8	5.7	5.4	4.8	8.10	66
	5 years	2.5	5.1	4.8	4.3	7.70	61
	1 year	2.1	4.4	4.1	3.7	7.30	50

Some wave measurements under similar wind parameters differ due to the impact of sailing ships that cause additional waves in the Klaipėda Strait. For example, on 17 07 2005 and on 07 31 2005, when wind direction was 270º and wind speed 8 m/s, the average wave heights, the periods of which were 6.2 and 5.6 s, were recorded to be 0.44 and 0.50 m, whereas on 01 06 2005 and 05 08 2005, when wind direction was 300º and wind speed 10 m/s, wave heights, the periods of which were 5.6 and 5.4 s, were recorded to be 0.34 and 0.45 m. Therefore, when calibrating the model it is necessary to take into account only general wave height tendencies in case of similar wind parameters. The biggest wave heights were recorded when the wind was coming from 270º, whereas smaller wave heights were originated by 250º and 290º. Compiled data on the measured wave parameters and simulated wave parameters in the shallow Baltic Sea near Klaipėda harbour in the above mentioned projects were used as primary information in the development of wave propagation model of the Klaipėda Strait.

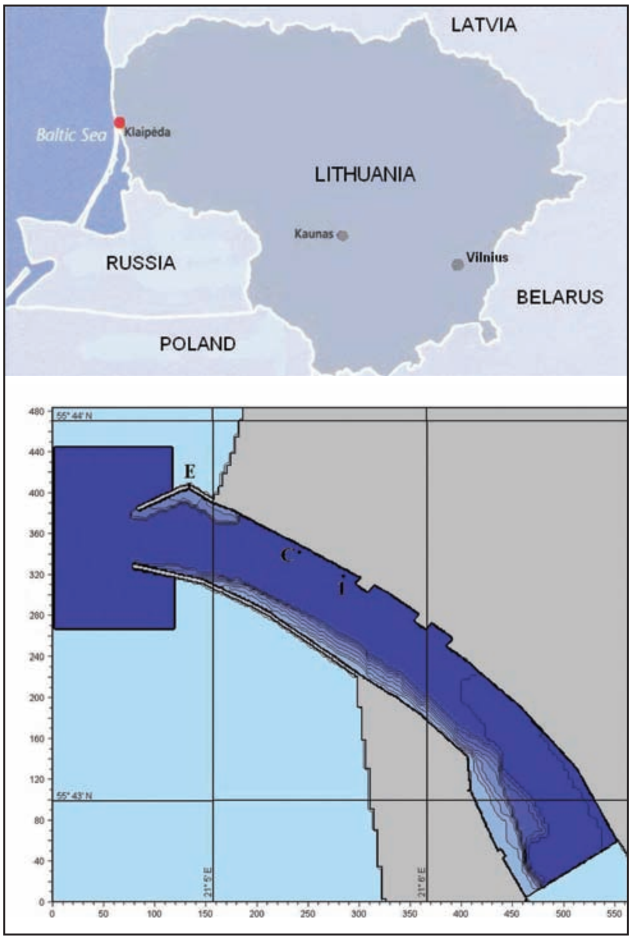


Fig. 1. Location scheme: (a) the Klaipėda Port; (b) bathymetry of modelled area of the Klaipėda Strait (C, E – locations of the measurement stations, 1 – water point near the quay No. 1).

WAVE PROPAGATION MODEL IN THE KLAIPĖDA STRAIT

The wave propagation model of the Klaipėda Strait is developed using software MIKE 21 BW (Boussinesq Wave Module). This 2D module (two horizontal space co-ordinates) is based on the numerical solution of the new form of the two-dimensional Boussinesq equations. Enhanced Boussinesq type equations (Madsen *et al.* 1991) make the module suitable for the simulation of the propagation of directional waves travelling from deep to shallow water. The equations are solved by an implicit finite difference techniques with variables defined on a space-staggered rectangular grid. The convective terms are discredited using central differences and the normal ADI algorithm is used for numerical integration (MIKE 21, 2002).

The MIKE 21 BW module has combined effects of most wave phenomena in the port water territory: shoaling, refraction, diffraction, directional spreading,

Table 5. Wind and wave parameters measured at the automatic stations E and C in 2005.

