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Numerical Simulation of Tsunami Wave Propagation to the Balaklava Bay

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Abstract
Purpose. To investigate the process of tsunami wave propagation from the hypothetical earthquake foci to the Balaklava Bay, and to zone the tsunami impact upon the bay coastline based on the results of numerical modeling, are the purposes of the paper.
Methods and Results. The results of numerical simulation of the tsunami wave propagation to the Balaklava Bay with subsequent flooding of the coast are presented. The problem of the tsunami wave propagation from three hypothetical earthquake foci and their evolution in the Black Sea was solved using the nonlinear model of long waves. Time dependences of the sea level fluctuations at the entrance to the Balaklava Bay were obtained. They were applied as boundary conditions at the liquid boundary of the computational domain, where the *SWASH* model had been used to simulate numerically the tsunami wave propagation in the bay with their subsequent run-up to the coast.
Conclusions. Propagation of tsunami waves in the Balaklava Bay is accompanied by formation of the sea level seiche oscillations with a period ~ 8 min which correspond to the Helmholtz mode. Inside the bay, the tsunami heights increase by 5–6 times as compared to those at the entrance to the computational domain. The sea level fluctuations are maximal at the bay top, where its rise achieves 1.4–1.5 m. The eastern coast of the Balaklava Bay and the one adjacent to its top are subject to the strongest flooding. The values of water level on land measured from the ground level, reach 1.0–1.5 m, and at the bay top – 1.8 m. At the eastern coast of the bay, the flooding maximum length constitutes 60 m, at its top – 90 m.

Keywords: numerical simulation, tsunami, tsunami zoning, *SWASH*, Balaklava Bay

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Introduction. A tsunami in the Black Sea is a rare but not safe phenomenon for the coast of this region. Over the past 3,000 years, 50 events that caused a tsunami [1] have occurred here. The vast majority of these events were seismic in nature, and some probably were landslide or meteorological. It is possible that they may happen in the future. There is little information about the tsunami in the Black Sea today. This makes it necessary to carry out numerical calculations to determine possible wave heights and the areas of the Black Sea coast most affected by the tsunami.

The main studies of the Black Sea tsunamis using numerical modeling were carried out in [2–8]. These works aim to study the dynamics of tsunami waves in the Black Sea as a whole. They estimated the possible sea level heights along the coast during wave propagation from the model tsunami foci. At the same time, it is important to note that certain coastal areas, especially bays and gulfs, require more detailed research, since when the waves penetrate them, significant increases in sea level fluctuations can occur.

During the Yalta earthquake on September 12, 1927, tsunami waves were recorded by coastal mareographs at several points of the Crimean-Caucasian coast – from Yevpatoria to Batumi. The eyewitnesses also reported sudden changes in sea level along various sections of the coast [9, 10]. According to their testimonies, on September 12, after the main shock, the sea level in the Balaklava Bay decreased by 0.7 m, draining a part of the bay and leaving small vessels and boats stranded near the shore. Then, after 40 minutes, the sea level began to rise rapidly, rising above the average by more than 0.5 m and flooding the space 15 m in length. Thus, the oscillation amplitude was ~ 1.2 m [11, 12]. According to the eyewitnesses, the sea level fluctuations in the shallow edge part of the bay were especially noticeable. It was noted that these level variations were observed at full calm. According to [11], the cause could have been seismic fluctuations caused by the penetration of waves from the open sea into the bay.

Based on the set of rules for design in tsunami-prone areas [1] and construction in seismic areas [2], for the Balaklava Bay, the normative seismic intensity on the *MSK*-64 scale for three degrees of seismic hazard (10, 5, 1%) for 50 years has been 8, 8 and 9 points, respectively, which characterizes destructive (8 points) and devastating (9 points) earthquake. In addition, this area is classified as a particularly earthquake-prone one due to the fact that there is a zone boundary of earthquakes of different magnitude.

The Balaklava Bay is a narrow semi-enclosed bay with impaired water exchange with the Black Sea. The propagation of long waves in such bays can be accompanied by significant sea level rises and land flooding [13]. Therefore, there is a need to clarify the characteristics of tsunami hazard in the Balaklava Bay on the basis of numerical modeling.

In [14], a modeling of the long wave propagation in the Balaklava Bay was carried out without taking into account the run-up on the shore. It is demonstrated that when entering the bay, the wave amplitude increases 4–5 times, due to the narrowness and curvature of the bay, rather prolonged fluctuations in sea level are observed along its water area with partial wave propagation into its deeper water zone. Thus, it is acceptable to assume that tsunamis can lead to seiche formation in the bay. According to [15], in the bays with an open outer boundary, seiches are induced, i.e. their excitation occurs through an open boundary.

Seiche oscillations affecting the entire Black Sea area were studied in [16–18]. However, the coastline configuration and the bottom relief can affect the formation of the spectrum of natural oscillations of each gulf or bay [19]. The seiche parameters for each specific coastal area are different due to the fact that the coastal waters differ significantly in their resonant characteristics [20].

[1] SP 292.1325800.2017. *Buildings and Structures on Tsunami Hazardous Areas. Regulations of Design*. Moscow, 147 p. (in Russian).

[2] SP 14.13330.2018. *Seismic Building Design Code*. Moscow, 238 p. (in Russian).

The study of seiche oscillations in the Balaklava Bay was carried out in [21], where the periods of the first four modes of natural oscillations were obtained based on the analysis of energy dependencies.

