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BRIDGE ACROSS THE KERCH STRAIT - HISTORY AND MODERNITY

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ABSTRACT

The present study provides a brief description of the geological conditions in the Kerch Strait, as well as a historical aspects on the complexity of building a bridge across it. The bridge consists of a four-lane road and of another double-track railaway spanning the extensive Staight. The paper provides estimates of expected maximum heights of tsunami waves for the pillars of the Crimean bridge if a significant catastrophic earthquakes occurs in the northwest of the Crimean Peninsula and in the localization of the earthquake source in the basin of the Black and Azov Seas in front of the entrance to the Kerch Strait. The main purpose of this work is to provide estimates of the tsunami mhazard for the area of the Crimean bridge in the Kerch Strait during earthquakes with sources in the nearest basin areas of the Black and Azov Seas, with magnitudes M = 7, 7.5 and 8. Comparative histograms of possible maximum wave heights near the bridge pillars are given. It is shown that in the area of the western pillars of the Crimean Bridge, the tsunami wave heights for all scenarios do not exceed 0.3–0.5 m, and in the area of the eastern pillars, the range of possible wave heights lies in the range of 0.6–1.95 m.

Keywords: Kerch Strait Bridge; Crimean Peninsula; Black Sea; Sea of Azov; Bridge tsunami impact

1. INTRODUCTION

The Kerch Strait is the most important water artery connecting the basins of the Black and Azov Seas [1,2]. According to hydrogeologists, the Kerch Strait is actually the site of a tectonic fault. The bottom relief of the Kerch Strait has a rather complex structure. The geological conditions in the strait are quite complex: seismicity, tectonic fault, soft soils. The area of the Kerch Strait is located in close proximity to the South Azov source zone, which runs sublatitudinally near the coast of the Kerch Peninsula [3,4]. The Kerch Strait coincides with the East Crimean (Kerch) source area. This area corresponds to the fault-shear zone of the strait [4-6]. The seismic potential of the mentioned zones is determined by the possibility of occurrence of crustal earthquakes with M ≥ 7.0 with an average frequency of one earthquake every several hundred years. The magnitudes of these earthquakes can reach $M \geq 8$ [6-8]. However, in addition to taking into account the possibility of an earthquake in the very water area of the Kerch Strait, it is necessary to take into account the possibility of a repetition of the earthquakes of 1927 in the Black Sea and the probability of the passage of tsunami waves into the strait.

2. THE KERCH STRAIT

The Kerch Strait, which separates the Kerch Peninsula of Crimea and the Taman Peninsula of continental Russia, is the most important water artery connecting the basins of the Black and Azov Seas [1,2]. The length of the Kerch Strait in a straight line is about 43 km, along the fairway - 48 km. The width of the strait varies widely: from 3.7 to 42 km. The strait is shallow: the greatest depths at the entrance to the strait from the Sea of Azov do not exceed 10.5 m, from the Black side - 18 m. Towards the middle of the strait, the depths gradually decrease and over a larger area are about 5.5 m. The total area of the Kerch Strait is approximately equal to 805 km^2, water volume – 4.56 km^3.

The strait plays a significant role in the formation of the features of the hydrological and hydrochemical regime of the Azov-Black Sea basin and is the most important fishing area and navigable highway [1,2,4] form the variability of coastlines and shoals dangerous for the navigation service. The transverse profile of the bed of the strait is asymmetric, and the strait itself is delimited by two sandbars into three parts [1-3]. A characteristic feature of the geological structure of the site in the transition area is the relatively high occurrence of the roof of bedrock clay near the Crimean coast of the strait and their sharp decrease to a depth of 50 m in the eastern part of the strait. Very weak silty soils lie above bedrock. The shores of the Kerch Strait are partially low-lying and marshy with sandy spits (Chushka, Tuzla), in some places steep and rocky [1-3].

Water level oscillations in the Kerch Strait are of different nature, the most significant in magnitude are surge oscillations, seasonal and climatic level oscillations have a significantly lower amplitude. The range of seasonal oscillations reaches approximately 25 cm. The main cause of mesoscale sea level oscillations in the Kerch Strait is the wind. The surge oscillations caused by it are superimposed on smooth seasonal level oscillations and, on average, exceed them in amplitude by 5–6 times, and in very strong storms by 8–10 times. Most often, surge phenomena occur in the northern part of the strait with a northeast wind, which is characterized by the greatest frequency, strength and duration [4,7-9]. For almost two centuries, the climate of the Sea of Azov and the Caspian Sea has been characterized by intra-secular cyclicity - the alternation of warm and extremely cold winters with snowfalls. The duration of freeze-up in the Sea of Azov during cold periods reached 50–80 days. In this regard, there were delays in shipping (for two to three months). At the end of winter, ice jams and hummocks, as well as blocks of ice drifting at high speed, became a common occurrence in the Sea of Azov. The drift of the Azov ice into the Kerch Strait under the pressure of hurricane northeast winds seems to be extremely dangerous. In addition to drifting ice, hurricane-force southwesterly and southerly winds, reaching a speed of 38 m/s, which cause waves over 3–4 meters high in the Kerch Strait [7, 10], present a danger.