No	Date	Wind speed. m/s	Wind direction, °	Wave height		Wave direction, °	Wave period, s
				H_{max} , m	H_o , m		
1	05.16	10	230	0.62	0.5	270	6.5
2	06.12	6	240	0.36	0.28	270	5.6
3	06.05	10-11	240	0.78	0.58	270	7.2
4	06.06	6.5-7	250	0.5	0.4	270	5.8
5	08.07	7	250	0.4	0.35	270	5
6	05.07	7	260	0.45	0.35	280	4.9
7	07.27	8	260	0.48	0.38	270	5.4
8	08.10	22	260	1.8	1.45	270	10
9	06.22	7	270	0.6	0.47	270	6.4
10	07.15	7	270	0.54	0.44	270	5.6
11	07.17	8	270	0.56	0.44	270	6.2
12	07.31	8	270	0.65	0.5	270	5.6
13	04.06	10	270	0.75	0.6	270	5.8
14	04.21	10	270	0.8	0.62	280	5.3
15	06.28	11	270	1.15	0.85	280	8
16	07.20	11-12	270	0.98	0.76	270	8
17	08.02	13-14	270	1.35	1.05	270	8.4
18	08.03	7-8	280	0.65	0.5	260	8.0
19	05.19	7.5-8	290	0.52	0.4	280	4.8
20	05.25	8-9	290	0.5	0.4	280	4.7
21	06.01	10	300	0.42	0.34	280	5.6
22	08.05	10	300	0.55	0.45	260	5.4
23	08.09	17-20	320	0.5	0.4	260	8
24	06.30	9	350	0.33	0.22	280	8
25	06.18	9.5-10	350	0.34	0.27	280	7.2
26	05.13	10	350	0.20	0.14	250	4.9

and bottom friction. This module also includes porosity for the simulation of partial reflection from breakwaters. Sponge layers are applied when full absorption of wave energy is required. Internal generation of waves is used for the formation of the open sea boundary.

The main tasks of the creation and application of wave propagation model are as follows:

1. Initial data.
2. Setting up the model.
3. Calibration and validation of the model.
4. Simulation and results of the model.

Initial data comprise bathymetry of model area, boundary data (observations, wave statistics), information on types of breakwaters for assessment of the reflection coefficients, calibration and validation data (measured wind and wave parameters at selected locations).

Setting up the model means that all collected data are resolved on a spatial grid of model. Setting up the bathymetry includes the selection of the modelled area, the grid spacing, location and type of boundaries. The total simulation time should allow the waves to reach the complete model area. From this time the simulation should continue at least 20 minutes for the calculation of statistical wave parameters. The time step should be sufficiently small to resolve the shortest individual wave periods. It also depends on the grid spacing. At an open boundary the incident waves are specified as time series of surface elevations or flux densities perpendicular to the boundary. The effect of porosity is included in the model. Partial reflection, absorption and transmission of wave energy at porous structures are described by porosity layers (Madsen 1983). Sponge (or absorbing) layers can be used along model boundary conditions, which absorb wave energy propagating out of the model area.

The results of the wave propagation model comprise water level, significant wave height H_{mo} and the wave disturbance coefficient (ratio of the significant wave height relative to the incoming significant wave height) in the every grid of modelled area. The significant wave height H_{mo} is defined by $H_{mo} = 4\sigma$, where σ is the standard deviation of surface elevation.

Bathymetry is prepared for wave propagation model of the Klaipėda Strait and is presented in Fig. 1b. The following primary parameters were chosen

Table 6. Calibration and verification of the Klaipėda Strait wave propagation model according to measured wave heights in the station C.

Date	Measured wind parameters			Modelled wind parameters		
	Wind speed, m/s	Wind direction, º	Wave height, m	Wind speed, m/s	Wind direction, º	Wave height, m
Calibration						
08/10	22	260	1.45	25	270	1.63
				20	270	1.38
08/02	13–14	270	1.05	15	270	1.06
Verification						
08/09	17–20	320	0.40	20	315	0.37

for the wave modelling: the average wave height at the 14-m depth was 4.2 m and wave period was 8.0 s, when wave direction was 270º. The size of grid of the simulated area is 5 m and time step is 0.3 s. These parameters fulfil the criteria of model stability (Courant number <1). The external wave generation is carried out at a 320 m distance from the channel mouth at the open sea boundary, coinciding with axis *y*. Employing JONSWAP random wave generation spectrum, unit discharge values, corresponding to the determined wave parameters, were simulated for the whole modelling period.