This paper presents the results of a numerical simulation of the tsunami wave penetration into the Balaklava Bay, taking into account the mechanism of the coast flooding – drainage. Two types of boundary conditions at the entrance to the bay are considered. In the first case, a nonlinear model of long waves was applied to solve the problem of the evolution of tsunami waves in the Black Sea from three seismic foci. Dependences on the time of sea level fluctuations at the entrance to the Balaklava Bay were obtained. In the second type of boundary conditions at the entrance to the bay, the initial elevation in the form of a soliton was set. These dependencies were used as boundary conditions on the liquid boundary of the computational domain for the Balaklava Bay, with the help of the *Simulating WAves till SHore* [3] (*SWASH*) model numerical simulation of the tsunami wave propagation in the bay with the subsequent run-up to the shore was performed. Some of the results presented here were discussed in the dissertation of one of the authors [4].

Materials and methods. In order to calculate tsunami waves in the Azov-Black Sea basin, bathymetry, set on a rectangular grid with a 30-second spatial resolution, was applied. Calculations of the tsunami evolution in the Black Sea from a seismic focus were carried out using the model of nonlinear long waves described in [22]. Three cases of the tsunami with a magnitude of 7 points were simulated since stronger earthquakes were not noticed near the Crimean coast [1]. The parameters of tsunami generation foci were determined by empirical formulas [23]. The foci had elliptical shapes and were oriented along the 1500 m isobath since all known Black Sea tsunamigenic earthquakes occurred on the mainland slope along the isobaths not exceeding this magnitude. The position of the model earthquake foci for three tsunami cases is given in Fig. 1.

At the first stage, using the tsunami propagation model for the entire Black Sea [22], the dependences on the time of sea level fluctuations on the approach to the Balaklava Bay were obtained. Then, for each focus, calculations of the tsunami in the Balaklava Bay were carried out using the *SWASH* model for 3 h time period with 5 m step in space and a time integration step of 0.01 s.

The wave dynamics in the hydrodynamic non-hydrostatic *SWASH* model is described by nonlinear shallow water equations including a term with non-hydrostatic pressure:

$$\frac{\partial \zeta}{\partial t}+\frac{\partial hu}{\partial x}+\frac{\partial hv}{\partial y}=0, \tag{1}$$

[3] The SWASH team, 2012. *SWASH User Manual. SWASH version 7.01*. Delft: Delft University of Technology, 144 p. Available at: https://swash.sourceforge.io/online_doc/swashuse/swashuse.html [Accessed: 28 July 2022].

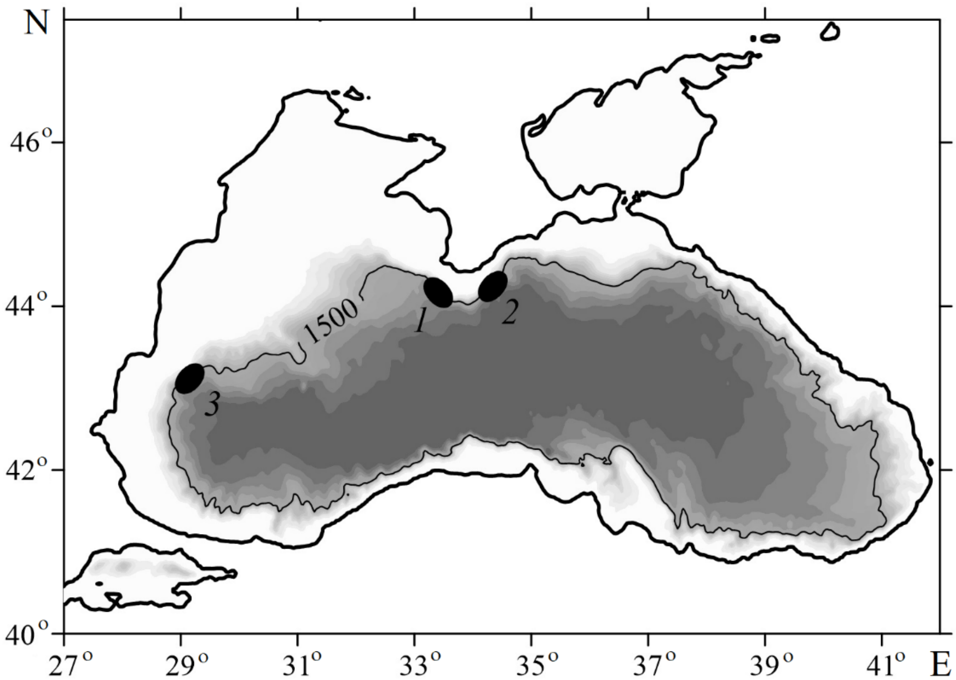
[4] Belokon, A.Yu., 2022. [*Mathematical Modeling of the Propagation and Transformation of Tsunami Waves in the Coastal Zone*]. Thesis Cand. Phys.-Math. Sci. Sevastopol, 163 p. (in Russian).

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}+g\frac{\partial \zeta}{\partial x}+\frac{1}{h}\int_{-d}^{\zeta}\frac{\partial q}{\partial x}dz+c_f\frac{u\sqrt{u^2+v^2}}{h}=\frac{1}{h}\left(\frac{\partial h\tau_{xx}}{\partial x}+\frac{\partial h\tau_{xy}}{\partial y}\right), \quad (2)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}+g\frac{\partial \zeta}{\partial y}+\frac{1}{h}\int_{-d}^{\zeta}\frac{\partial q}{\partial y}dz+c_f\frac{v\sqrt{u^2+v^2}}{h}=\frac{1}{h}\left(\frac{\partial h\tau_{yx}}{\partial x}+\frac{\partial h\tau_{yy}}{\partial y}\right), \quad (3)$$

