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ASSESSMENT OF THE MAXIMUM TSUNAMI WAVE HEIGHTS ON THE CRIMEA-CAUCASUS COAST OF THE BLACK SEA FROM POSSIBLE UNDERWATER EARTHQUAKES AND LANDSLIDES IN THE DZHUBGA AREA

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ABSTRACT

In the present work, the problem of tsunami wave generation is solved by considering two source mechanisms: a seismic source and a landslide source. The numerical simulation was performed with the localization of the source in the Dzhubga area, where the Blue Stream pipeline comes ashore. For both problem statements, different source localizations were considered: at depths of 350 m and 750 m. For the seismic setting, a two-block source with any directional movement of blocks was considered. The landslide problem was considered within the framework of a solid-block segmental model. Numerical simulation of the generation of the tsunami source and the propagation of tsunami waves over the Black Sea from Sochi to the Crimea peninsula has been performed. Landslide danger sections of the Turkish Stream and Blue Stream pipelines were examined in the most detailed way. For each scenario, the characteristics of wave fields in the computation water area were obtained. A comparison of the results obtained within the framework of the considered models is carried out.

Keywords: *tsunami waves, seismic and tsunami danger, tsunamigenic earthquakes, numerical simulation, Black Sea coast.*

1. INTRODUCTION

The assessment of the seismic and tsunami hazard of the Black Sea, both Russian and other coasts of this water area, is an actual task of recent decades (see, e.g., [1-9]). The importance of such computations is connected, in particular, with the problem of operation of the Russia-Turkey offshore gas pipelines connecting the territories of these countries along the bottom of the Black Sea, which operate in conditions of increased seismicity and landslide danger on the Russian and Turkish slopes of the Black Sea. The Turkish Stream gas pipeline, through which Russian gas flows through the Black Sea to Turkey and further to the south of Europe, started operating in January 2020. It consists of two parallel pipes. The Blue Stream gas pipeline started operating in 2003 (Fig. 1).

Fig. 1. The water area of the Black Sea; red and white lines are schematic representation pipelines "Turkish Stream" and "Blue Stream".

It is well known that the safety of laying and operating underwater gas pipelines requires an assessment of seismic and landslide hazards in the area of underwater slopes where these gas pipelines come ashore. As known, the Blue Stream underwater gas pipeline connects the Russian coast near the Dzhubga point and the Turkish coast and goes on land in the area of the. Kiyikay and Ipsala. Located on the Russian Black Sea coast, the terminal section of the Blue Stream underwater gas pipeline is located in a zone with high seismicity (Fig. 1). This is due to the fact that the Krasnodar Territory, where this site is located, is one of the most dangerous areas of seismic risk in Russia. The Crimea-Caucasus coast of the Black Sea is a zone of high industrial potential (large ports, gas and oil pipeline terminals) and the largest Russian resort area, so assessing the risk of a tsunami attack on this coast is an important task. According to the map of maximum shaking in the North Caucasus, the Black Sea coast from Anapa to Sochi falls into the seven-magnitude earthquake zone [1,2]. This corresponds approximately to the magnitude M = 6. The risk of earthquakes, landslides and tsunamis also applies to such unique transport facilities as the offshore sections of the Russia-Turkey gas pipelines (the Blue Stream and Turkish Stream projects) connecting the territories of these two countries along bottom of the Black Sea and operating under conditions of increased seismicity and landslide hazard on the Russian and Turkish slopes of the Black Sea [11,12]. Detailed seismological observations with highly sensitive bottom stations in the Dzhubga region, where the Russia-Turkey gas pipeline terminal is located, revealed a very high level of activity for micro- and weak earthquakes. Seismic activity is associated not only with faults of the Caucasus strike, but also with transverse faults. During the preparation of the route of the Blue Stream gas pipeline at the test site in the Dzhubga region, observations were made with bottom seismographs. At the same time, a large number of weak ($M < 2$) earthquakes with hypocenter depths from 8 to 30 km or more were recorded. An extended large fault zone is distinguished in the water area, which can be traced in the area from Anapa in the northwest to Adler in the southeast, and is expressed in the form of ledges, hollows and gorges at the bottom of the sea. A feature of the seismicity of the northeastern part of the Black Sea region is the confinement of most earthquakes, including strong ones, to the coast, shelf, and continental slope of Crimea and the northwestern Caucasus [3, 12]. Because of this underwater earthquakes in the Black Sea are potentially dangerous from the point of view of excitation of tsunami waves on the Russian coast of the Caucasus, many works are devoted to this problem (see, e.g., [2–9]). The most adequate is to perform the numerical simulation with the maximum possible earthquake magnitude for a given point [13]. Figure 2 shows diagrams of active faults in the Crimea-Caucasus region, which depict various types of faults in the earth's crust [2, 12]. It is well seen that in the northeastern part of the Black Sea there is a large number of transverse faults that are highly active [12].