Wave propagation model for the Klaipėda Strait was calibrated and verified, comparing measured wave height values with the simulated values in case of strong winds. Only measured wave height and period values, when strong winds blow (>15 m/s), are needed for the calibration of the model. Having analysed data of the automatic station C (Fig. 1) in the period from 05 04 2005 to 11 08 2005, it was determined that only three measuring data are needed for the model calibration and verification (Table 5).

The strongest average west wind with a speed of 22 m/s was recorded on 10 08 2005. Waves excited by the wind, at speeds of 15, 20 and 25 m/s, are important for the calibration of wave model of the Klaipėda Strait. Therefore, in accordance with the situation on 10 08 2005, when speeds of west winds were 20 and 25 m/s, wave propagation was calculated for the model calibration. In the place of automatic station C the average wave height of 1.63 m was calculated blowing the wind with speed of 25 m/s, and waves with a height of 1.38 m were calculated, when wind speed was 20 m/s. At the wind speed of 22 m/s, the measured average wave height was 1.45 m. On 02 08 2005 the west wind with speed of 13–14 m/s was observed at the automatic station E. Calculation of wave propagation in the Strait was carried out, when west wind speed was 15 m/s. The calculated wave height was 1.06 m, height of the observed wave was 1.05 m. The observed and measured heights differ insignificantly (Table 6), thus, primary conditions of the model have been determined correctly.

Model verification was carried out according to observation data on 09 08 2005. Primary modelling conditions (wave height and period) were chosen according to model calibration results with wind speed 20 m/s. In the place of automatic station C, the calculated wave height was 0.37 m, when wind direction was 315º, whereas the observed wave height was 0.40 m, when wind direction was 320º. A conclusion is made that wave propagation model of the Klaipėda Strait was calibrated properly. Model calibration should be repeated if the additional data on waves were available.

RESULTS AND DISCUSSION

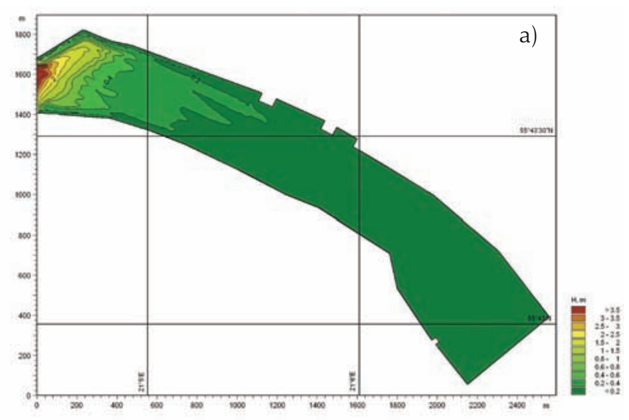
The wave propagation modelling of the Klaipėda Strait provided results on distribution of wave height and wave disturbance coefficient, when wind direction is 225º, 247º, 270º, 292º and 315º and wind speed 15, 20 and 25 m/s.

Parameters (average wave height and period) of wave boundary conditions, necessary for external wave generation, were defined for wind from western direction with a certain speed. For 15 m/s wind, offshore waves in the open model wall were generated according to the parameters of the wave with the height of 3.2 m and the period of 7.6 s; when wind speed was 20 m/s, the wave with the height of 4.2 m and the period of 8.0 s was obtained, whereas when wind speed was 25 m/s, the wave with the height of 5.6 m and the period of 8.6 s was induced.