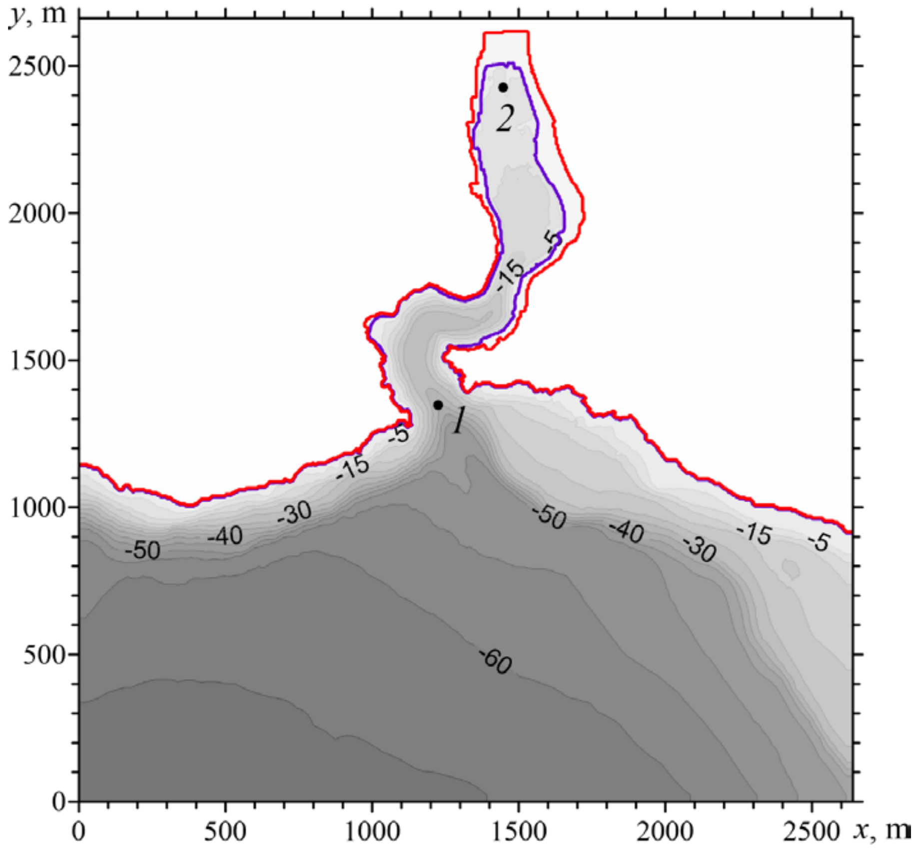
$$\tau_{xx}=2\nu_t\frac{\partial u}{\partial x},\ \tau_{xy}=\tau_{yx}=\nu_t\left(\frac{\partial u}{\partial y}+\frac{\partial v}{\partial x}\right),\ \tau_{yy}=2\nu_t\frac{\partial v}{\partial y}.$$

Here t is time; x, y are cartesian coordinates; the axis z is directed upwards; $\zeta(x,y,t)$ is a deviation of the free surface from the undisturbed level; $h=d+\zeta$ is the total depth equal to the sum of the free surface deviation and the depth d in the undisturbed state of the liquid; u and v are the depth-averaged x and y velocity components; $q(x,y,z,t)$ is a non-hydrostatic pressure; g is the free fall acceleration; $c_f=gn^2/h^{1/3}$ is a bottom friction coefficient, n = 0.022 is the Manning roughness parameter; τ_{xx}, τ_{xy}, τ_{yx}, τ_{yy} are the components of the horizontal turbulent stress tensor; ν_t is a turbulent viscosity coefficient.



F i g. 1. Position of three hypothetical tsunami foci in the Black Sea: *1* – the focus nearest to the Balaklava Bay; *2* – the focus similar to that which caused the Yalta earthquake on September 12, 1927; *3* – the remote focus

Computational domain that includes the Balaklava Bay bottom and land relief is represented in Fig. 2.



F i g. 2. Bottom relief (m) of the calculation domain: entrance to the Balaklava Bay – point *1*; the bay top – point *2*; line of constant depth – blue curve; line of constant height at land – red curve

Mareograms, obtained using the tsunami propagation model for the Black Sea, were used as boundary conditions at the southern boundary of the computational domain (Fig. 2, $y = 0$) [22]. For clarifying the possibility of occurrence of seiche oscillations in the Balaklava Bay under short-term external influence, a numerical experiment, in which the tsunami wave was set as a solitary wave – a soliton, was carried out [24]:

$$\zeta(y,t) = \zeta_0 \cosh^{-2}\left(\frac{y-ct}{\lambda}\right), \qquad (4)$$

where ζ_0 = 0.35 m is a soliton height; t is time; $\lambda = 2H\sqrt{H/3\zeta_0}$ is a soliton horizontal scale; $c = c_0(1+\zeta_0/2H)$ is a phase velocity of a soliton; $c_0 = \sqrt{gH}$; H = 70 m is a sea depth.

To estimate the periods of seiche oscillations in the bay, the mareograms were subjected to spectral analysis (scripts developed in [25] were used).

