Resonance Oscillations in the System of Adjacent Bays

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Purpose. The paper is aimed at studying both resonance response of a system of two model bays to the initial disturbance of free surface induced by the sea bottom motion and mutual influence of the adjacent bays.

Methods and Results. Based on the numerical hydrodynamic ADCIRC model, including the method of finite elements, studied is the resonance response of two adjacent bays (*A* and *B*; rectangular form, certain dimensions and depths) similar to the Sevastopol and Karantinnaya bays, respectively, to the initial disturbance of free surface induced by the sea bottom motion. The calculations were carried out at different dimensions of the initial disturbance area both for the system of two adjacent bays and individually for each bay.

Conclusions. Initial disturbance generates in the Bay A four lowest modes of eigen-oscillations with the periods 45, 15, 9 and 6 min., and in the bay *B* – two lowest modes with the periods 12 and 4 min. The obtained periods are in good agreement with the analytical estimates. Presence of the adjacent bay gives rise to intensification of the Helmholtz mode in each of them. External disturbance with the period 11.7 min. constitutes potential danger for the bay *B* since, in such a case, resonance with its Helmholtz mode occurs. The analytically obtained dependence between the periods of the infra-gravity waves and the average periods of the wind waves in the Sevastopol region (resulted from the retrospective analysis of waves) permitted to reveal theoretical possibility of generating short-period seiches by the infra-gravity waves in both bays.

Keywords: Sevastopol Bay, seiches, resonance oscillation, infra-gravity wave, numerical modeling, ADCIRC.

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Introduction

The phenomenon, known as “harbor resonance”, occurs in semi-closed basins, such as bays or gulfs, in case the parameters of external impacts coincide with the periods of natural oscillations of the basin, being determined by the geometric dimensions, the coastline profile and bathymetry. The energy of external wave disturbances can be captured by a semi-closed area, causing amplification of the oscillations in this area [1]. This can lead to a harbor oscillation[1] leading to a collision of ships rupture of mooring lines and problems during cargo operations. Intense oscillations in bays can be caused by a variety of dynamic effects: trains of short-period waves, infragravity waves, sudden changes in atmospheric pressure, tsunamis from distant earthquakes and waves caused by underwater landslides [1].

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[1] Labzovsky, N.A., 1971. [*Non-periodic Sea Level Fluctuations*]. Leningrad: Gidrometeoizdat, 237 p. (in Russian).

As a result of the reflection of waves coming from the open sea from the coast and the edge of the shelf, offshore seiches[2] are formed. These seiches can appear in bays adjacent to the shelf, such as, for example, in the Far Eastern Alekseev Bay located on Popov Island [2].

Of great theoretical and practical interest is the study of seiche oscillations in systems of several closely situated (adjacent) bays. A typical example is the system of Sevastopol bays, which includes seven main bays of different size and configurations.

Generally, the study of resonance properties in such a system is rather complicated. Therefore, as the first step in this paper, the problem for two adjacent bays having the dimensions and depths of the Sevastopol and Karantinnaya bays is considered. This will make it possible to first study the resonance properties with a simple example and then proceed to consider a real system of bays.

The following two techniques are usually applied in mathematical modeling of seiches. The first one is based on finding the periods of the resonance modes and their spatial structure by solving the spectral eigenvalue problem for the elliptic operator[3], and the second – on solving a series of non-stationary problems with different types of disturbing forces acting on the water body surface. Motion of cyclones [3], baric fronts [4], the stationary wind field [5] and the wave generator at the liquid boundary of the basin [6], producing waves in an interval including resonant frequencies, are usually considered as disturbances. In [7], the resonance properties of the Alekseev Bay under the effect of an initial tsunami-type disturbance were studied. A similar method is used in the present work.

Numerical model and selection of parameters. To simulate resonant oscillations in a system of adjacent bays, a linear version of the numerical hydrodynamic *ADCIRC (Advanced Circulation Model for Shelves Coasts and Estuaries)* model was used [8, 9]. The initial equations of the model have the following form

$$\frac{\partial U}{\partial t} + g\frac{\partial \eta}{\partial x} = A_h \frac{\Delta q_x}{H}, \tag{1}$$

$$\frac{\partial V}{\partial t} + g\frac{\partial \eta}{\partial y} = A_h \frac{\Delta q_y}{H}, \tag{2}$$

$$\frac{\partial \eta}{\partial t} + \frac{\partial q_x}{\partial x} + \frac{\partial q_y}{\partial y} = 0. \tag{3}$$