In addition, the area is characterized by high seismic activity, accompanied by strong underwater tremors. The ability to bypass the tectonic fault zones is rather problematic [1-5]. When erecting any hydraulic structures in the Kerch Strait, it is necessary to take into account the existing dangers and threats: a) Azov Sea ice drift through the strait; b) Hurricane surge winds up to 37 m/s; c) Unpredictable lithodynamics (erosion and collapse of coasts and islands); d) Underwater earthquakes. The most powerful of them can cause sea gravity waves (including tsunamis) [10]. The passage of the tsunami on September 11–12, 1927, December 28, 1939, and July 12, 1966 from the Black Sea to the Sea of Azov through the Kerch Strait was noted: the echoes of these tsunamis were recorded at Opasnoe or Mariupol of the Sea of Azov [10].

3. BRIDGE ACROSS THE KERCH STRAIT

3.1. Brief historical tour of the construction of the bridge

It was planned to communicate the western shore of the strait, namely the Kerch Peninsula of Crimea, and the eastern one - the Taman Peninsula of the Krasnodar Territory of Russia - more than a thousand years ago [11-12]. Projects for the construction of a bridge across the Kerch Strait arose repeatedly, but all attempts were unsuccessful [11-12] (see also [13-15]). Starting from the 7th century BC, there was communication between the western and eastern shores of the Bosporan kingdom, which was located on two peninsulas - Kerch and Taman. The width of the Kerch Strait allowed merchants and fishermen to cross in boats. In 1068, historians recall, the henchman of Kyiv, Prince Gleb Tmutarakansky, measured the sea on ice to Korchevo. A message about this action was inscribed on the famous Tmutarakan stone. In 1903, it was decided to build a bridge across the Kerch Strait. The best Russian engineers were involved in the design, who by 1910 had developed a project for the Kerch crossing, the implementation of which was prevented by the First World War, then the October revolution and the Civil War. In the Soviet years, along with the bridge, the reconstruction of railways was also conceived, along which trains were supposed to drive up to the structure. In the 1930s, Soviet engineers designed a large-scale construction - a railway line from Kherson to Poti through the Kerch Strait. Large-tonnage parts of the bridge structures could not be manufactured by domestic factories, and they were ordered in Germany. The project was not implemented due to the outbreak of World War II [11-12]. The war began, and in 1942 German troops captured the Crimea, there were battles for the Caucasus. German military engineers began to develop their own project for a bridge across the Kerch Strait, which would make it possible to build a railway and a highway from Kerch to the Novorossiysk region. However, after a change in the situation on the Caucasian front, the construction of the bridge was stopped. And already in the summer of 1943, German military engineers were forced to design and build an aerial cableway across the Kerch Strait for the transfer of military cargo as soon as possible, which was partially blown up during the retreat.

After the liberation of Crimea from German troops, Soviet engineers began to connect the two banks of the Kerch Strait. In February 1944, the cable crossing over the Kerch Strait began to operate again. In the same 1944, the Kerch railway bridge was built in 7 months. The length of the bridge was 4.5 km, the width was 22 meters, it had 115 spans of 27.1 m each and a 110-meter turning device in the middle part to ensure the passage of large-capacity vessels [11-12]. At the end of February 1945, the ice, blown up by the wind from the Sea of Azov, destroyed 42 out of 115 pillars and they collapsed, dragging the spans with them. The bridge operated in this way for only a little over three months.