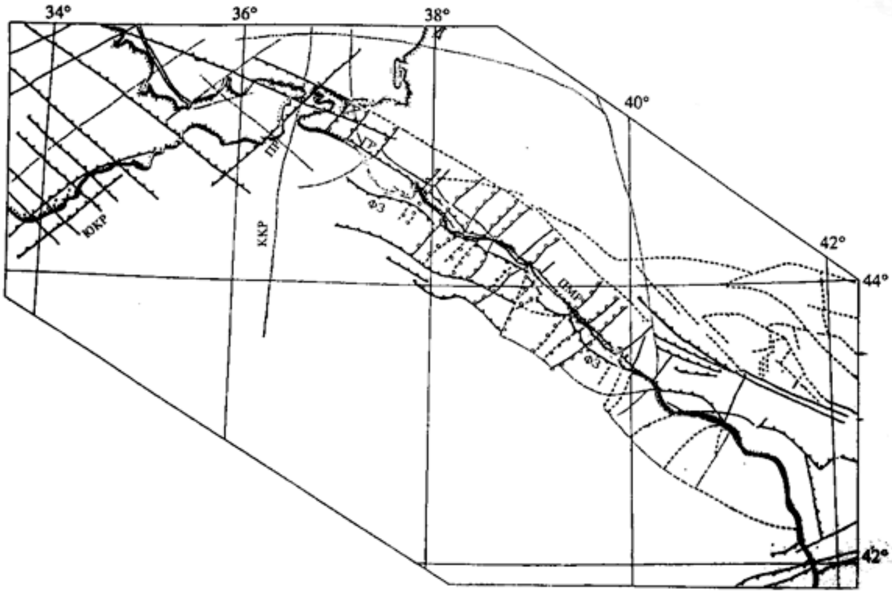

Fig. 2. Scheme of seismically active faults in the Crimea-Caucasus region [12].

Therefore, during the construction and operation of any underwater engineering structures (oil and gas pipelines, telecommunications, etc.), it is necessary to study in detail those sections of the Crimea and Caucasus coasts where breaks in oil pipelines and telecommunications lines are possible during events such as earthquakes and landslides. Intense tectonic activity, together with the frequent destruction of sedimentary masses, leads to the formation of landslide sections of underwater slopes. In addition, intensive industrial use of this offshore area may lead to a landslide process with further formation of tsunami waves.

In addition, seismic activity can also lead to the sliding of part of the slope, which can be the source of the formation of a surface long wave (tsunami), the movement of which will be directed against the movement of the landslide. In this paper, computations for a specific section of the Black Sea coast are performed (Fig. 3).

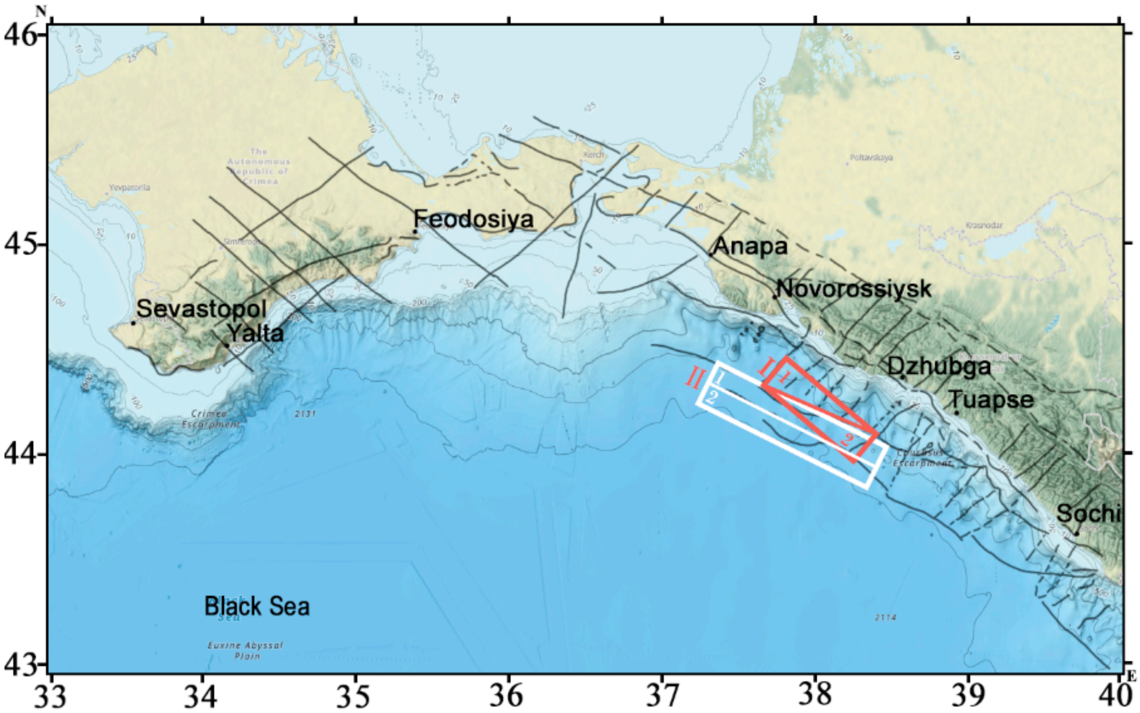

Fig. 3. Computation water area on a bathymetric map with a diagram of active faults in the Crimea-Caucasus region [4]. Dashed lines indicate parts of the Turkish Stream and Blue Stream pipeline routes; the red and white lines are a schematic representation of the localization of seismic sources at a depth of 350m and 750m, respectively.

Using information about possible zones of active faults and features of the main structures of various parts of the coast [2, 12], the position of possible seismic sources was determined. Estimated seismic sources are located in the sea area near the coastline of the Turkish Stream and Blue Stream gas pipelines. The shelf width in the Dzhubga area is 7450 m. The maximum depth is 981 m.

