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GEOPHYSICS

Generation and Propagation of Catastrophic Tsunamis in the Sea of Okhotsk Basin: Possible Scenarios

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Because of the probability of the occurrence of a strong earthquake in the central part of the Kuril–Kamchatka Arc, which corresponds to the seismic gap (SG) region [1], it is necessary to take into account the possibility of tsunami wave generation and the risk of its occurrence not only at the Kuril Islands but also on the coast of the Sea of Okhotsk. The necessity of the prediction of such event became especially urgent after the catastrophic tsunami on the coasts of several countries in Southeast Asia caused by the strong earthquake on December 26, 2004, whose epicenter was located near the northwestern edge of Sumatra Island (Indonesia). The latter event occurred in the SG region in the Sunda subduction zone after an almost 200-yr-long silence. The source of this earthquake appeared unusually long (more than 1300 km) and very nonuniform. Taking into account the strong indentation and block structure of the near-island slope of the trench, the above fact indicates the keyboard mechanism of the displacement of the ocean bottom [2, 3]. In this process, the initial perturbation in the source is transferred horizontally to the neighboring blocks unevenly with jumps and stops [4]. Coastal services in the countries of Southeast Asia were unprepared for the arrival of a tsunami. These countries lack systems of tsunami warning and notification of the population about the approaching hazard. Therefore, the number of casualties and material losses from the breaking wave were very high. In principle, if timely information about the localization of the tsunami source is provided, modern computer capabilities will allow us to perform real-time numerical modeling of the possible spreading of the tsunami wave, the expected arrival time of the wave at the given coast, the altitude of its runup, and so on. However, the calculation results generally depend on the source model used in the calculations. Usually, a monoblock is chosen, the uplift of which at the bottom triggers the perturbation of the ocean surface (see, for example, [5]). Application of the keyboard model [2, 3] allows us to consider various versions of the motion of block-keys at the ocean bottom and determine the optimal version in terms of correspondence to the observed data.

In numerical modeling of the characteristics of potential tsunami related to the occurrence of a strong earthquake in the SG region in the Middle Kuril Islands, it is reasonable to start from the structure of the possible source, the geometry of which was distinguished during the Kurils-2005 marine hydrophysical expeditions (cruise 37 of the R/V *Akademik Lavrent'ev* in summer 2005) [6].

In this paper, we present the results of numerical modeling of the propagation and rolling of a tsunami wave on the coast. The generation of a tsunami wave by this potential source in the SG zone was based on the keyboard subduction model. A nonlinear system of equations for shallow water was used in the numerical modeling for the description of the generation and propagation of the tsunami wave (see, for example, [7]). The calculations took into consideration the Coriolis force and bottom friction. The modeling yielded wave fields of displacement and velocity fields for the entire basin of the Sea of Okhotsk along all coasts of the continent and islands. A calculation area in the square 40°–60° N and 140°–160° E with a grid of 1201 × 1201 points was chosen for modeling.

Figure 1 shows the two types of hypothetical earthquake source (~330 and 465 km long) chosen for modeling a possible earthquake located between the Bussol Strait and Shiashkotan Island (70 and 130 km wide, respectively). The mean distance to the islands of the Kuril–Kamchatka Ridge is approximately 35 and 25 km, respectively. In both cases, the source was assumed to be a set of keyboard elements consisting of 3 to 8 different blocks (keys), which could move both