Dynamics of wave heights in the Klaipėda Strait, when wind speed is 20 m/s and wind direction 225º, 247º, 270º, 292º and 315º is presented in Fig. 2. The smallest wave propagation occurs when wind direction is 225º (Fig. 2a). The wave was directed towards the northern breakwater, and waves, higher than one meter, are observed only at a 400-m distance from the breakwater heads. Larger wave propagation occurs during wind from 247º (Fig. 2b). The highest waves are observed in the Klaipėda Strait, when wind directions lie between 270º and 292º (Fig. 2c-2d). Wave direction in the Strait, when west wind blows, is directed towards northern breakwater, whereas at wind direction of 292º, the wave is directed towards the Strait. When wind direction is 270º, the wave exceeding 2 m height spreads at a distance of 600 m from the harbour breakwater heads. The highest waves (>3.5 m) access the Strait, when the wind direction is 292º, whereas insignificant waves spread in the whole analysed area of the Strait. Wave height diminishes significantly, when winds come from 315º. Waves higher than 2 m spread at 400 m distance from the breakwater heads, and wave direction is towards the southern breakwater (Fig. 2e).

At wind direction of 270º and wind speed of 15 m/s, the waves higher than 3 m spread as far as 300 m from the harbour breakwater heads. At wind speed of 25 m/s the 4-m high waves penetrate into the Strait as far as 400 m from the breakwater heads. Even the highest waves were observed to fade to 0.3–0.6 m at a distance of 1–1.5 km from breakwater heads.

Wave disturbance coefficient defines the nature of wave propagation in the Strait. Disturbance coefficient is measured as a ratio between wave height in any grid of the simulated water area and generated wave height. At the wind speed of 15 m/s the height of the generated wave is 3 m, and at wind speed of 20 and 25 m/s, the height of wave is considered to be, respectively, 4 and 5 m. The nature of disturbance coefficient distribution corresponds to the peculiarities of wave height propagation in the Strait. The high disturbance coefficients (0.8–0.9) are observed in the water area of the harbour breakwaters. At wind direction of 225º and speed of 25 m/s, the disturbance coefficient lower than 0.1 is observed only at a distance of 400 m from the sea gate, whereas when wind direction is 247º such value is seen at 600 m distance (Fig. 3a-b). Hence, in the remaining part of the Strait, the height of the scattered wave is 10 times lower than the external wave height. At the wind direction of 270º, such disturbance coefficient is observed at 1.7 km distance from the sea gate (Fig. 3c). Disturbance coefficient >0.5 is observed at 800 m distance from the sea gate. At the wind direction of 292º and speed of 25 m/s, disturbance coefficient > 0.1 is observed at 2 km distance from the sea gate (Fig. 3d), whereas at the wind direction of 315º such disturbance coefficient is observed only at 1 km water area (Fig. 3e). Similar distributions of wave disturbance coeffi-