The study performed is related to the generation of tsunami waves by a kinematic source, considered within the framework of the keyboard model of an earthquake [14]. Any seismic or other impact in this area can trigger tsunami waves along the entire Black Sea coast, including in the areas of the terminals of the Turkish Stream and Blue Stream gas pipelines. To determine the possible tsunami waves that can be caused by earthquakes with magnitude M=7, M=7.5, M=8, formulas were used that relate the earthquake magnitude to the characteristics of ruptures at interplate boundaries in subduction zones [14,15]. Given that the probability of a tsunami even during moderate earthquakes with magnitude M = 7 is 0.81 [15], these magnitudes were chosen to assess the parameters of possible tsunamis in the considered water area (Fig. 3). The paper also considers the modeling of the process of slope slumping of the tsunamigenic landslide section of the coast located in the Black Sea in the Dzhubga area (between the cities of Gelendzhik and the city of Tuapse), where the offshore sections of the Russia-Turkey gas pipelines pass (Fig. 4).

The present study solves the problem of underwater landslides that generate a wave on the sea surface. A schematic representation of the localization of landslides on an underwater slope is shown in Fig. 4.

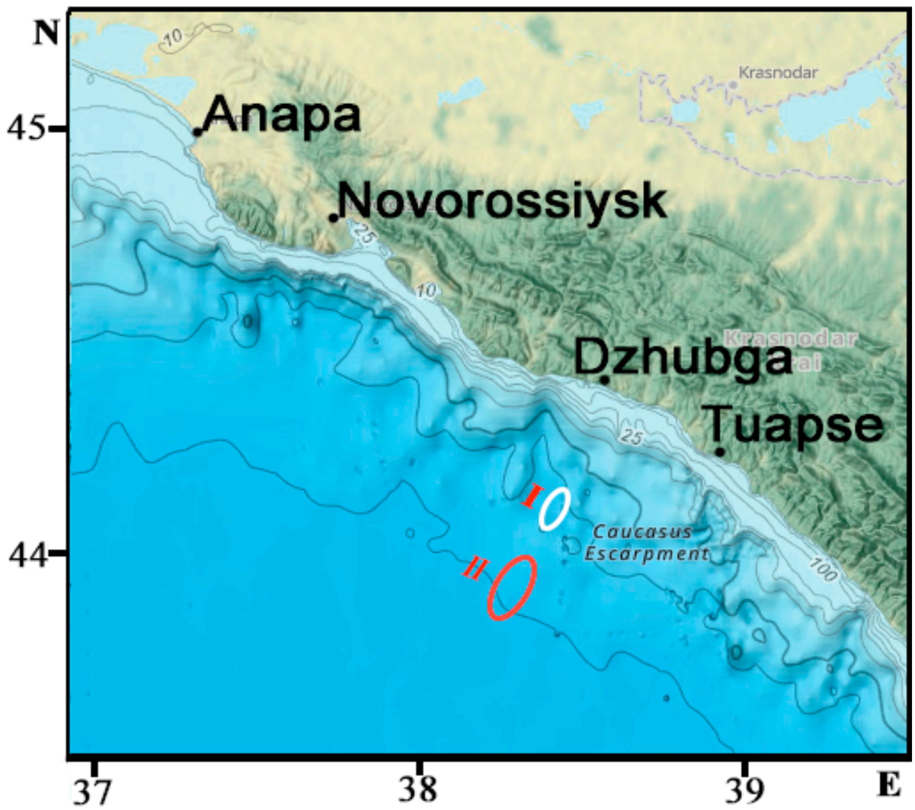

Fig. 4. Computation water area on the bathymetric map. Red and white ellipses schematically indicate the localization of landslide masses on the shelf.

2. NUMERICAL SIMULATION OF A POSSIBLE TSUNAMIGENIC EARTHQUAKE IN THE DZHUBGA AREA

Numerical schemes simulating waves caused by undersea collapses or landslides are usually based on the "shallow water" theory approximation (see for example [5,6]). Such numerical simulation was performed in the framework of nonlinear shallow water equations for possible strong tsunamis from two seismic sources in the Dzhubga area of the eastern part of the Black Sea basin (Fig. 4). Three scenarios of possible earthquakes were chosen, with magnitudes M=7.0, M=7.5, and M=8.

In order to estimate the initial parameters of tsunami waves that can be generated by a seismic source, such formulas were used relating to the relationship between earthquake magnitudes and the characteristic parameters of ruptures in the interplate boundary in the subduction zone, developed for active regions of the globe that determine the seismic source, and specifically the extent of the rupture in the source, the rupture's width, and the possible height of the vertical displacement of the sea bottom at the source [16,17]. This part of the study is based on the keyboard mechanism of the earthquake source, in which the source is roughly assumed to be rectangular, divided into two blocks. Our estimates of this approximation allow us to use the connection relations available in [16] for this model as well.

During the first two computations, moderate earthquakes with magnitude M=7 were considered with the epicenter opposite Dzhubga point northwest of Sochi for depths of 350m (Scenario 1) and 750m (Scenario 2). Table 1 shows the nature of the movement of blocks, where the sign (-) determines the displacement of the block down, and the sign (+) up. Figure 6 shows the formation of a tsunami source when blocks are displaced in the seismic source for both scenarios.