3.2. The state of the problem since the end of the last XX and the beginning of this XXI century

The Kerch Bridge is a transport crossing over the Kerch Strait. It was planned to build a bridge with railway and road passages [11-12]. The bridge was supposed to pass between the Kerch and Taman Peninsulas through the island of Tuzla and the Tuzla Spit. The road junction of the bridge from the side of Taman was to be built simultaneously for the bridge and for the largest Russian port on the Black Sea, the port of Taman, which was under construction [11-12]. It was planned that the bridge should be part of the ring road being created around the Black Sea for the needs of the Black Sea states by 450 km, shortening the road without the need for a detour through Rostov-on-Don [11-12]. In the early 1990s, a competition was announced for participation in the implementation of a transport crossing project across the Kerch Strait; at that time there were 4 crossing projects (two bridges and two tunnels). The Crimean authorities believed that the implementation of this project would facilitate contacts with Russia and consolidate the “intermediate” position of Crimea between neighboring states. In addition, for a long time the bridge was put forward as one of the elements of the ring road along the Black Sea coast. The issue of building a bridge was discussed in the Ukrainian government in 2006, which believed that such construction would be "a plus for Crimea." In the same year, the design and construction of the bridge was included in the "Transport Strategy of the Russian Federation until 2030", which included, as one of the main directions for the development of transport infrastructure in the Southern Federal District, the design of a bridge across the Kerch Strait and the reconstruction of road approaches and entrances to the sea port of the Caucasus.

Fig. 1. Model of the bridge across the Kerch Strait.

On December 17, 2013, an agreement was signed between the Government of the Russian Federation and the Cabinet of Ministers of Ukraine on joint actions to organize the construction of a transport passage through the Kerch Strait. In March 2014, preparations for the construction of the bridge intensified significantly. In June 2014, the project for the construction of a bridge in the alignment of the Tuzla Spit was recognized as optimal (see, for example, [2,12,13]. During the construction of the bridge, complex tectonic conditions in the zone of possible earthquakes and a layer of plastic sedimentary rocks of silt at the bottom of the strait required the creation of a very long pile foundation to semi-hard clays at a depth of up to 58 meters, which required the use of piles up to 94 meters long [13,14]. The large-scale project was planned to be implemented in a short time. The bridge does not create obstacles for the movement of ships because the height of the bridge is 35 m. The length of the bridge is 19 km (see also [15-17]. On December 18, 2019, the construction of the Crimean railway bridge was officially completed - an acceptance certificate was signed allowing the commissioning of the railway bridge. Freight traffic opened on June 30, 2020. On January 20, 2020, the first 100 trains passed through the Crimean bridge.

Fig. 2. Top view of the Crimean bridge

4. FORECAST OF TSUNAMI HAZARD FOR THE CRIMEAN BRIDGE.

Tsunami prediction in the Black and Azov seas was carried out by a number of authors (see, for example, [15-27]). So, in the work by Dotsenko and Ingerov [22], a numerical analysis of the propagation of tsunami waves in the Sea of Azov was carried out. As they write, “the question of the efficiency of tsunami generation in the Sea of Azov by seismic sources remains relevant and little studied”.

4.1. Numerical modeling of tsunamis during strong and catastrophic earthquakes

For numerical modeling of tsunami waves, the northeastern part of the Black Sea, the Kerch Strait and the southern part of the Sea of Azov were considered (Fig.3, Fig.8). For numerical simulation of tsunami wave generation by a seismic source, we used a keyboard model of an earthquake (see, for example, [15–17]) and a nonlinear system of shallow water equations in a two-dimensional formulation, taking into account dissipative effects and bottom friction (see, for example, [28]). Displacement wave fields were obtained and histograms of maximum wave heights were constructed along the northwestern coast of the Black Sea and along the coasts of the Kerch Strait.

4.1.1. Tsunami hazard of the Crimean bridge during the localization of the seismic source in the northwest of the Crimean Peninsula

To describe the process of generation and propagation of a wave caused by the movements of keyboard blocks in a seismic source, a nonlinear system of shallow water equations in a two-dimensional formulation was used (see, for example, [17,28]). In the numerical description of the generation and propagation of a tsunami wave over the water area, a scheme was used that was constructed in analogy with the Sielecki difference scheme [29]. A computational grid is introduced with spatial intervals , and with a time integration step of 1 sec. (see, for example, [15-17]). The calculations presented in this paper used the bathymetry of the Black Sea, the spatial step in which was approximately 900 m. The simulation was carried out with a time step of 1 s. At the last seaward point at a depth of 3 m, the condition of total reflection (vertical wall) is set, which makes it possible to fix the maximum and minimum values of the wave level shift at this depth.