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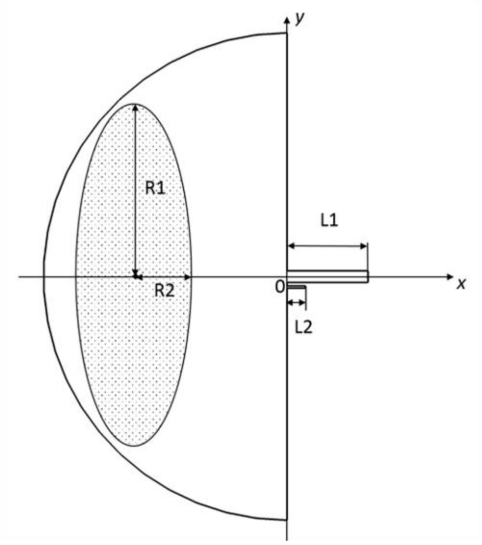
[2] Rabinovich, A.B., 1993. [*Long Gravitational Waves in the Ocean: Capture, Resonance and Radiation*]. Saint Petersburg: Gidrometeoizdat. 325 p. (in Russian).

[3] Arkhipkin, V.S., Ivanov, V.A. and Nikolaenko, E.L., 1989. [*Modeling of Barotropic Seiches in the Southern Seas. Modeling of Hydrophysical Processes and Fields in Closed Basins and Seas*]. Moscow: Nauka, pp. 104-117 (in Russian).

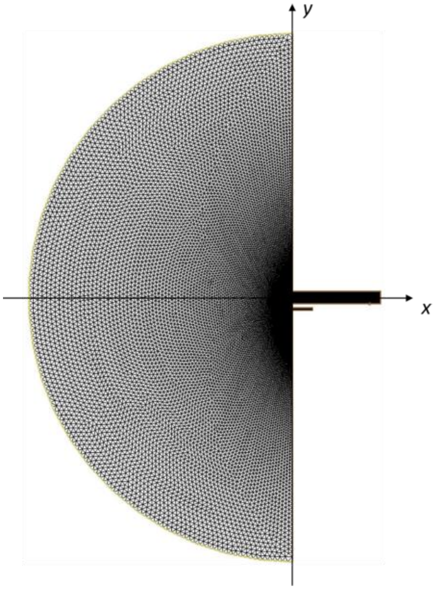
Here, U and V are depth-average components of the current velocity vector along the x and y axes, respectively; t is the time; η is the water level in the basin; $H = h + \eta$ is the dynamic depth; Δ is Laplace operator with respect to spatial variables; A_h is the horizontal turbulent viscosity coefficient; $q_x = UH$, $q_y = VH$ are the complete flow vector components.

The numerical algorithm of the *ADCIRC* model is based on the finite element method using triangular elements with linear basis functions. To reduce the level of computational noise during the numerical integration of system (1)–(3), the continuity equation (3) is represented in the form of the *GWCE* (*Generalized Wave Continuity Equation*) equation [8].

Numerical experiments and discussion of the results. Specific calculations for two adjacent bays of rectangular shape and constant depth were carried out. The computational domain geometry is shown in Fig. 1. The largest bay (Bay A) had the dimensions and average depth of the Sevastopol Bay (length 7 km, width 1 km and depth 11.7 m), the smaller one (Bay B) – of the Karantinnaya Bay (length 2.4 km, width 370 m and depth 11.8 m). The greatest width of the computational domain outside the bays was 21 km, its depth was 30 m, which corresponds to the average depth of the coastal zone of the Sevastopol region. The unstructured computational grid (Fig. 2) consisted of nearly 40,000 nodes. The integration step of system (1) – (3) over time was 0.025 s. Coefficient $A_h = 3$ m^2/s.



F i g. 1. Scheme of the computational domaim



F i g. 2. Non-structured computational grid

The initials conditions were of the following form

$$U = 0\ ,\ V = 0\ ,\ \eta = \eta_0 \begin{cases} \sqrt{1 - r^2}\,, & r < 1 \\ 0\,, & r \geq 1 \end{cases}, \tag{4}$$

where $r = \sqrt{(x - x_0)^2 / R_1^2 + (y - y_0)^2 / R_2^2}$; η_0 is the maximum level elevation; x_0, y_0 are the ellipsis center coordinates; R_1, R_2 are the transverse and longitudinal semiaxes of an ellipse lying at the base of the initial disturbance. The constant η_0 in the formula (4) was chosen so that the amplitude of the generated wave was approximately 0.5 m at the entrance to the Bay A.

The initial disturbance area was oriented parallel to the coast (see Fig. 1). Its longitudinal size did not change and was 30 km. The transverse size of the disturbance area was chosen from the following considerations. According to governing document[4], the tsunami wave period in the coastal zone of Sevastopol is about 10 min. Then, within the long-wave approximation, the following quantity can be taken

$$\lambda = c\tau = \sqrt{gh} \cdot \tau\,. \tag{5}$$

Hence under h = 30 m and τ = 10 min, we obtain $\lambda \approx 10$ км. In [10] sizes of the earthquake-specific foci of the Black Sea, determined by the Wells formula [11, p. 984], make up about 16.4 × 68 km. Based on these estimates, in numerical experiments, the values varied from 10 to 16 km.