Table 1. The character of the key-block movements.

Movement parameters	Scenario 1 Block N		Scenario 2 Block N	
	1	2	1	2
Start of motion (s)	0	40	0	40
Time of motion (s)	40	40	40	40
Height of shift (s)	-0.6	+1.7	-1.3	+2.6

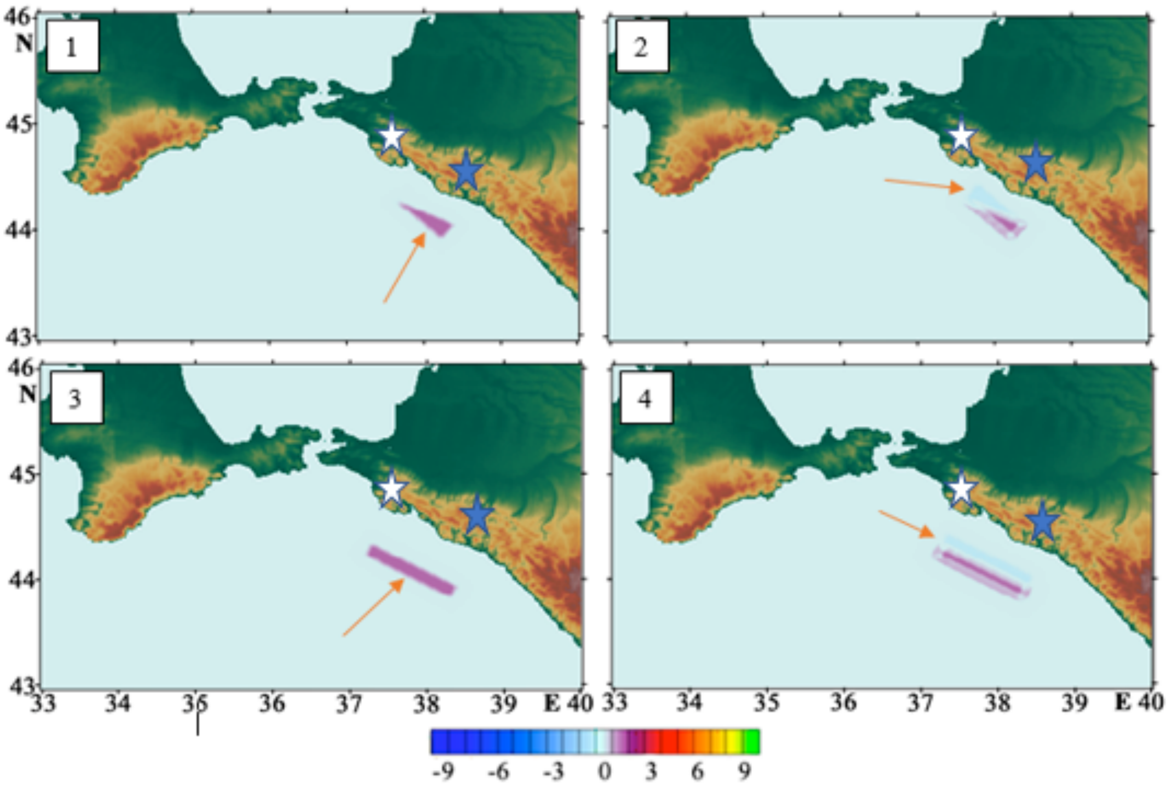

Fig. 5. Formation of a tsunami source to localize a seismic source at a depth of 350 m (Scenario 1, panels 1 and 2); at a depth of 750 m (Scenario 2, panels 3 and 4) for earthquake magnitude M=7.5 and M=8, respectively.

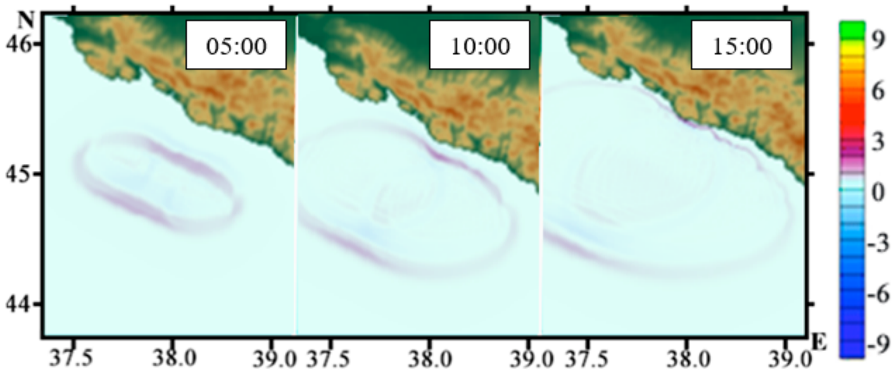

Fig. 6. Propagation of tsunami wave fronts for three time moments from a source localized at a depth of 750 m.

Figure 6 above, shows the propagation of tsunami wave fronts from a seismic source for 3 time moments. It is clearly seen that the first wave approaches with a negative phase, then the runup wave follows. Similar computations were performed for earthquake magnitudes *M*=7.5 and *M*=8.

Figure 7 shows one-dimensional histograms for 6 computations: three computations from a seismic source located at a depth of 350 m for magnitudes *M* = 7. 7.5 and 8 and the corresponding computations for a source located at a depth of 750 m.