For the first stage of modeling the tsunami source, an elliptical seismic source was chosen, located, in accordance with the historical data of the earthquake on September 12, 1927, south of Yalta and extended along the coast with approximate coordinates of the epicenter: 34.5 ° E, 44.4 ° N (Scenario 1) (Fig. 3 purple). An earthquake with magnitude M = 7 was considered. With the source localized on the same fault, a hypothetical earthquake with a magnitude M = 7.5 was considered, with a source consisting of two semi-elliptical blocks, and the block separation line intersects with the fault line of the Earth's crust (Scenario 2) (Fig. 3 black line). In addition, two hypothetical earthquake sources were selected. They were located in possible zones of active faults of the Earth's crust near the Crimean Peninsula. The sources have close localization, both are blocky, the division line into blocks coincides with the major axis of the ellipse and passes along the fault line of the Earth's crust (2). The first of them has a magnitude of M = 7.2 (Scenario 3), for the second M = 8 (Scenario 4). The localization of the sources for Scenario 3 and Scenario 4 is shown in Fig. 3 in yellow and blue, respectively.

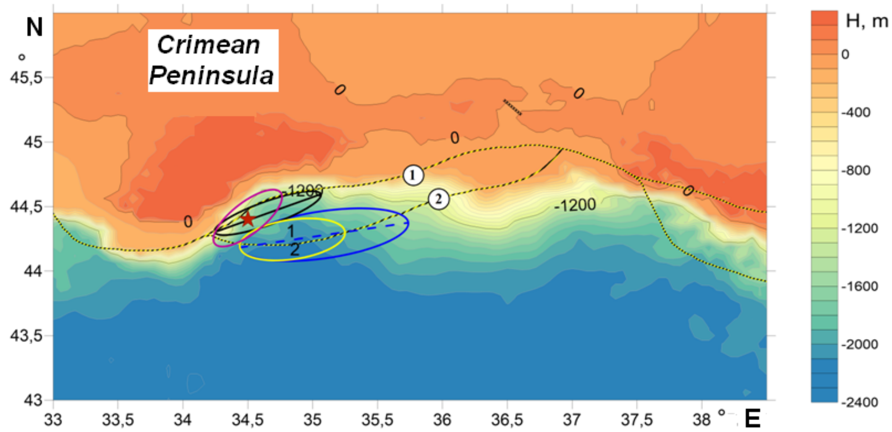
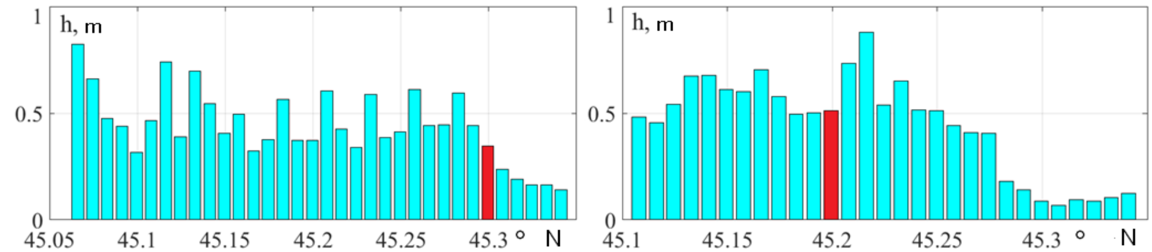


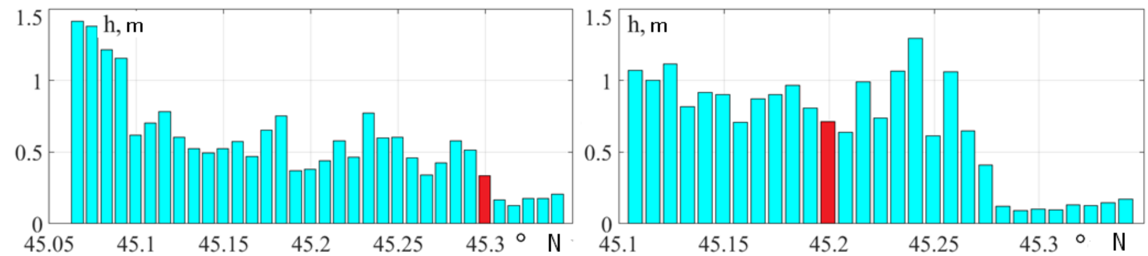
Fig. 3. Bathymetric map of the Black Sea in the region of the Crimean Peninsula and the Kerch Strait. In the figure: black-yellow line - shows the fault lines in the northeastern part of the Black Sea, ellipses - localization of simulated earthquake sources, red asterisk - localization of the epicenter of the historical earthquake of 1927.

When tsunami waves propagate from the considered sources (Scenarios 1-4), the waves reach the Kerch Strait and propagate along it. Figure 4 shows histograms for the maximum tsunami wave heights for the eastern and western coasts of the Kerch Strait. The geographic location of the pillars of the Crimean bridge in the projection is marked in red on them (slice in longitude). It should be noted that for the considered scenarios of the occurrence and propagation of a tsunami, with an increase in the magnitude of the seismic source, the level of water rise on 3-meter isobaths in the Kerch Strait also increases.