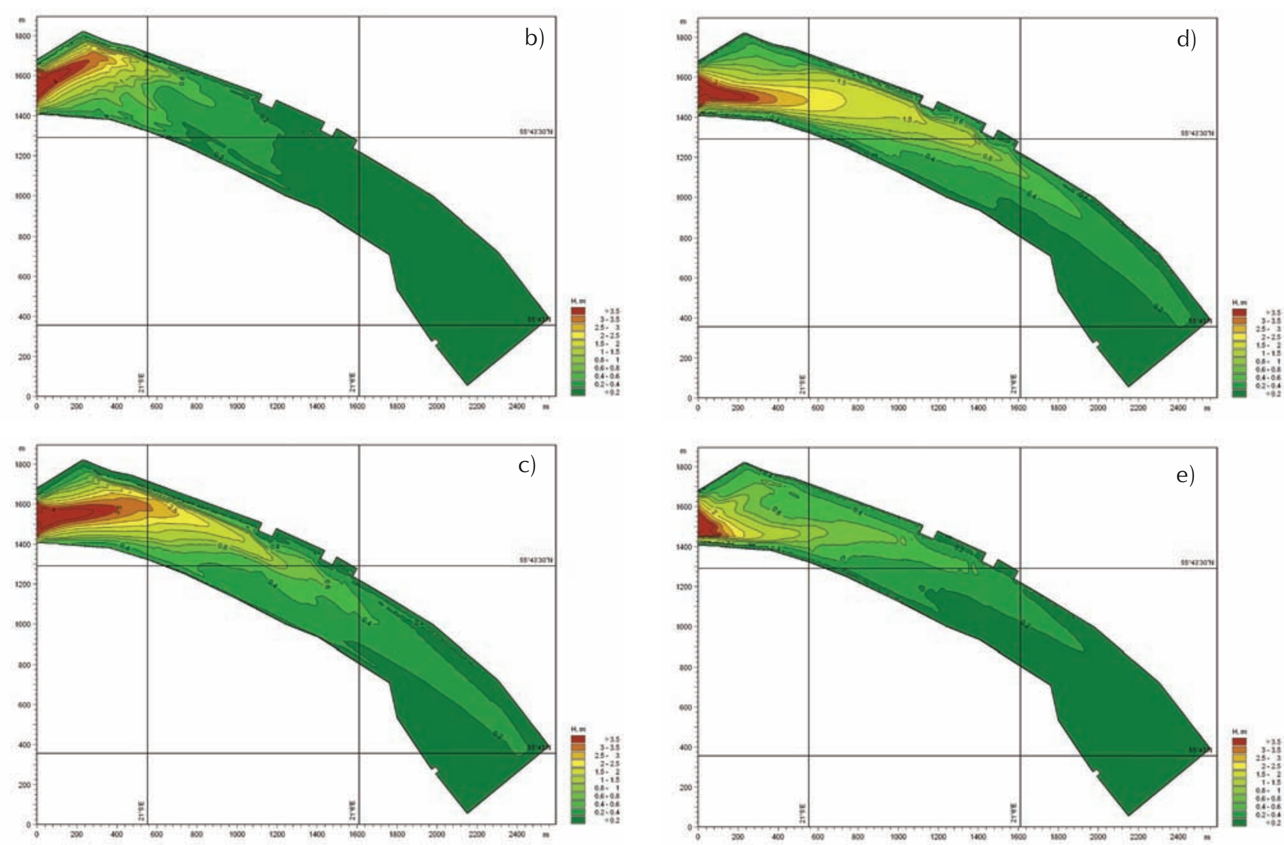


Fig. 2. Distribution of significant wave height in the Klaipėda Strait for the 20 m/s wind speed and directions of 225° (a), 247° (b), 270° (c), 292° (d), and 315° (e).

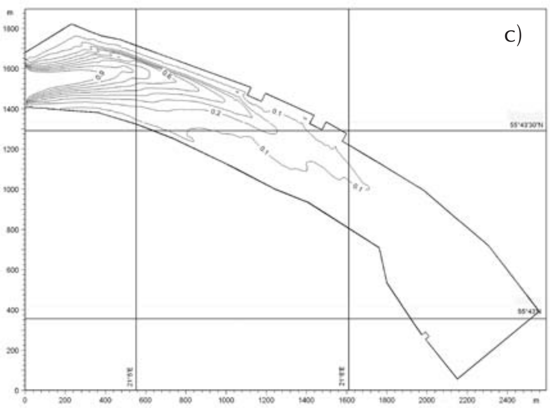
Table 7. Significant wave height (m) near the quay No. 1 (point 1 in Fig. 1b) for different wind directions and speed of 15, 20 and 25 m/s.

Wind speed, m/s	Wind direction, °				
	225	247	270	292	315
15	0.13	0.18	0.50	0.43	0.19
20	0.16	0.25	0.60	0.48	0.26
25	0.20	0.30	0.68	0.53	0.31

cients are observed for the winds of the same direction and different speeds.

The developed wave penetration model of the Klaipėda Strait allows evaluating safety of navigation conditions in the northern part of the strait when strong winds blow. At present the activity of the Klaipėda Seaport is restricted when the wind is stronger than 18 m/s. In any simulated area of the Strait, concrete wave heights may be determined, when winds of different direction and strength occur. Table 7 presents the wave heights near the quay No. 1 (point 1 in Fig. 1b). The maximum wave height was determined when west winds were blowing, and the lowest height was determined when wind direction was 225º.