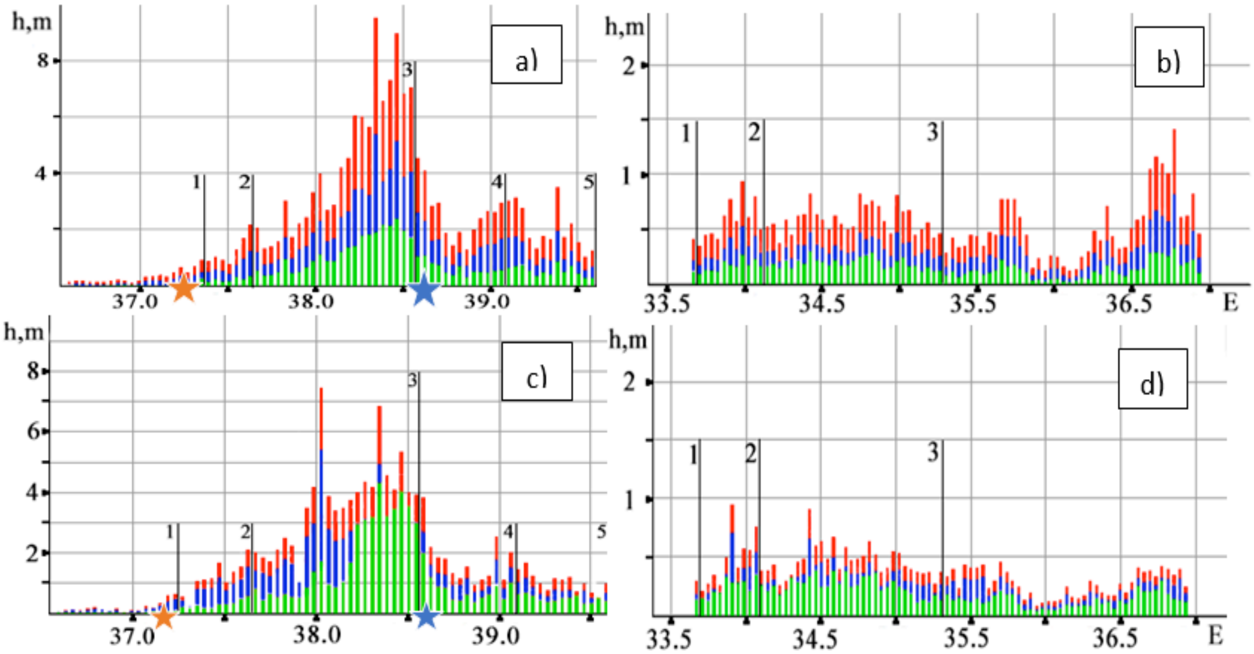

Fig.7. 2D histograms of tsunami wave heights along the coast for a part of the water area for the source at a depth of 350 m (a), (b) and at a depth of 750 m (c), (d) for three earthquake magnitudes: green *M*=7; blue *M*=7.5; red *M*=8. The cities are marked with numbers: a) 1 - Anapa, 2 - Novorossiysk, 3 - Dzhubga, 4 - Tuapse, 5 - Sochi; b) 1 - Sevastopol, 2 - Yalta, 3 - Feodosia. The red and blue asterisks indicate the exit points for the Turkish Stream and Blue Stream pipelines.

Figure 8 shows three-dimensional histograms for the maximum wave heights for Scenario 1, , in which the earthquake source is localized at a depth of 350 m. for the northeastern part of the Black Sea coast and for the Crimea peninsula.

It is clearly seen that at the maximum possible magnitude of the considered earthquakes for the Black Sea region, magnitude *M*=8, the wave heights on the Black Sea coast to the east of Anapa can reach very large values, up to 9 m. In the area of the Dzhubga point up to 7m. However, in the region of Anapa, the wave heights on do not reach 1m. On the Crimea coast, with such an earthquake magnitude, with a given localization of the source, the heights of tsunami waves do not exceed 1.4 m.