At the solid boundaries of the computational domain, a non-leakage condition was set. At the liquid boundary, the condition of free passage [7, p. 60] was used:

$$\frac{\partial \eta}{\partial t} + \sqrt{gh}\,\frac{\partial \eta}{\partial n} = 0\,.$$

Four series of numerical experiments were carried out. In the first series, the computational domain included both bays, in the second one – only Bay A, in the third – only bay *B*, in the fourth – only the coastal shelf area without bays. In each series of experiments, the parameter λ was 10, 14 and 16 km. The total integration time was 4 hours.

Model sea level values were derived at 21 points. Its location is shown in Fig. 3. Then, using a spectral analysis of sea level oscillations, resonance periods were identified at these points. To reduce the effect of transients on the result of determining resonance periods, the spectra were calculated for truncated series, from which the initial time interval of 90 min was excluded.

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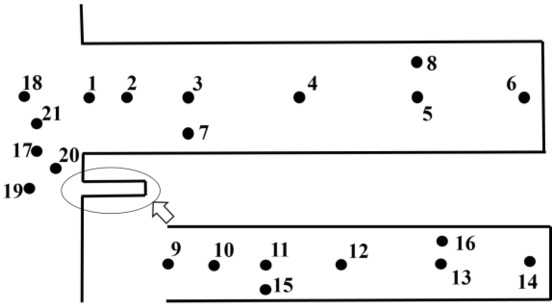
[4] Standartinform, 2017. [*Buildings and Structures in Tsunami-Hazardous Areas. Design Rules*]. SP 292.1325800.2017. Accepted 2017-12-24. Moscow: Standartinform, 117 p. (in Russian).



F i g. 3. Scheme of location of virtual mareographs

The resonance periods obtained based on the numerical model were compared with the periods calculated by the following formula [12, p. 76]:

$$\tau_{km} = \frac{4}{\sqrt{gh}} \frac{ab}{\sqrt{(1+2k)^2 b^2 + 4m^2 a^2}}, \qquad (6)$$

where a, b and h are the length, width and depth of the corresponding bay; $k = 0, 1, 2, \ldots$ is the longitudinal mode number; $m = 0, 1, 2, \ldots$ is the transverse mode number.

In Tab. 1, 2 the values of the resonance periods are presented for each of the bays, ordered by decreasing energy contribution of the corresponding modes and amounting to at least 10% of the maximum. Arabic numerals indicate the numbers of control points (Fig. 3). Roman numerals denote a series of numerical experiments.

As can be seen from Tab. 1, modes with periods of 45, 36, 20, 15, and 9 min dominate in Bay A. Analysis of the calculation results showed that at the top of the bay (points 5, 6) a mode with a period of 6.4 minutes is also traced. The periods of 45, 15, and 9 min are in satisfactory agreement with the analytical solution (6) (Tab. 3), and they can be interpreted as periods of natural oscillations of basin A. According to formula (6) and Tab. 3, a value τ of 45 min corresponds to the zero mode τ_{00} (Helmholtz mode); a value τ of 15 min is a single-node longitudinal mode τ_{10}; a value τ of 9 min is a two-node longitudinal mode τ_{20}. The mode τ_{10}, regardless of the width of the disturbance area and the presence of an adjacent bay, dominates inside the Bay A, with the exception of the entrance to the bay (point 1, Fig. 4, *a*), the nodal line of this mode passing through point 5 (Fig. 4, *b*) and open sea (point 18, Fig. 4, *d*). A characteristic periodogram demonstrating the predominance of mode τ_{10} in Bay A is shown in Fig. 4, *c*.

The periods of 36 and 20 min are not periods of eigen oscillations of bays *A* and *B* (in which they are also noticeably expressed, see Tab. 2). They can be interpreted as standing oscillations resulting from the interaction of an incident wave with a vertical wall[2]. This assumption is confirmed by calculations for cases when the coastline has no bays. Moreover, it was found that for all the considered values λ in the coastal zone, oscillations with periods of about 20 and 34 minutes are distinguished.