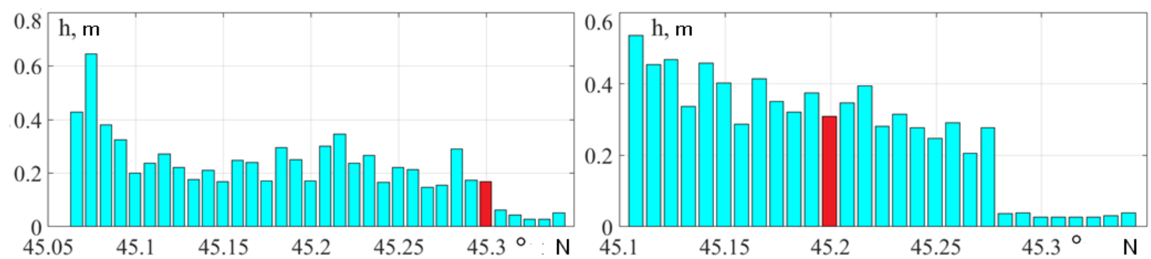
a) Western shore of the strait b) eastern shore of the strait

Fig. 4. Histograms of maximum tsunami wave heights on the 3-m isobath for the coast of the Kerch Strait for Scenario 1 ($M = 7$)



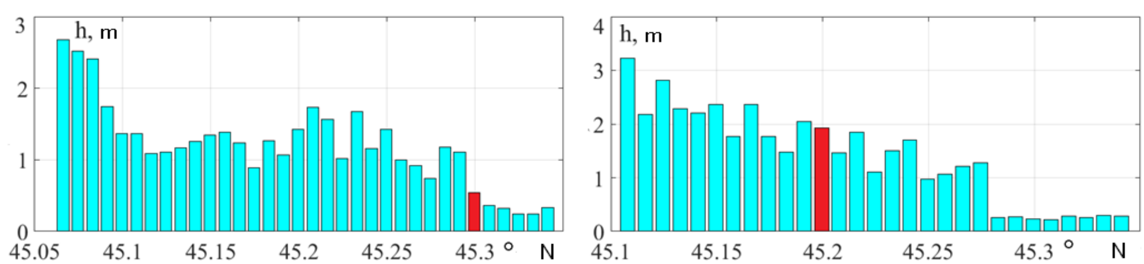
a) Western shore of the strait b) eastern shore of the strait

Fig. 5. Histograms of maximum tsunami wave heights on the 3-m isobath for the coast of the Kerch Strait for Scenario 2 ($M = 7.2$)



a) Western shore of the strait b) eastern shore of the strait

Fig. 6. Histograms of maximum tsunami wave heights on the 3-m isobath for the coast of the Kerch Strait for Scenario 3 ($M = 7.5$)



a) Western shore of the strait b) eastern shore of the straiT

Fig. 7. Histograms of maximum tsunami wave heights on the 3-m isobath for the coast of the Kerch Strait for Scenario 4 ($M = 8$)

As can be seen from Figure 4, for Scenario 1, the maximum water level rise was 0.32 m and 0.51 m for the western and eastern pillars, respectively. In general, in the water area of the strait, the height was slightly less than 1 m. For Scenario 2, the maximum height of sea level rise for the area of the western bridge pillars was 35 cm (Fig. 5), and for the area of the eastern pillars it was 0.53m. It can be also noticed that at the entrance to the Kerch Strait from the Black Sea, the wave heights on the 3-meter isobath reached 1.5 meters. On average, for both coasts of the Kerch Strait under this scenario, the height of the tsunami waves on the 3-meter isobath did not exceed 40 cm. Under Scenario 3 (Fig. 6), with a block source with a magnitude of M = 7.5, the maximum wave height at the western pillars was 18 cm, and in the eastern ones it is about 32 cm. For the case of a hypothetical block source with M = 8 (Fig. 7), the maximum heights near the pillars were: at the western pillars of the bridge 0.5 m, at the eastern ones 1.95 m; the highest height for this scenario for the area of the western bridge pillars was 3.2m. All these data on the maximum values of the wave rise height on the 3-meter isobath near the pillars of the Crimean bridge are given in Table 1.