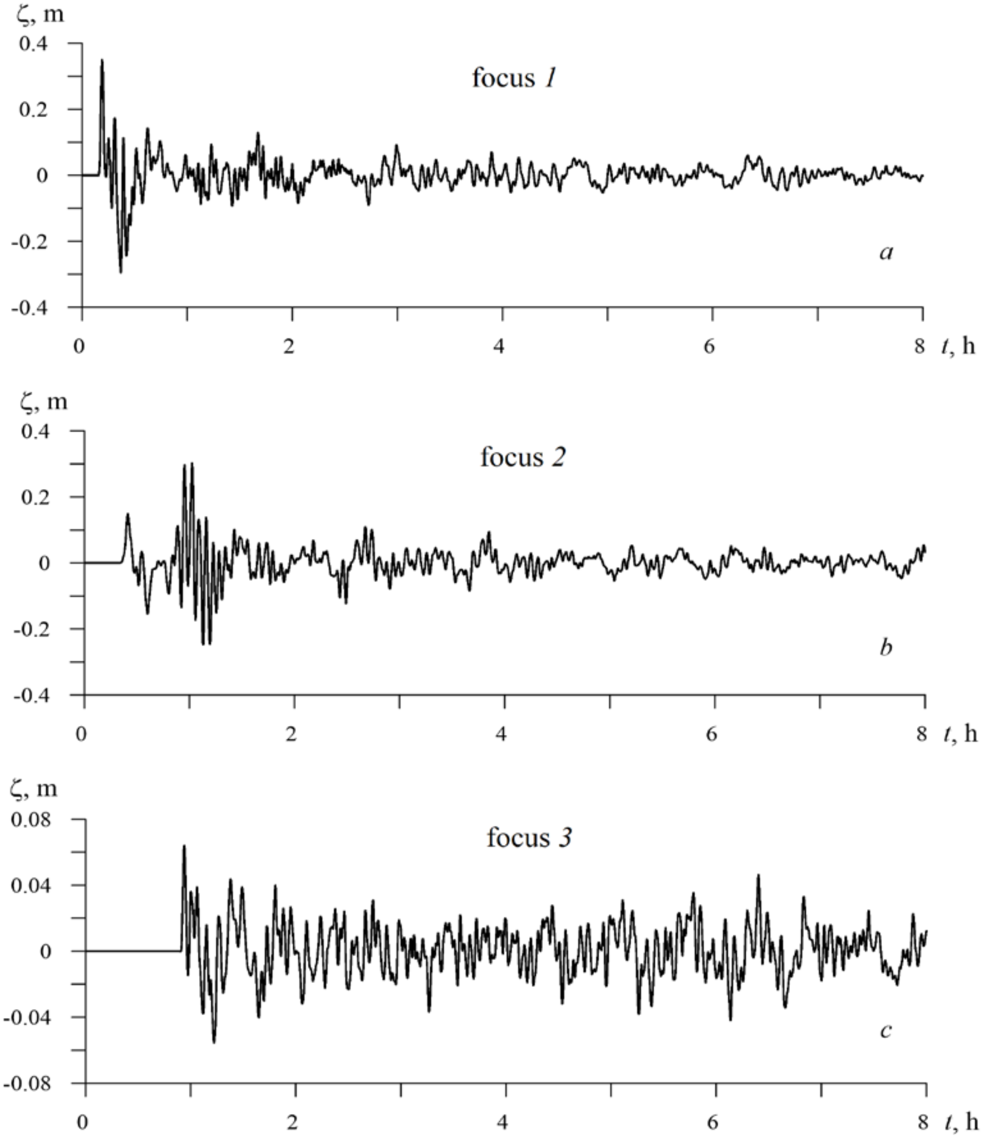
In order to analyze the tsunami impact on a specific coastal area, according to the set of rules [1], the following characteristics are used: vertical run-up – exceeding the level of maximum penetration of a tsunami (water line) above undisturbed sea level during a tsunami; flow depth (dynamic depth) – the water level during a tsunami, measured vertically from the ground level at a given location at a given moment of time; horizontal run-up – the magnitude of the horizontal projection of the flooding zone; the flooding zone – the part of the coast that has been flooded, bounded from above by the water line.

At each point of the studied area (x, y) the value $H_f(x, y) = \max\limits_{0<t<\tau}\left[D(x, y, t)\right] - D(x, y, 0)$ was calculated, where $D(x, y, t)$ is the flow depth at a given time; $D(x, y, 0)$ is the flow depth at the initial time; τ = 3 h is the time of the tsunami impact. The meaning of H_f value is as follows. If (x, y) point is on the land, then H_f corresponds to the maximum possible depth of a coastline flooding. If (x, y) point is located in the sea, then H_f corresponds to the maximum possible sea level rise. The maximum possible boundary of the flooding zone (the boundary of the maximum vertical splash) was determined by H_f = 0.05 m value.

The study results and their discussion. For three foci of tsunami generation, the mareograms on the seashore of the Balaklava Bay coastal area (Fig. 3) at a point with 65 m depth located on the computational domain boundary, are calculated. Their comparison demonstrates that for the near tsunami foci (*1* and *2* in Fig. 1) the maximum sea level amplitudes on the approach to the bay are ± 0.3 m, and for a distant tsunami focus (*3* in Fig. 1) ±0.05 m.