Table 1

Bay *A*: Resonance periods (min) corresponding to decrease of oscillations' energy at different values of the initial disturbance area width

Control points																	
1			2			3			4			5			6		
Series of experiments																	
I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
$\frac{20}{20}$	$\frac{20}{20}$	$\frac{20}{15}$	$\frac{15}{20}$	$\frac{15}{15}$	$\frac{20}{15}$	$\frac{15}{15}$	$\frac{15}{15}$	$\frac{15}{15}$	$\frac{15}{15}$	$\frac{15}{15}$	$\frac{15}{15}$	$\frac{9}{9}$	$\frac{9}{45}$	$\frac{9}{45}$	$\frac{15}{15}$	$\frac{15}{15}$	$\frac{15}{15}$
$\frac{15}{15}$	$\frac{15}{15}$	$\frac{15}{15}$	$\frac{20}{15}$	$\frac{20}{9}$	$\frac{15}{20}$	$\frac{20}{20}$	$\frac{20}{20}$	$\frac{9}{20}$	–	–	$\frac{9}{45}$	$\frac{20}{20}$	$\frac{36}{9}$	$\frac{36}{9}$	$\frac{20}{20}$	$\frac{20}{20}$	$\frac{9}{45}$
–	–		$\frac{9}{9}$	$\frac{9}{9}$	$\frac{9}{9}$	–	$\frac{9}{9}$	$\frac{20}{9}$	–	–	$\frac{20}{20}$	$\frac{45}{45}$	$\frac{20}{20}$	$\frac{20}{20}$	–	$\frac{9}{45}$	$\frac{20}{20}$
Control points																	
7			8			17			18			20			21		
Series of experiments																	
I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
$\frac{15}{15}$	$\frac{15}{15}$	$\frac{15}{15}$	$\frac{9}{45}$	$\frac{9}{45}$	$\frac{9}{45}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$	$\frac{-}{20}$
$\frac{20}{20}$	$\frac{20}{20}$	$\frac{9}{20}$	$\frac{20}{20}$	$\frac{36}{9}$	$\frac{36}{9}$	$\frac{-}{13}$	$\frac{-}{13}$	$\frac{-}{13}$	$\frac{-}{13}$	–	–	$\frac{-}{13}$	$\frac{-}{13}$	$\frac{-}{13}$	$\frac{-}{13}$	$\frac{-}{13}$	$\frac{-}{15}$
– –	$\frac{9}{9}$	$\frac{20}{9}$	$\frac{45}{9}$	$\frac{20}{20}$	$\frac{20}{20}$	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –	– –

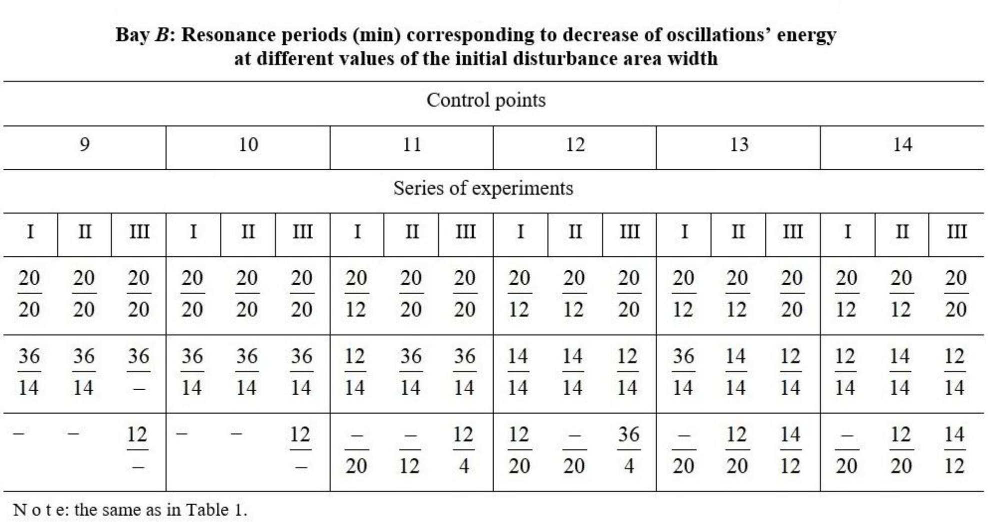
Note:

1. In the experiment series I $\lambda = 10$ km; in those II and III – 14 and 16 km, respectively.
2. Values of the periods are given in a form of a simple fraction; the numerator represents the result of calculation without the adjacent bay, and the denominator – with the adjacent bay.

In Bay A, sea level fluctuations with a period of 36 min occur only in cases where adjacent Bay B is not taken into account. According to Tab. 1 and Fig. 4, *a*, a mode with a value of 20 min dominates both at the entrance to Bay A (point 1) and beyond (points 17–21).

Thus, at the entrance to Bay A, the eigenmodes have practically no effect on sea level fluctuations, which indirectly confirms the validity of the boundary condition $\eta = 0$, which is often used in modeling, assuming the presence of a nodal line at the entrance to the bay at the level of eigenmodes. Oscillations with periods of 20, 36 minutes are noticeably manifested in the vicinity of the nodal line of the single-node longitudinal mode (its period is 15 minutes) passing through points 5, and 8.