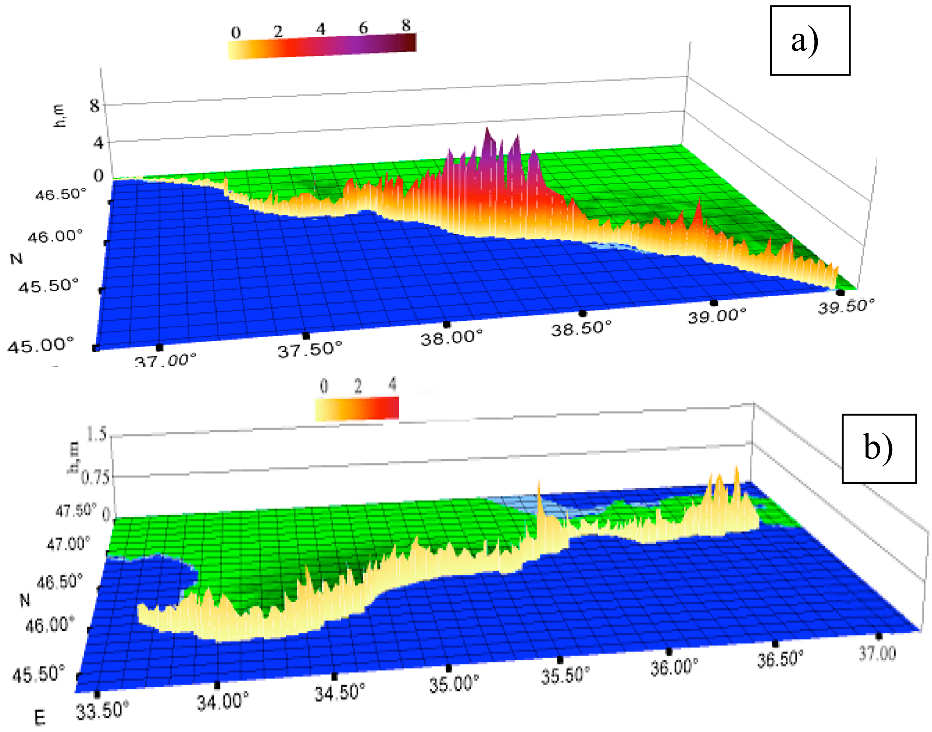

Fig. 8. 3D histogram of tsunami wave height along the coast for the northeastern part of the Black Sea and along the coast of the Crimea Peninsula (Scenario 1, *M*=8).

3. NUMERICAL SIMULATION OF POSSIBLE TSUNAMIGENIC LANDSLIDES IN THE DZHUBGA AREA

In most cases, landslide bodies are formed on the underwater slopes, which usually have a large extension. Most tsunami models generated by landslides are based on the response of the sea surface to the movement of a solid bottom. In this paper, the movement of a landslide is modeled as the movement of a rigid body divided into a number of blocks-segments, and the landslide process was modeled by the dynamic vertical displacement of segment blocks along the landslide slope, simulating the slumping of the landslide mass [18]. The kinematics of the movement of blocks is determined by the schematic behavior of the landslide movement, corresponding to a typical implementation of the computation in the framework of the elastic-plastic model - the sliding of the upper part of the landslide layer with a simultaneous increase in the thickness of the lower part of the slope (see, e.g., [19]). Figure 9 shows a schematic representation of the localization of landslide bodies on the underwater slope.

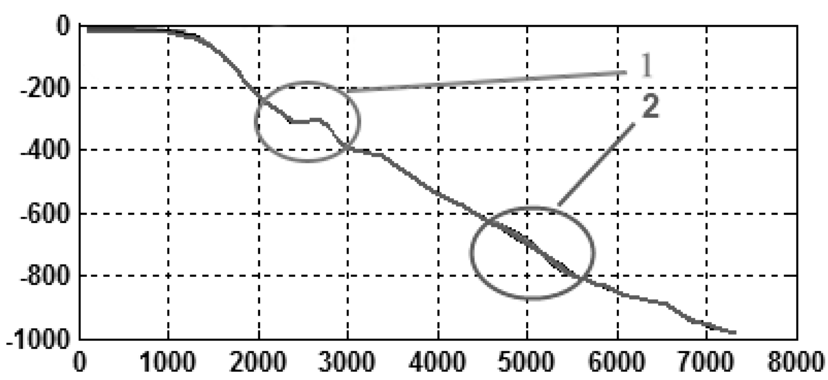

Fig. 9. Localization of landslide sources at a depth of 350 m (1) and 750 m

To implement this simulation, the landslide body is represented by 12 segmental blocks located along the slope (Fig. 10).

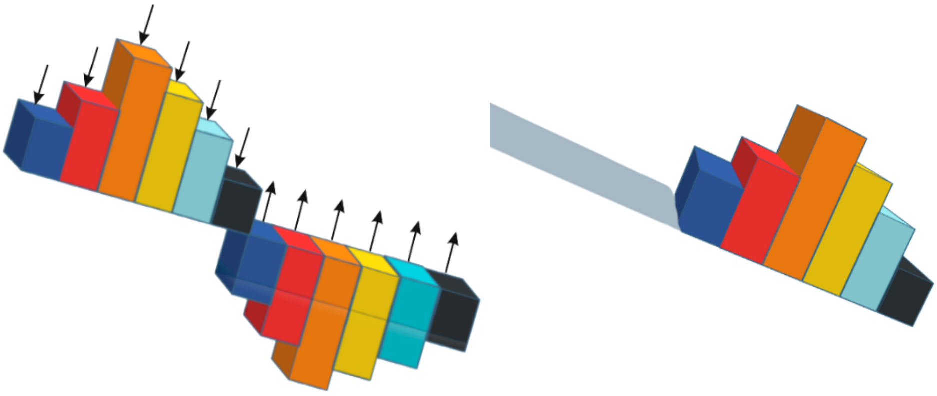

Fig. 10. Schematic representation of the movement of segmental blocks

This process can be principally approximated by the displacement of the upper segment blocks downwards, with the simultaneous displacement of the corresponding lower blocks upwards. To simulate landslide processes at a depth of 350 m and 750 m, options for shifting the segments into which the landslide is divided are proposed. At the same time, the upper segments sequentially shift down, with simultaneous sequential movement of the lower segments upwards (Fig. 11). So, for example, the height of the blue block on the left is reduced to zero and at the same time the blue block on the right is raised to the same height that the blue block on the left had. Then the red block moves down to zero and the corresponding red block on the right reaches the initial height of the red block. And so on. Each reverse movement takes 30 sec. In the problem, an underwater slope is considered, consisting of a layer of sediments lying on a solid basal plate (Fig. 10). The thickness of the layer of these sediments is about 4 m. Under seismic or other impact, the strength of this layer is violated, what can lead to its movement down the slope (sliding).