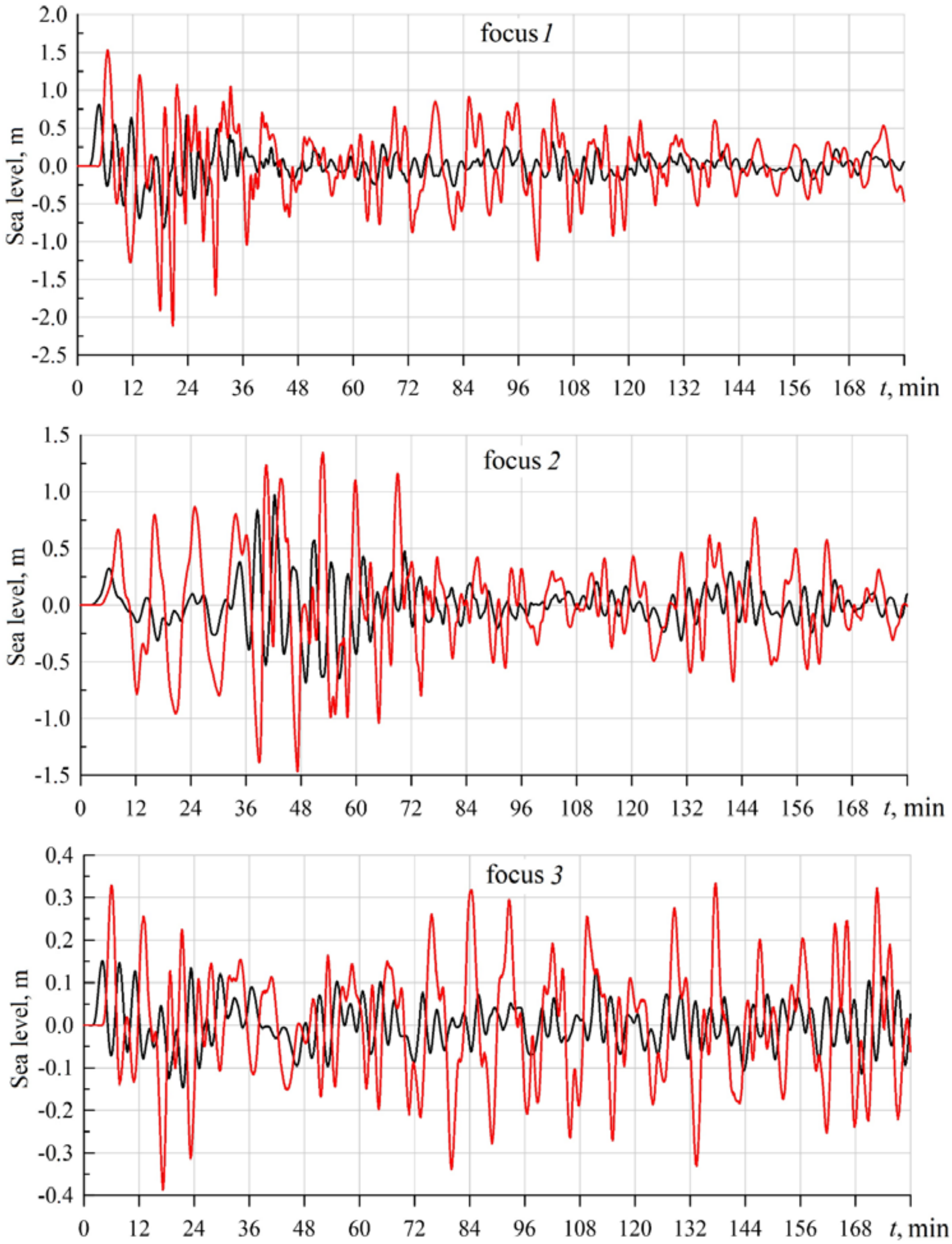
Further, for three cases, the calculations of the tsunami in the Balaklava Bay were carried out on a high-resolution grid (Fig. 2). Fig. 4 shows fluctuations in sea level at the entrance to the Balaklava Bay and at its top. As can be seen, at the entrance to the bay, the wave amplitudes increase by 1.5–2 times compared to the amplitudes at the southern boundary of the region. When a tsunami reaches the top of the bay, the oscillation amplitudes increase approximately twice more (up to 1.4–1.5 m for foci *1* and *2* and up to 0.33 m for foci *3*) compared to the amplitudes at the entrance to the bay. Thus, inside the bay, the tsunami heights increase 5–6 times compared to the heights on the southern boundary of the region. For foci *1* and *2*, the maximum level fluctuations in the bay occur in the initial 60 minutes of tsunami propagation.

The mareograms in Fig. 4 have a well-pronounced oscillatory character. This suggests that the tsunami excites seiche oscillations in the Balaklava Bay. The analysis of the graphs provides the construction of the energy spectra of sea level fluctuations for the Balaklava Bay top (Fig. 5). It can be seen that all the spectra have a well-defined peak in the interval of 8–9-minute periods.



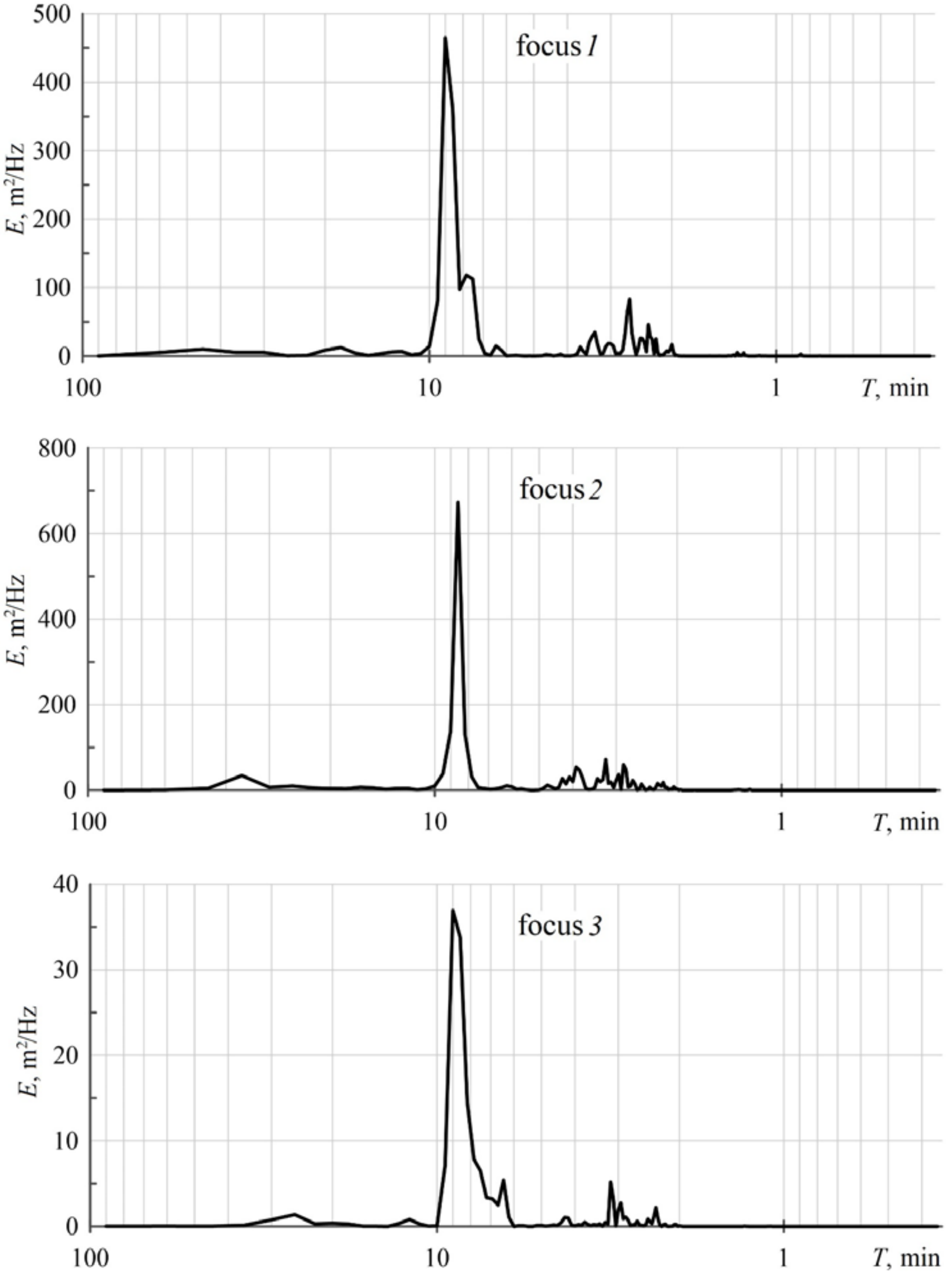
F i g. 3. Sea level fluctuations at the coast of the Balaklava Bay caused by tsunami foci *1–3* ($y = 0$)