Table 1. Data on the maximum values of the wave height at the pillars of the Crimean bridge (Localization of the source near the Crimean peninsula)

Scenario №	Max. water level rise (western pillars)	Max. water level rise (eastern pillars)
1	0,32 m	0,51 m
2	0,35 m	0,53 m
3	0,18 m	0,32 m
4	0,5 m	1,95 m

4.1.2. Tsunami hazard of the Crimean bridge during the localization of the seismic source near the Kerch Strait in the Black Sea and in the Sea of Azov

We also performed numerical simulation for two hypothetical earthquake sources located in front of the entrance to the Kerch Strait (Fig. 8) below.

It should be noted that for the scenarios considered in this paper, for the corresponding magnitudes of earthquakes, the wave heights in the strait, and, in particular, in the area of the Crimean bridge, have lower values. Thus, the maximum wave height at the eastern pillars of the Crimean bridge (see also [16,17]) was 1.5-2 m. the height of the tsunami waves at the eastern pillars of the bridge is 0.5 - 1.9 m. For these areas of the sea area, three scenarios of possible strong earthquakes with magnitude M = 7 from two hypothetical ellipsoidal earthquake sources located in front of the Kerch Strait to the northeast of the Crimean Peninsula in the Black Sea at magnitudes M = 7 (Scenario 1) and M=7.6 (Scenario 2) and the earthquake source localized in the Sea of Azov in front of the Kerch Strait (Scenario 3) were considered.

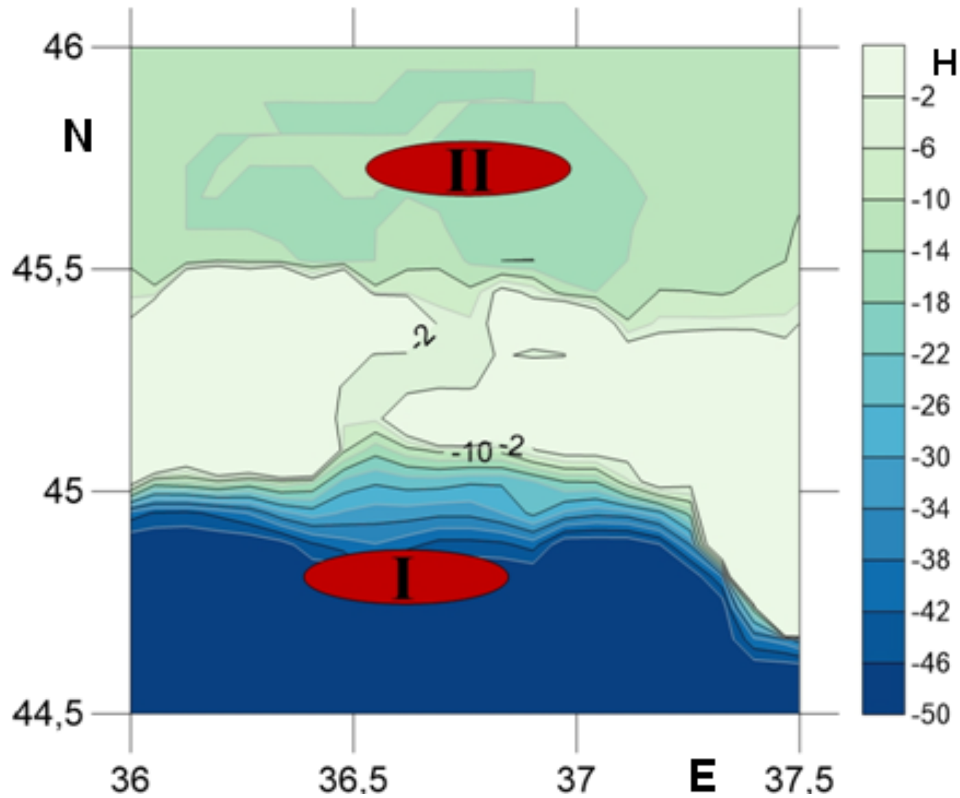
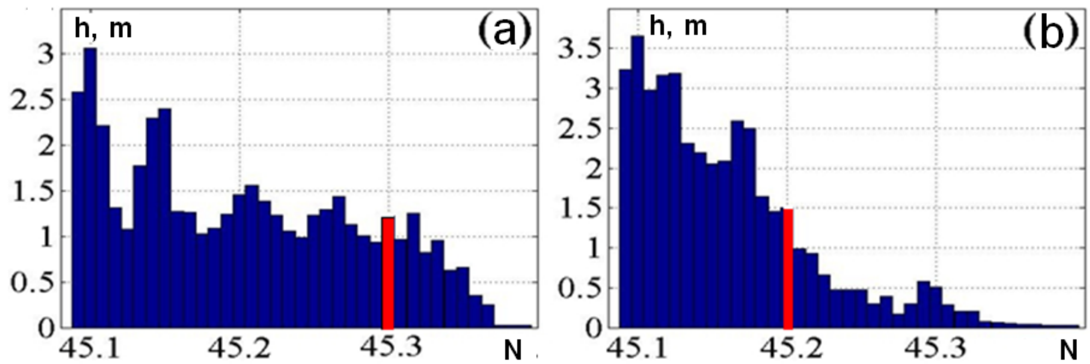