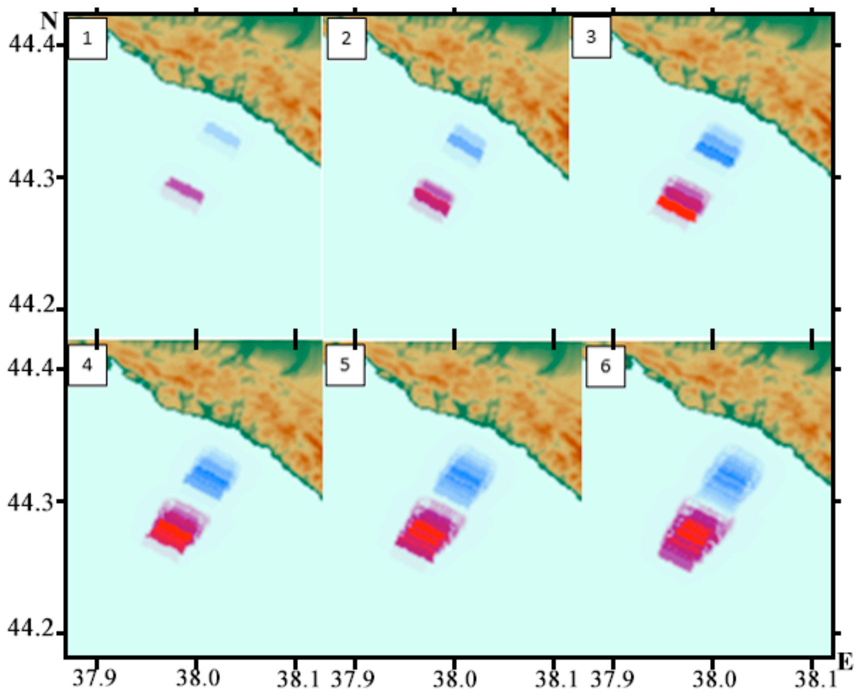

Fig. 11. Six time moments when the tsunami source is generated by segmental blocks into which the landslide body is divided. Panel (6) presents the moment when the movement of the segments has ended and the landslide has stopped

The movement of a landslide body is considered at a depth of 750 m slope, on the shelf, about 8 km long. The landslide source is about 2 km long and 600 m wide. For this case, a 12-segment source was constructed with a maximum displacement of a segmental block of 4m. Figure 11 shows 6 time moments of the tsunami source generation when moving up and down the slope of the corresponding two blocks (see Fig. 11).

Figure 12 shows 3 time moments for the propagation of wave fronts in the part of the water area closest to the exit to the Blue Stream pipeline terminal. It is clearly seen that, just as during a seismic impact, the first wave of depression approaches the coast, followed by a positive wave.

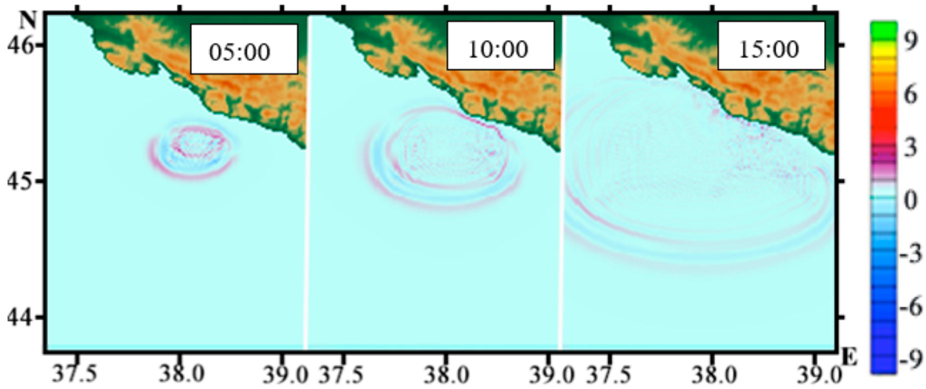

Fig. 12. Generation of a tsunami source when a landslide moves along a slope

Figure 13 shows two-dimensional histograms on a 3-meter isobath.