Table 2



Bay *B*: Resonance periods (min) corresponding to decrease of oscillations' energy at different values of the initial disturbance area width

Control points: 9			10			11			12			13			14		
Series of experiments																	
I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
$\frac{20}{20}$	$\frac{20}{20}$	$\frac{20}{20}$	$\frac{20}{20}$	$\frac{20}{20}$	$\frac{20}{20}$	$\frac{20}{12}$	$\frac{20}{20}$	$\frac{20}{20}$	$\frac{20}{12}$	$\frac{20}{12}$	$\frac{20}{20}$	$\frac{20}{12}$	$\frac{20}{12}$	$\frac{20}{20}$	$\frac{20}{12}$	$\frac{20}{12}$	$\frac{20}{20}$
$\frac{36}{14}$	$\frac{36}{14}$	$\frac{36}{-}$	$\frac{36}{14}$	$\frac{36}{14}$	$\frac{36}{14}$	$\frac{12}{14}$	$\frac{36}{14}$	$\frac{36}{14}$	$\frac{14}{14}$	$\frac{14}{14}$	$\frac{12}{14}$	$\frac{36}{14}$	$\frac{14}{14}$	$\frac{12}{14}$	$\frac{12}{14}$	$\frac{14}{14}$	$\frac{12}{14}$
–	–	$\frac{12}{-}$	–	–	$\frac{12}{-}$	$\frac{-}{20}$	$\frac{-}{12}$	$\frac{12}{4}$	$\frac{12}{20}$	$\frac{-}{20}$	$\frac{36}{4}$	$\frac{-}{20}$	$\frac{12}{20}$	$\frac{14}{12}$	$\frac{-}{20}$	$\frac{12}{20}$	$\frac{14}{12}$

Note: the same as in Table 1.

Table 3

Periods of Eigen-Oscillations in the Bays *A* and *B* Calculated by Formula (6)

k	m	τ_{km}, min	
		Bay A	Bay *B*
0	0	43.6	11.7
1	0	14.5	3.9
2	0	8.7	2.3
3	0	6.3	1.7
0	1	3.1	0.7
1	1	3.0	0.7

In Bay A, sea level fluctuations with a period of 36 min occur only in cases where adjacent Bay B is not taken into account. According to Tab. 1 and Fig. 4, *a*, a mode with a value of 20 min dominates both at the entrance to Bay A (point 1) and beyond (points 17–21).

Thus, at the entrance to Bay A, the eigenmodes have practically no effect on sea level fluctuations, which indirectly confirms the validity of the boundary condition $\eta = 0$, which is often used in modeling, assuming the presence of a nodal line at the entrance to the bay at the level of eigenmodes. Oscillations with periods of 20, 36 minutes are noticeably manifested in the vicinity of the nodal line of the single-node longitudinal mode (its period is 15 minutes) passing through points 5, and 8.

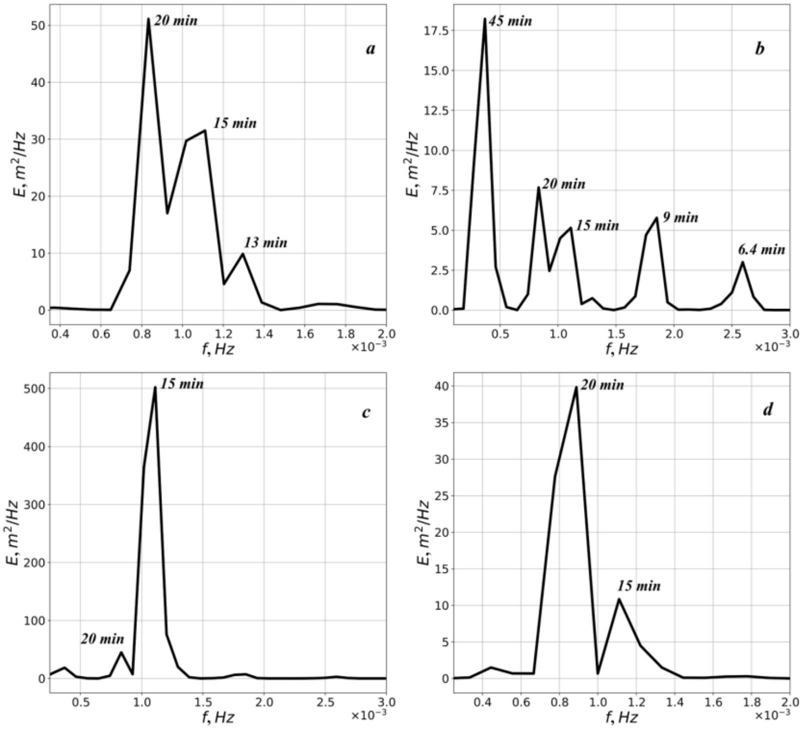


Fig. 4. Sea level period-grams for the model Bay Approximating the Sevastopol Bay (width of the disturbance area is 10 km) for the control points 1 (*a*), 5 (*b*), 6 (*c*) and 18 (*d*)