The wave model of the Klaipėda Strait allows to evaluate the variations of wave propagation in the Strait, after the harbour area was deepened and the constructions of harbour breakwaters and quays were changed. Extension of old breakwaters at the Klaipėda harbour gate was carried out in 2002. This reconstruction had to diminish wave invasion into the harbour area. This proposition was confirmed using the wave model, after the bathymetry (structure of breakwaters till reconstruction) of Klaipėda harbour area was changed. Under these conditions wave propagation in the Strait was simulated at a wind direction of 270º and a wind speed of 20 m/s. The obtained results are compared to wave propagation in the Strait under current conditions. Fig. 4 presents distribution of wave disturbance coefficient before and after the reconstruction of harbour breakwaters at the same direction and speed of the wind. Obvious differences of wave invasion in to



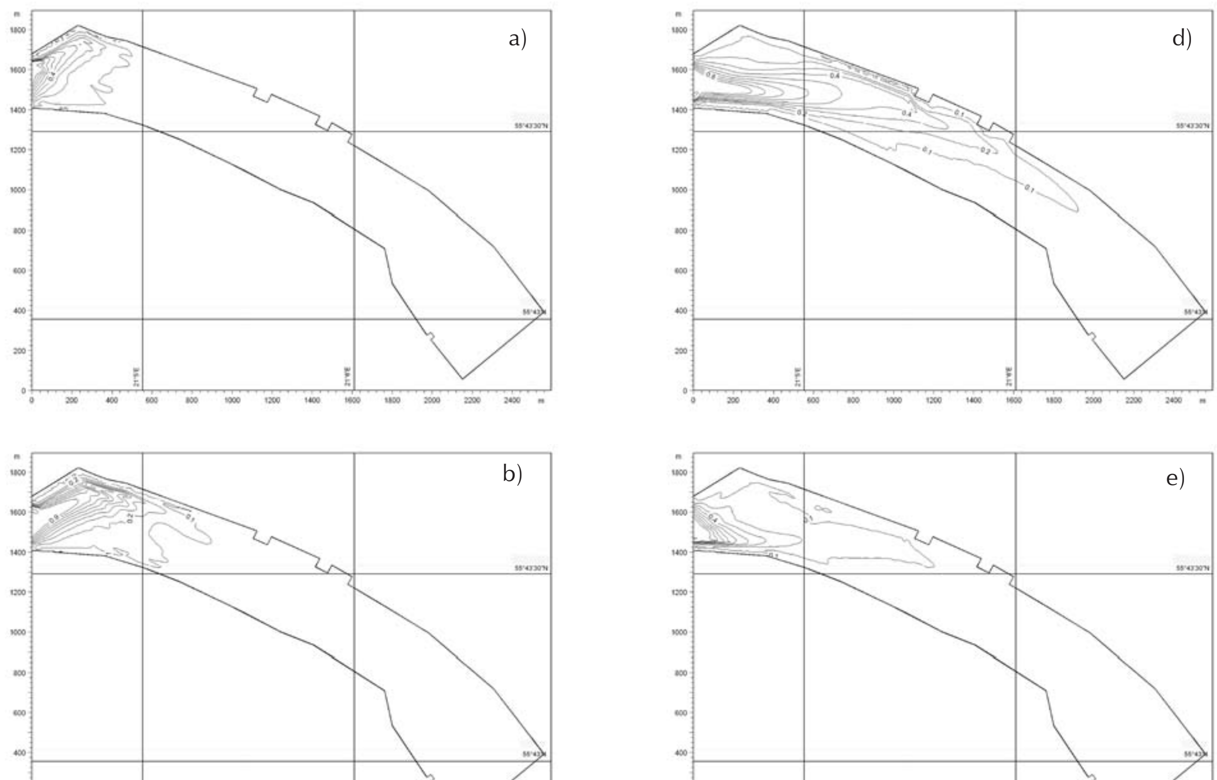


Fig. 3. Distribution of wave disturbance coefficient in the Klaipėda Strait for the 20 m/s wind speed and directions of 225° (a), 247° (b), 270° (c), 292° (d), and 315° (e).

the Strait may be traced: before the reconstruction of breakwaters, waves with disturbance coefficient higher than 0.9 (i.e., the height of wave exceeds 3.5 m) spread at 500 m distance from the sea gate, whereas after the reconstruction these waves would spread only as far as 400 m from the sea gate. The invasion front of high waves before breakwater reconstruction encompasses all Klaipėda Strait width, after breakwater reconstruction the spread of the high waves is significantly smaller (approximately 100 m).