In [21], based on the analysis of energy dependencies, the following periods of the first four modes of seiche oscillations were obtained: T_0 = 8.2 min, T_1 = 2.5 min, T_2 = 1.9 min, T_3 = 1.3 min. Thus, in all three cases, when tsunami waves penetrate into the Balaklava Bay, the lowest mode of seiche oscillations T_0 (the so-called Helmholtz mode) is generated in it. It is also worth noting that in the interval of 2–4 min periods there are minor energy fluctuations caused by excitation of higher modes of natural oscillations.

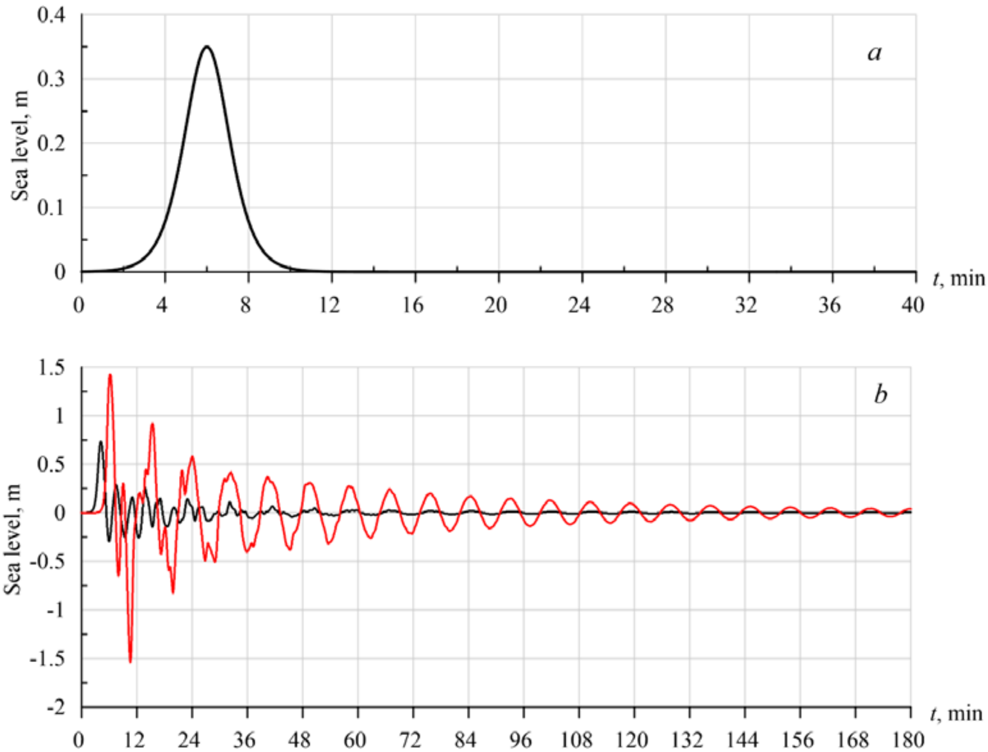


F i g. 4. Sea level fluctuations in the Balaklava Bay caused by tsunami foci *1–3*, at the entrance to the bay (black curve) and at its top (red curve)

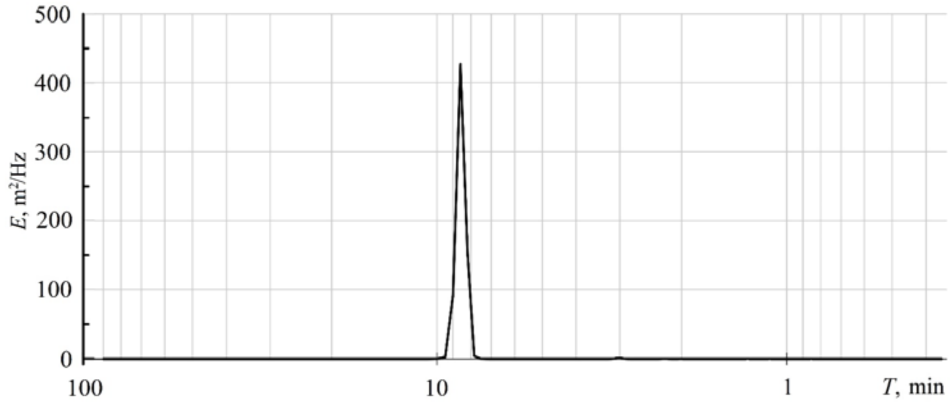
Another stage of the work was the mathematical modeling of level fluctuations in the Balaklava Bay under short-term external effect. Figure 6, *a* shows sea level fluctuations at the southern boundary of the calculated area ($y = 0$) during the soliton passage towards the Balaklava Bay. The level fluctuations caused by the soliton at the entrance to the bay (at point *1*) and at its top (at point *2*) are shown in Fig. 6, *b*. As can be seen, there is a periodic mode of oscillations with attenuation. Fig. 7 demonstrates the energy spectrum of sea level fluctuations at the top of the bay, corresponding to Fig. 6, *a*. One peak in the spectrum at 8.5 min period, which very precisely coincides with the period of the lowest Helmholtz seiche mode T_0, can be traced.