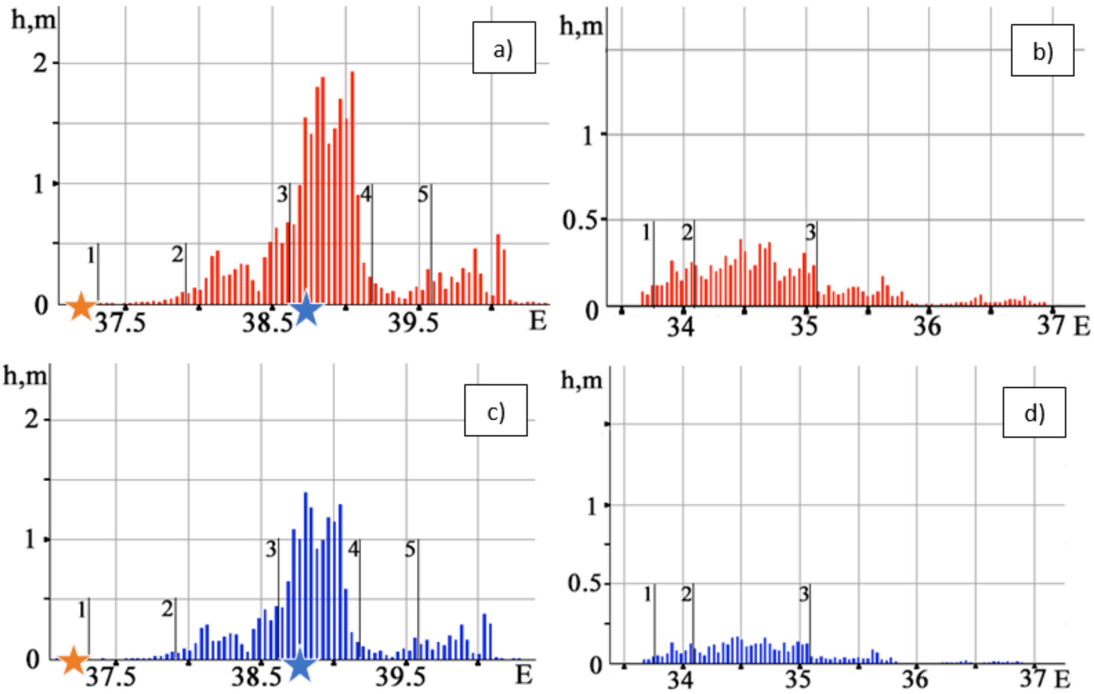

Fig.13. Histograms of tsunami wave heights along the northeastern coast (a) and the coast of the Crimea coast (b) during the implementation of wave processes from a landslide localized at a depth of 750 m. The cities are numbered 1 - Sevastopol, 2 - Yalta, 3 - Feodosia. The red and blue asterisks indicate the exit points for the Turkish Stream and Blue Stream pipelines.

Figure 14 shows a 3D histogram for a landslide source localized at a depth of 750 m. Figures 14 and 15 clearly show that in the areas where the pipelines exit, the possible heights of tsunami waves from a landslide localized in the Dzhubga area are either completely absent or their height will not exceed 1.4 m.

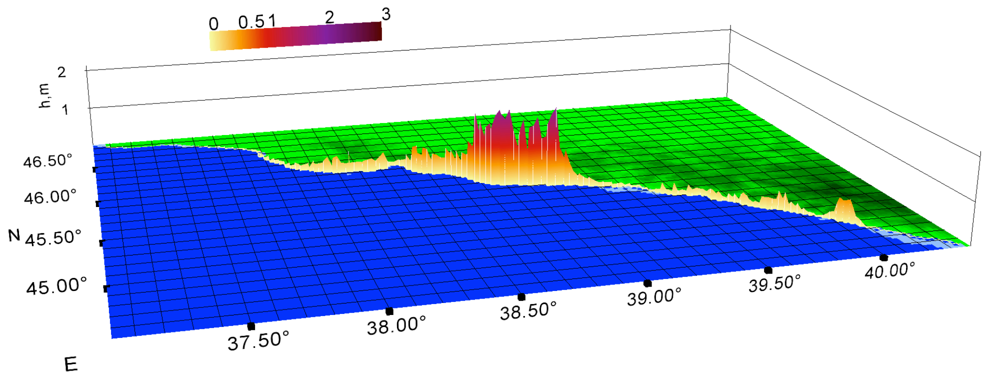

Fig. 14. 3D histogram of tsunami wave height along the coast for the northeastern part of the Black Sea and along the coast of the Crimean Peninsula

Computation data for possible tsunami wave heights at the places where the Turkish Stream and Blue Stream pipelines land on the coast are given in Table 2.

Table 2. Wave heights near pipeline terminals

	Seismic source						**Landslide source**	
Source depth, magnitude	**350 m**			**750 m**			**350 m**	**750 m**
	M=7	**M=7,5**	**M=8**	**M=7**	**M=7,5**	**M=8**		
Wave height (compressor station Russkaya (Anapa)), m	**0.4**	**0.7**	**1.1**	**0.1**	**0.4**	**0.6**	**0.05**	**0.05**
Wave height (compressor station Beregovaya (Dzhubga)), m	**0.9**	**2.3**	**4.2**	**2**	**2,8**	**3,8**	**1.05**	**1.5**

4. CONCLUSIONS

In this work, numerical simulation of tsunami wave generation by a dynamic seismic source and their propagation for specific coastal points in the Black Sea is performed. It is shown that with the considered limit values of earthquake magnitudes M=8, a seismic source can give values of wave heights near the exit points to the coast of the Blue Stream pipeline up to 4.2 m. Considering that the computation was performed up to a 3-meter isobath, recalculation of the wave height to a dry coast will provide additional gain. It is shown that with the landslide nature of the occurrence of tsunami waves, approximately at the same localization as the seismic source (approximately at $M = 7$, since the earthquake is a trigger, it “pushes” the landslide mass on the slope), it was obtained that more dangerous is a seismic event. The computation of possible catastrophic consequences from a tsunami for technological facilities in the northeast of the Black Sea coast showed that the Dzhubga area is most susceptible to tsunami wave attack, while the area of Anapa, where the Turkish Stream pipeline exits, is the most calm. The analysis also showed that with such localization of seismic and landslide sources, the coast of the Crimea peninsula will not be subject to any strong effects of tsunami waves.

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