Comparison of periods of seiches from Tab.1 and 3 shows that an increase in the value from 10 to 16 km leads to an expansion of the mode composition of seiches generated in Bay A. When increasing to 14–16 km, a mode with a period of 9 min starts to appear at points 3 and 4, and at point 6, either a mode with a period of 9 minutes (when the adjacent bay is not taken into account), or a mode with a period of 45 minutes (when the adjacent bay is taken into account).

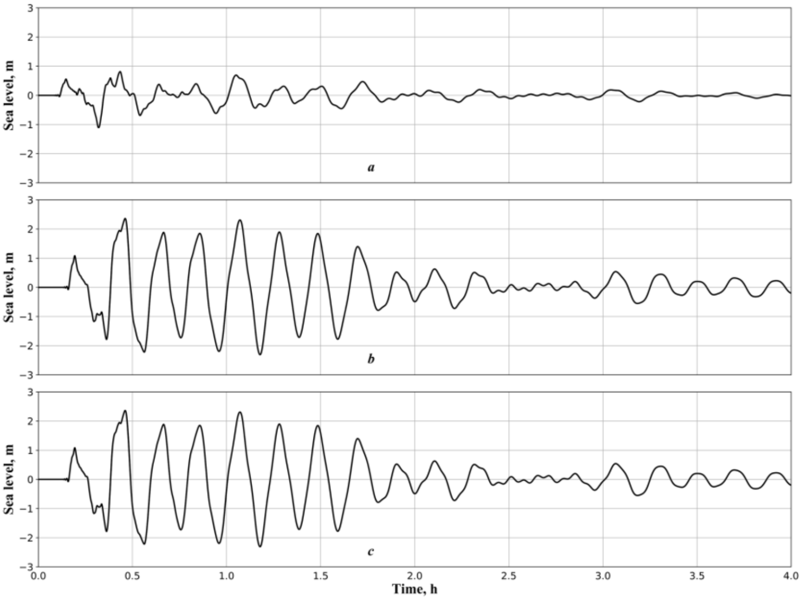
As follows from the analysis of the Tab. 1 data, Bay *B* gas effect on the wave processes in Bay *A*. This is manifested in the Helmholtz mode intensification in Bay *A*. This mode appears at points 4, 5 and 6, remote from the bay entrance. In this case, the energy contribution of the Helmholtz mode, in comparison with other modes, grows as the disturbance area width increases. At point 5, under $\lambda \geq 14$ km, the Helmholtz mode becomes predominant. It can be assumed that the Helmholtz mode of the Sevastopol Bay is generated by disturbance caused by the movement of the sea bottom. Therefore, the tsunami caused by the catastrophic

Yalta earthquake of 1927 led to the generation of seiches of this mode in the Sevastopol Bay with a period of 52 min, with a wave height of 23 cm[5].

The analysis of virtual mareograms showed that the presence of an adjacent bay increases the maximum level elevation by 5–10 %, depending on the width of the disturbance area. The greatest differences in elevation levels were observed at values of 10 and 16 km.

Let us now proceed to consider the resonance response of Bay B to the initial disturbance of the form (4). Tab. 2 data analysis shows that modes having periods 36, 20, 14, 12 and 4 minutes are generated in the bay. Comparison of the values of these periods with those given in Tab. 3, the values of the natural periods of the bay show that the seiches caused by the eigen oscillations of Bay B are modes with periods of 12 min (Helmholtz mode) and 4 min (single-node longitudinal mode). Oscillations with periods of 36 and 20 min, selected in Bay B, are caused by the penetration of standing oscillations arising near the vertical wall. The most intense of the modes generated in Bay B are modes with periods of 20 and 12 min.

Bay A has a significant effect on wave processes in Bay B. It intensifies the Helmholtz mode in it and significantly attenuates the oscillation with a period of 36 min, which, in the presence of an adjacent bay, does not appear in Bay B. As can be seen from Table. 2, if the adjacent bay is taken into account, the Helmholtz mode of Bay B prevails over the other modes in the top of Bay B (points 12–14), when λ is 10 and 14 km. An increase in the width of the initial disturbance area to 16 km leads to the fact that oscillation with a period of 20 min (a standing wave arising from the interaction of an incident wave with a vertical wall) begins to prevail in Bay B. At the same time, the 4 min period mode is intensified.