F i g. 5. Energy spectra of sea level fluctuations at the top of the Balaklava Bay for the tsunami foci *1–3* (*T* is the oscillation period at a logarithmic scale)



F i g. 6. Sea level fluctuations near the Balaklava Bay (y = 0) (*a*) and in the Balaklava Bay (*b*, the entrance to the bay – black curve, its top – red curve) for a tsunami wave caused by the propagation of a soliton (formula (4))

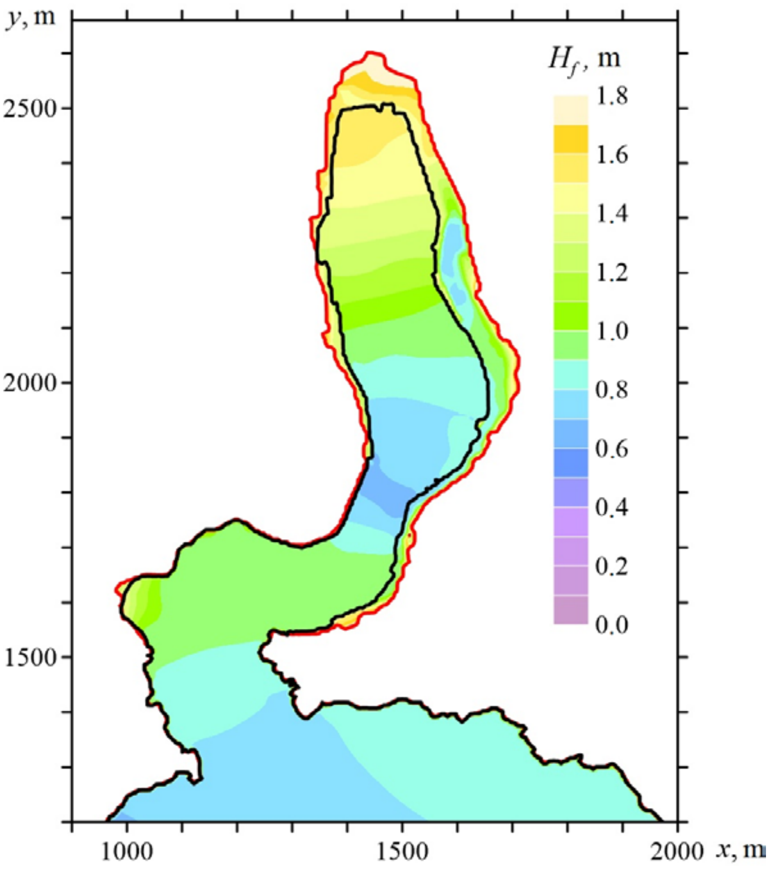


F i g. 7. Energy spectrum of the sea level fluctuations at the Balaklava Bay top for a soliton (formula (4))

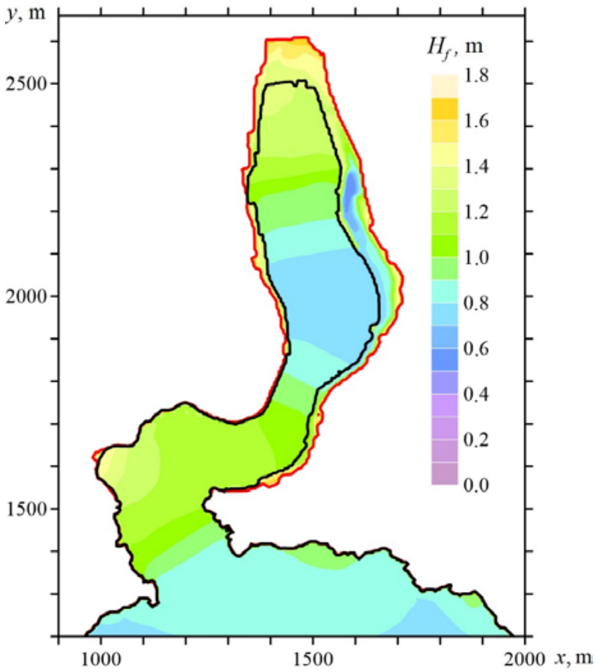
Thus, the results of numerical modeling show that when tsunami waves penetrate into the Balaklava Bay, sea level fluctuations with ~ 8 min period will be excited in it. These fluctuations are the greatest at the top of the bay, where the level rises can reach 1.4–1.5 m.

The analysis of the tsunami modeling results in the area under study made it possible to carry out tsunami zoning of the Balaklava Bay coastline and the adjacent seashore. The calculations reveal that when penetrating into the bay, the long wave is partially reflected from the solid boundaries of its southern part and partially passes through the knee-shaped narrowness into the central and northern parts of the bay. Wave energy is concentrated here and seiche-like fluctuations in the water level are formed, leading to flooding of the shallow sections of the bay coastal strip.