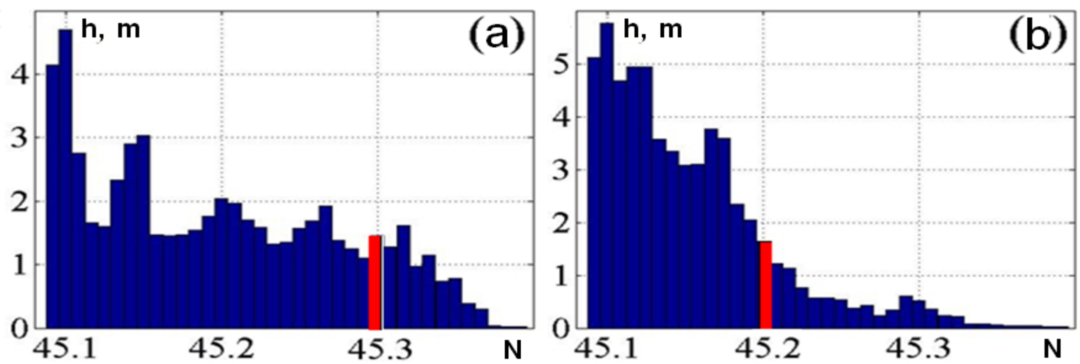
Fig. 8. Location of the tsunami sources considered: I - Scenarios 1, 3; II - Scenario 2

It should be noted that for the scenarios considered in this paper, for the corresponding magnitudes of earthquakes, the wave heights in the strait, and, in particular, in the area of the Crimean bridge, have lower values. Thus, the maximum wave height at the eastern pillars of the Crimean bridge (see also [16,17]) was 1.5-2 m. the height of the tsunami waves at the eastern pillars of the bridge is 0.5 - 1.9 m. For these areas of the sea area, three scenarios of possible strong earthquakes with magnitude $M = 7$ from two hypothetical ellipsoidal earthquake sources located in front of the Kerch Strait to the northeast of the Crimean Peninsula in the Black Sea at magnitudes $M = 7$ (Scenario 1) and M=7.6 (Scenario 2) and the earthquake source localized in the Sea of Azov in front of the Kerch Strait (Scenario 3) were considered. A sign-positive vertical displacement in the source up to 2.1 m was considered. Sea of Azov (Fig. 8). The computational domain in this problem was chosen in the square of 35–38^0 E, 44.5–47.5^0 N with a grid including the number of nodes 345 × 361 = 124545. Bathymetry of the Black Sea with a resolution of 500 m was used for modeling. When considering Scenario 1 (Scenario 2), hypothetical tsunami sources of an elliptical shape of magnitude $M = 7.0$ ($M = 7.6$, respectively) with the center in the point 36.6°E, 44.735°N were modeled. (Fig. 8). Wave fields of displacements and fields of velocities were obtained along the northwestern coast of the Black Sea, the coasts of the Sea of Azov and along the coasts of the Kerch Strait, histograms of maximum wave heights were constructed (Fig. 9, Fig. 10, Fig. 11). The geographic location of the pillars of the Crimean bridge in the projection is marked in red on them (slice in longitude).



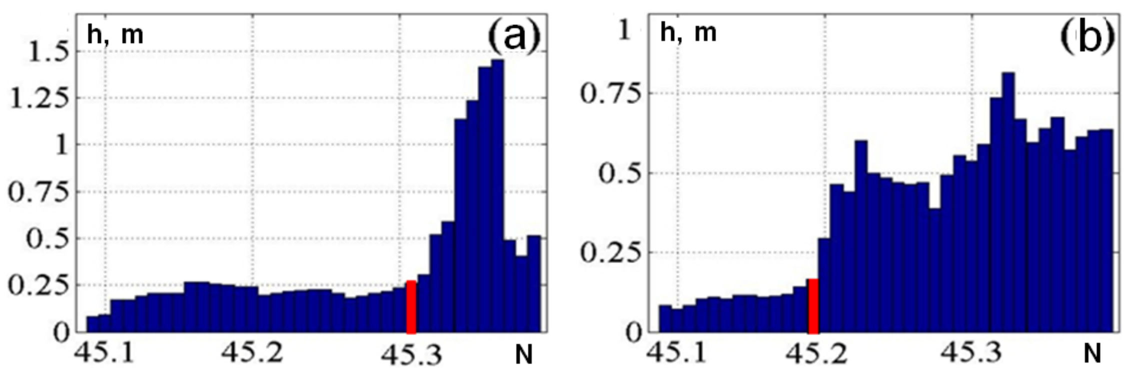
a) Western shore of the strait; b) eastern shore of the strait