F i g. 5. Virtual marigrams of the sea level in bay *B* (width of the disturbance area is 12 km, $\tau = 11.66$ min) for the control points 10 (*a*), 14 (*b*), 16 (*c*)

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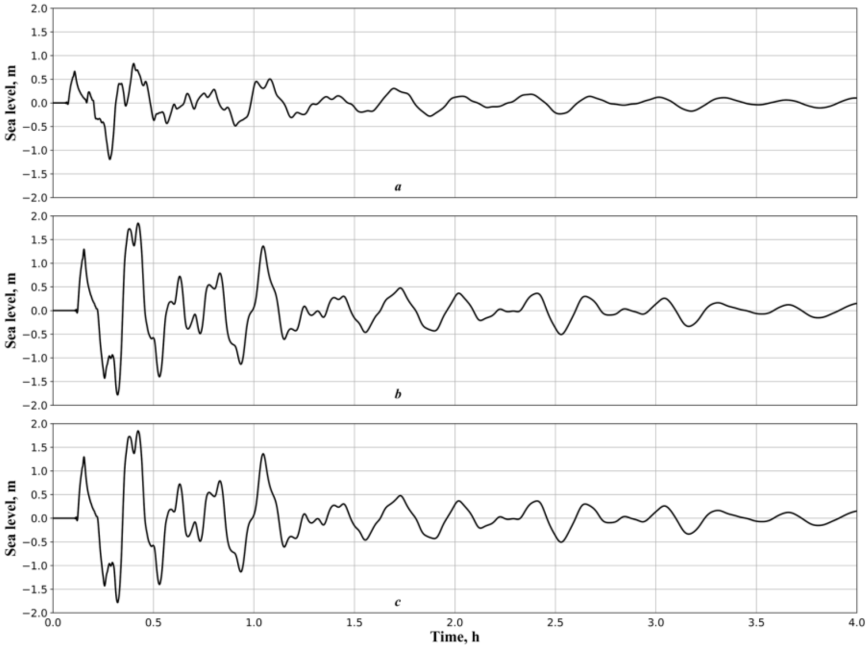
[5] Dotsenko, S.F. and Ivanov, V.A., 2010. [*Natural Disasters in the Azov-Black Sea Region*]. Sevastopol: ECOSI-Gidrofizika, 175 p. (in Russian).

A numerical experiment was additionally carried out for the case when the value τ of 11.7 min ($\lambda =$ 12.036 km) in formula (5) exactly coincided with the period of the Helmholtz mode of Bay B. In this case, only Bay B was considered.

Fig. 5 shows virtual sea-level marigrams in Bay B, when the width of the disturbance area is 12 km ($\tau = 11{,}66$ min) for the control points 10 (Fig. 5, *a*), 14 (Fig. 5, *b*) and, 16 (Fig. 5, *c*). And in Fig. 6 – virtual sea level marigrams in Bay B, when the width of the disturbance area is 12.036 km ($\tau = 11{,}7$ min) for the control points: 10 (Fig. 6, *a*), 14 (Fig. 6, *b*) and 16 (Fig. 6, *c*). At the entrance to the bay (point 10), the amplitude of the initial disturbance wave is about 0.5 m (Fig. 5, *a*; 6, *a*).

Analysis of Fig. 5 and 6 shows that the bay response to a disturbance of type (4) strongly depends on the width of the disturbance region (wave period τ). So, even if the periods of disturbances differ by 6 s, the wave characteristics noticeably differ. Firstly, when $\tau = 11{,}7$ min, the seiche with amplitude about 3 m (at control points 14, 16) is generated in the bay (Fig. 6, *b*, 6, *c*). If $\tau = 11{,}66$ min, then the amplitude of the seiche at the indicated points does not exceed 2 m (Fig. 5, *b*, 5, *c*). Secondly, in the case of resonance, the level performs four oscillations within an hour with a significant (at least 2 m) amplitude (Fig. 6, *b*, 6, *c*). If $\tau = 11{,}66$ min, then there is only one elevation of the level with an amplitude of more than 1.5 m (Fig. 5, *b*, 5, *c*).