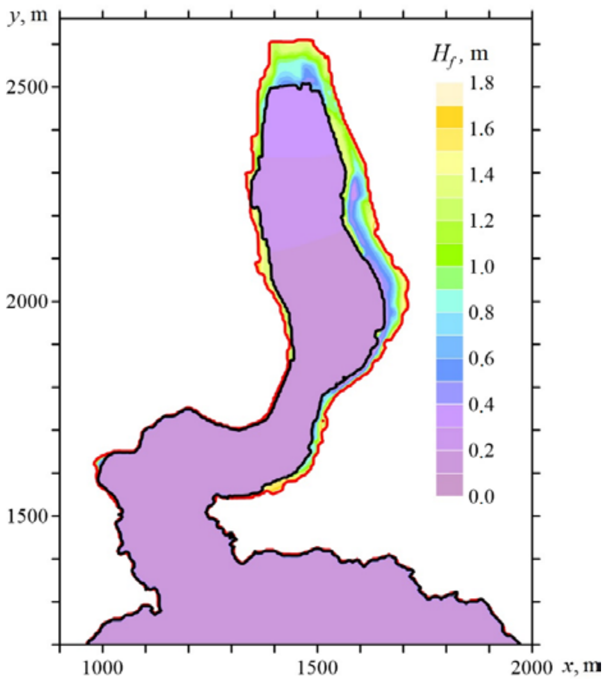
Fig. 8–10 shows the cartographic diagrams of possible boundaries of the flooding zone and the flow depth on the adjacent seashore and in the coastal strip of the Balaklava Bay for each of the three tsunami foci. The maximum possible for all tsunami foci, the boundary of the flooding zone and the flow depth are shown in Fig. 11. The maximum possible boundary of the flooding zone (the boundary of the maximum vertical run-up) was determined by the value $H_f = 0.05$ m.



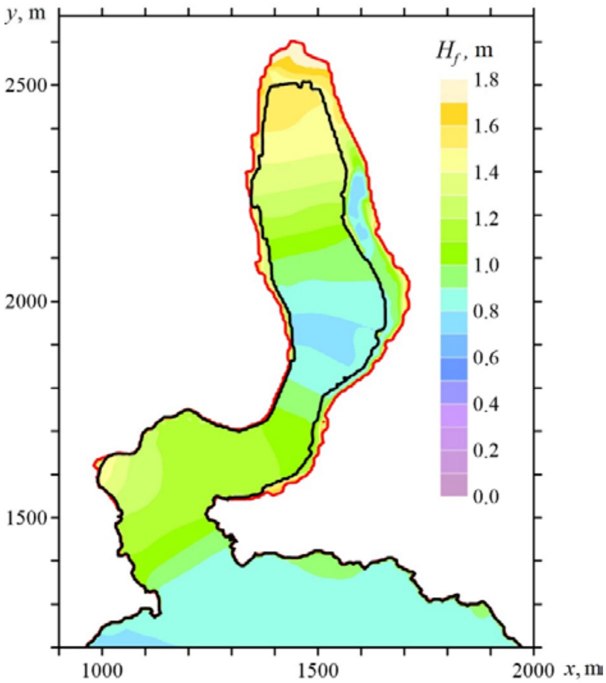
F i g. 8. Maximum possible sea level rise and flow depth (m) for the tsunami focus *1* at the Balaklava Bay coastline (0 m isobath – black curve, maximum spread of a horizontal flooding – red curve)



F i g. 9. Maximum possible sea level rise and flow depth (m) for the tsunami focus *2* at the Balaklava Bay coastline (0 m isobath – black curve, maximum spread of a horizontal flooding – red curve)



F i g. 10. Maximum possible sea level rise and flow depth (m) for the tsunami focus *3* at the Balaklava Bay coastline (0 m isobath – black curve, maximum spread of a horizontal flooding – red curve)



F i g. 11. Maximum possible sea level rises and flow depths (m) for all three tsunami foci at the Balaklava Bay coastline (0 m isobath – black curve, maximum spread of a horizontal flooding – red curve)

Analysis of the maps demonstrates that the areas adjacent to the top of the bay and to the eastern shore are most susceptible to flooding. This is due to the fact that these sections of the coastline are relatively flat and low-lying compared to other areas with higher banks and steep slopes. According to the simulation results, the flow depth on land is 1.0–1.5 m, the flow depth at the top of the bay is 1.8 m. The maximum length of the horizontal splash for the eastern shore reaches 60 m, for land areas at the top – 90 m.

Conclusion. The results of numerical modeling of tsunami wave penetration into the Balaklava Bay are presented. At the first stage, the evolution of tsunami waves from three seismic foci was studied using a nonlinear long wave model for the entire Black Sea. Mareograms were obtained at the entrance to the Balaklava Bay. At the second stage, these time dependences of sea level fluctuations were used as boundary conditions on the computational domain liquid boundary, for which numerical simulation of tsunami wave propagation in the bay was carried out using the *SWASH* model.

It is revealed that as a result of wave propagation in the bay, seiche sea level fluctuations with ~ 8 min period, corresponding to the Helmholtz mode, are formed. Mathematical modeling of level fluctuations in the Balaklava Bay under the short-term external influence has shown that in the energy spectrum of vibrations at the top of the bay there is one peak for 8.5 min period, which very precisely coincides with the lowest Helmholtz seiche mode period.

Inside the bay the tsunami heights increase by 5–6 times compared to the ones on the southern boundary of the region. Sea level fluctuations are the greatest at the top of the bay, where the rise reaches 1.4–1.5 m. The areas adjacent to its top and to the eastern shore are subject to the greatest flooding of the Balaklava Bay. The flow depth on land reaches 1.0–1.5 m, and at the top of the bay – 1.8 m. The maximum length of the horizontal run-up for the eastern shore is 60 m, and at the top of the bay – 90 m.

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