Fig. 9. Histograms of the maximum heights of tsunami waves on the 3-meter isobath for the coast of the Kerch Strait near the Crimean bridge from the Black Sea for M=7 (Scenario 1)



a) western shore of the strait; b) eastern shore of the strait

Fig. 10. Histograms of the maximum heights of tsunami waves on the 3-meter isobath for the coast of the Kerch Strait near the Crimean bridge from the Black Sea for M = 7,6 (Scenario 2)



a) western shore of the strait; b) eastern shore of the strait

Fig. 11. Histograms of the maximum heights of tsunami waves on the 3-meter isobath for the coast of the Kerch Strait near the Crimean bridge from the Sea of Azov for M = 7 (Scenario 3)

As follows from the data of the histograms (Fig. 9 and Fig. 10), for sources similar in localization (the Black Sea at the entrance to the Kerch Strait) and different in magnitude (*M* = 7 and *M* = 7.6), corresponding to scenarios 1 and 2, the maximum heights of sea level rise at the same points on the coast differ significantly. At the entrance to the strait, the maximum difference was 1.7 m, at the bridge pillars up to 0.25 m. The time of the movement of the front from the source to the coasts coincides, because the wave velocity in the shallow water approximation depends only on the depth of the considered basin. When implementing Scenario 3, if the potential tsunami source is located in the Sea of Azov, the wave heights in the Kerch Strait are noticeably lower - up to half a meter. The main impact of the wave falls on the southern coast of the Taman Bay, so that when part of the wave front approaches the bridge line, its energy has already been substantially extinguished. A characteristic feature of tsunami propagation along the strait is the flat shape of the wave front, both when moving along the Chushka Spit and when approaching the bridge directly. In contrast to the case of the localization of the source in the Black Sea considered above, the elevation wave attacks the bridge along the entire width of the bridge from the Tuzla Spit in the east to Ak-Burun Cape in the west [15-17]. Note that the wave height here is significantly less than in the first case, however, the entire bridge structure is immediately attacked. Of course, in this case, the bend of the bridge near Ak-Burun Cape experiences a compressive load, in contrast to the capsizing load in the case of a source in the Black Sea. All this data on the maximum values of the wave rise height on the 3-meter isobath near the pillars of the Crimean bridge are given in Table 2.

Table 2. Data on the maximum values of the wave height at the pillars of the Crimean bridge (localization of the source near the Kerch Strait)

Scenario №	Max. water level rise (western pillars)	Max. water level rise (eastern pillars)
1	1.3 м	1,5 м
2	1,4 м	1,8 м
3	0,26 м	0,15 м

CONCLUSIONS

It is shown that under scenarios when a seismic source with magnitudes *M* = 7 and *M* = 7.6 is located in the Black Sea at the entrance to the Kerch Strait, the height of the sea rise on the 3-meter isobath near the western pillars of the Crimean bridge can reach 1.3 m, in the eastern ones 1.5 m. With a source with a magnitude of *M* = 7, located in the Sea of Azov at the exit from the Kerch Strait, the maximum heights of water rise were 0.4 and 0.5 m for the western and eastern pillars of the bridge, respectively. For the *M* = 7.6 source located in the Black Sea at the southern entrance to the Kerch Strait, these values were 1.5 and 2m. The speed of the water flow in the vicinity of the western pillars of the bridge that goes around Ak-Burun Cape can reach 50 km/h, which can lead to damage to the bridge pillars and erosion of their base. It is shown that if the localization of the earthquake source is much further from the Kerch Strait, for example, near the southwestern coast of the Crimean Peninsula, then the maximum possible heights both at the western and eastern pillars of the bridge are about half a meter and lower. And only with a hypothetical earthquake with magnitude $M = 8$, which has not historically been observed in the basin of the Black and Azov Seas, and statistical estimates do not give such a significant natural event in the coming decades [27,30], wave heights near the rear and eastern pillars of the bridge can reach 1, 5 and 2m, respectively. When the bridge pillars are buried to a depth of 90m, such wave heights will not be able to cause significant damage to the bridge state.

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