F i g. 6. Virtual marigrams of the sea level in bay *B*, width of the disturbance area is 12.036 km ($\tau =$ $= 11.7$ min) for the control points 10 (*a*), 14 (*b*), 16 (*c*)

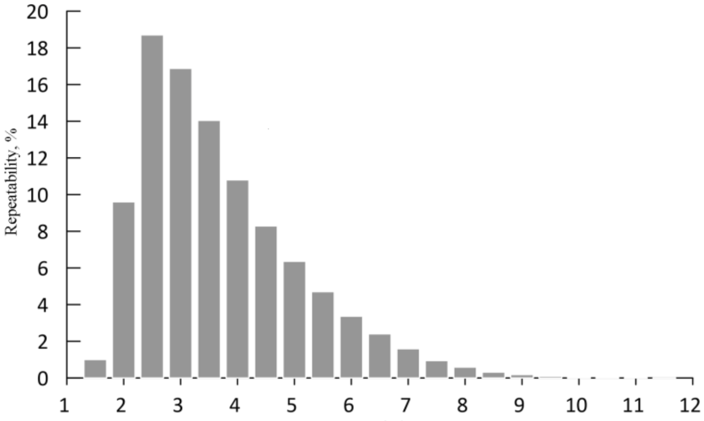
Analysis of the calculation results showed that the maximum amplitude of seiches with a width of the initial disturbance region of 10 km (min), 14 km (min), and 16 km (min) is about 2 m. Thus, a tsunami wave with a period of 11.7 min poses a potential danger to Bay B, since the amplitude of the seiches generated by it will exceed 1.5 times the amplitude of seiches for all other values of the initial width of the disturbance region considered. Moreover, level oscillations with such a high amplitude will be repeated at least four times.

Estimation of parameters of infragravity waves for the coastal zone of Sevastopol. The spectrum of natural oscillations of Bay B contains modes with periods τ_{km} <180 s. Modes with such periods can be excited by infragravity waves caused by non-linear interaction of wind waves. The average period of infragravity waves is estimated by the formula from [13, p. 32], $\tau_{IG} = 20\bar{\tau} - 50$, where $\bar{\tau}$ is the average period of wind waves.

The case of interest to find out whether there is a potential for generation of short-period seiches in a bay with characteristic dimensions of Bay B by infragravity waves. For this purpose, the results of numerical modeling of wind waves in the Black Sea using the *SWAN* model [14] and *ERA-Interim* atmospheric reanalysis data for 1979–2017 are used.

As can be seen from Tab. 3, the following periods of seiche oscillations are distinguished for Bay B: τ_{01} = τ_{11} = 42 s; τ_{30} = 102 s; τ_{20} = 138 s. Values of τ_{IG}, equal to τ_{km}, correspond $\bar{\tau}$, equal to $\bar{\tau}_1$ = 4.5 s, $\bar{\tau}_2$ = 7.5 s and $\bar{\tau}_3$ = 9.5 s.

Fig. 7 shows the repeatability histogram (%) of the value $\bar{\tau}$ at a point located on the Sevastopol seaside at a depth of 25 m. The histogram shows that the maximum repeatability of 8.3% corresponds to the period $\bar{\tau}_1$. The repeatability of periods $\bar{\tau}_2$ and $\bar{\tau}_3$ respectively, is 1.0 and 0.1%. Thus, from a theoretical point of view, short-period seiches in Sevastopol bays can be generated by infragravity waves.



F i g. 7. Repeatability (%) of the wind wave average period in the Sevastopol coastal zone based on the results of numerical modeling for 1979–2017

Conclusion

Based on numerical simulation, the resonance response of a system of two adjacent bays (Bays A and B) of rectangular shape, having dimensions and depths of the Sevastopol and Karantinnaya bays, respectively, to the initial disturbance of the free surface caused by the sea bottom movement is studied.

Four lower modes of eigen oscillations with periods of 45, 15, 9 and 6 min are shown to be generated in Bay A, and two lower modes with periods of about 12 and 4 min are generated in B bay. In both bays, an oscillation appears with a period of about 20 minutes, which is a standing wave caused by the interaction of the initial disturbance with a vertical wall. The oscillation is most intense in areas adjacent to the entrances to the bays.

In the presence of an adjacent bay, the Helmholtz mode is intensified in both bays. In this case, the oscillation amplitude grows by 5–10 %, depending on the width of the disturbance area. The expansion of the initial disturbance area increases the mode composition of seiches generated in Bay A, and oscillations with a period of 20 min are intensified in Bay B.

Wave disturbances with a period of 11.7 min are of a potential danger for Bay B, since in this case there is resonance with the zero mode of the bay having the same period. In this case, the amplitude of the generated seiche exceeds 1.5 times the amplitude of the seiche for all other values of the initial width of the disturbance area considered.

Based on the analytical dependence between periods of infragravity waves and average periods of wind waves in the Sevastopol region (obtained from data from a retrospective analysis of waves), the theoretical possibility of generating short-period seiches by infragravity waves in both bays was revealed.

The numerical calculations showed the *ADCIRC* model applicability for the study of resonance properties using model bays as an example (it describes well the resonance case), which later makes it possible to use it to study the resonance properties of the real configuration of Sevastopol bays.

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