Results of wave penetration model of the Klaipėda Strait may be applied:

- for determining navigation characteristics and loading conditions in the Klaipėda seaport water area under extreme conditions;
- for training of navigators;
- for determining wave loads of hydrotechnical constructions.

The advantages of wave propagation model of the Klaipėda Strait, if compared to similar models, are as follows:

– the internationally recognised software MIKE 21 BW, used for the development of the model, allows precise description of the processes of wave propagation in the harbour area;

– the model was calibrated according to data of the Klaipėda Strait automatic station of wave measurement (previously created models do not have these possibilities);

– the calculations of wave propagation in the Strait are performed for predominated wind speeds of 15, 20 and 25 m/s and winds of five directions, whereas in other works wave propagation is described only for two or three wind directions.

Wave propagation model of the Klaipėda Strait should be specified in case if new data on wave parameters are received, as well as in case if Strait bathymetry is changed and arrangement or reconstruction of quays takes place.

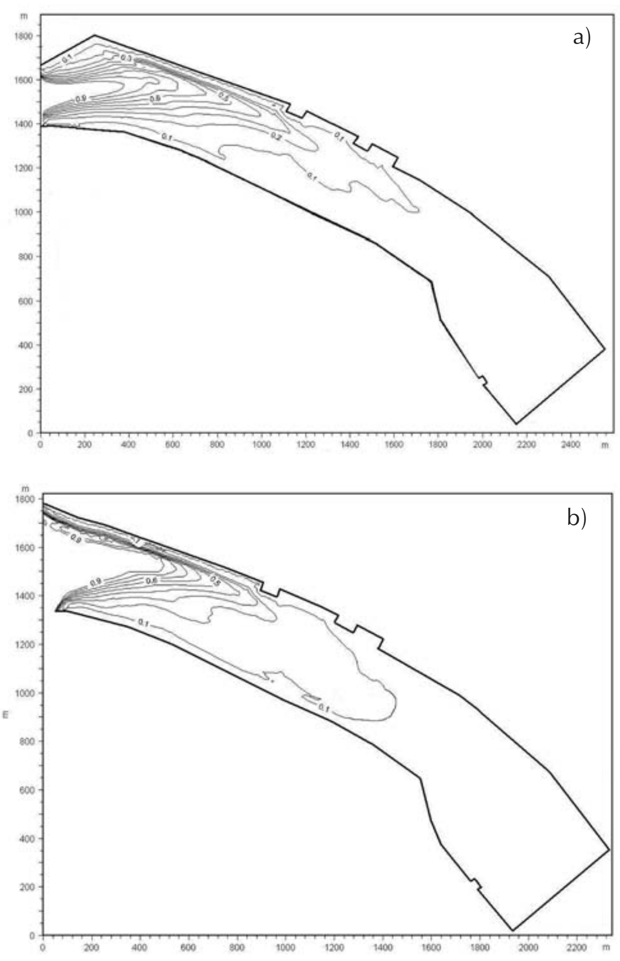


Fig. 4. Distribution of wave disturbance coefficient in the Klaipėda Strait for the 20 m/s wind speed and W direction: old construction (a); new construction (b) of breakwaters.

CONCLUSIONS

According to the meteorological observation data from 1995 to 2004, the most frequent storm periods at Klaipėda Strait occur from October till March, when southwest and west winds predominate.

Extreme values of propagation of short waves in the Klaipėda Strait have been calculated for strong winds blowing from 270º to 292º. Impact of storms on the swell is observed for a distance exceeding 2 km from the breakwaters of the Klaipėda Seaport gate.

The wave model created on the basis of modelling system MIKE 21 BW and on the basis of bathymetry of 2004 is calibrated according to wave observation data of May–August of 2005; it presents reliable values of wave elements in the Klaipėda harbour area.

Results of the developed wave model of the Klaipėda Strait may be used to deal with the issues of safe navigation and secure conditions of stevedoring.

Acknowledgements

Lithuanian State Science and Studies Foundation and the Klaipėda State Seaport Authority supported the research described in this paper. The authors also thank Dr. Vaižgantas Kirlys, Lithuania, Dr. Ing. Peter Froehle, Germany, and Dr. Doris Milkert, Germany for reviewing the manuscript and giving very useful remarks.

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