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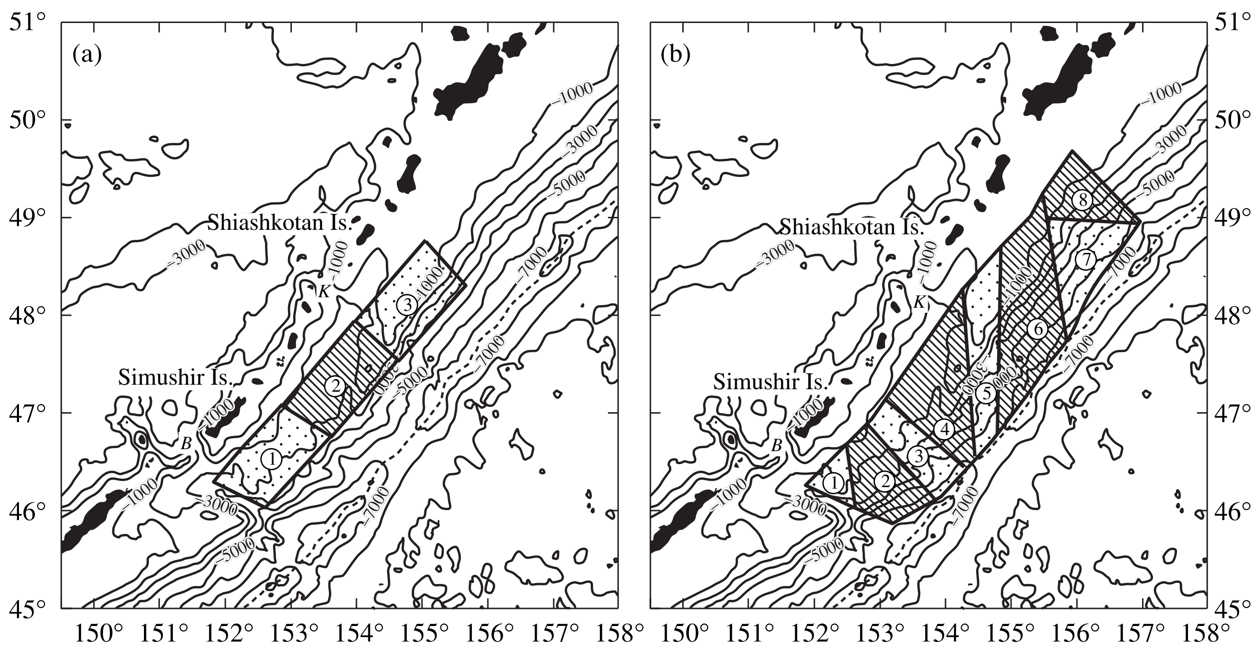

Fig. 1. Location of tsunami sources used in the modeling. (a) Tsunami source consists of three blocks; (b) tsunami source consists of eight blocks. In the second case, the data for identification of blocks were obtained on the Kurils-2005 expedition [6]. Dashed line shows the axis of the trough. Deep straits are indicated: (*B*) Bussol, (*K*) Kruzenshtern.

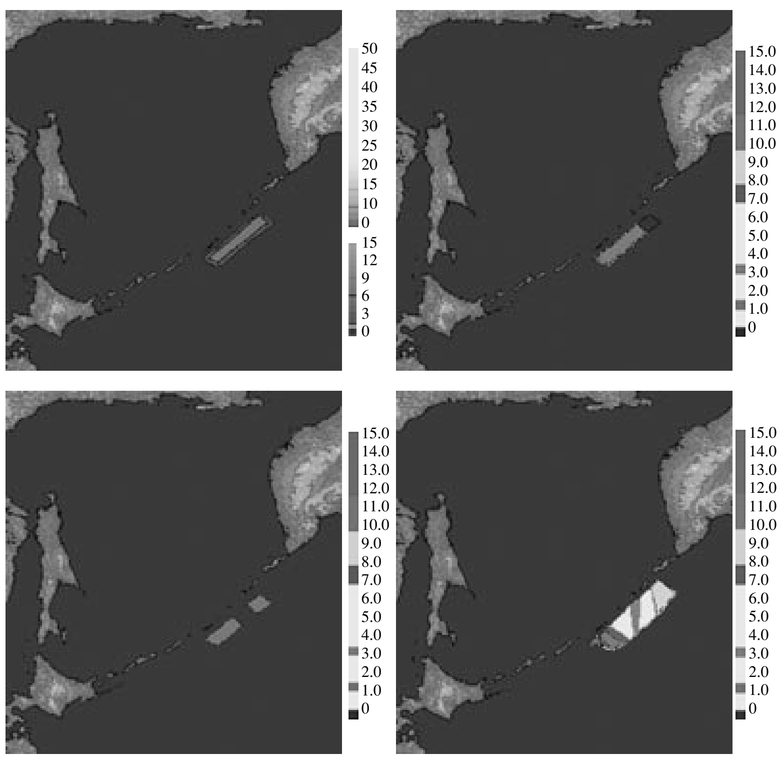

Fig. 2. Versions of the calculation of tsunami source generation by a seismic source. Upper panel: (i) the source consists of three blocks, which move simultaneously upward with equal speeds; (ii) the source consists of three blocks (two blocks move upward, while the third block moves downward), and the motion has different velocities. Lower panel: (i) the source consists of two blocks, which move simultaneously upward with different velocities; (ii) the source consists of eight blocks, which move simultaneously upward with different velocities.

(a)

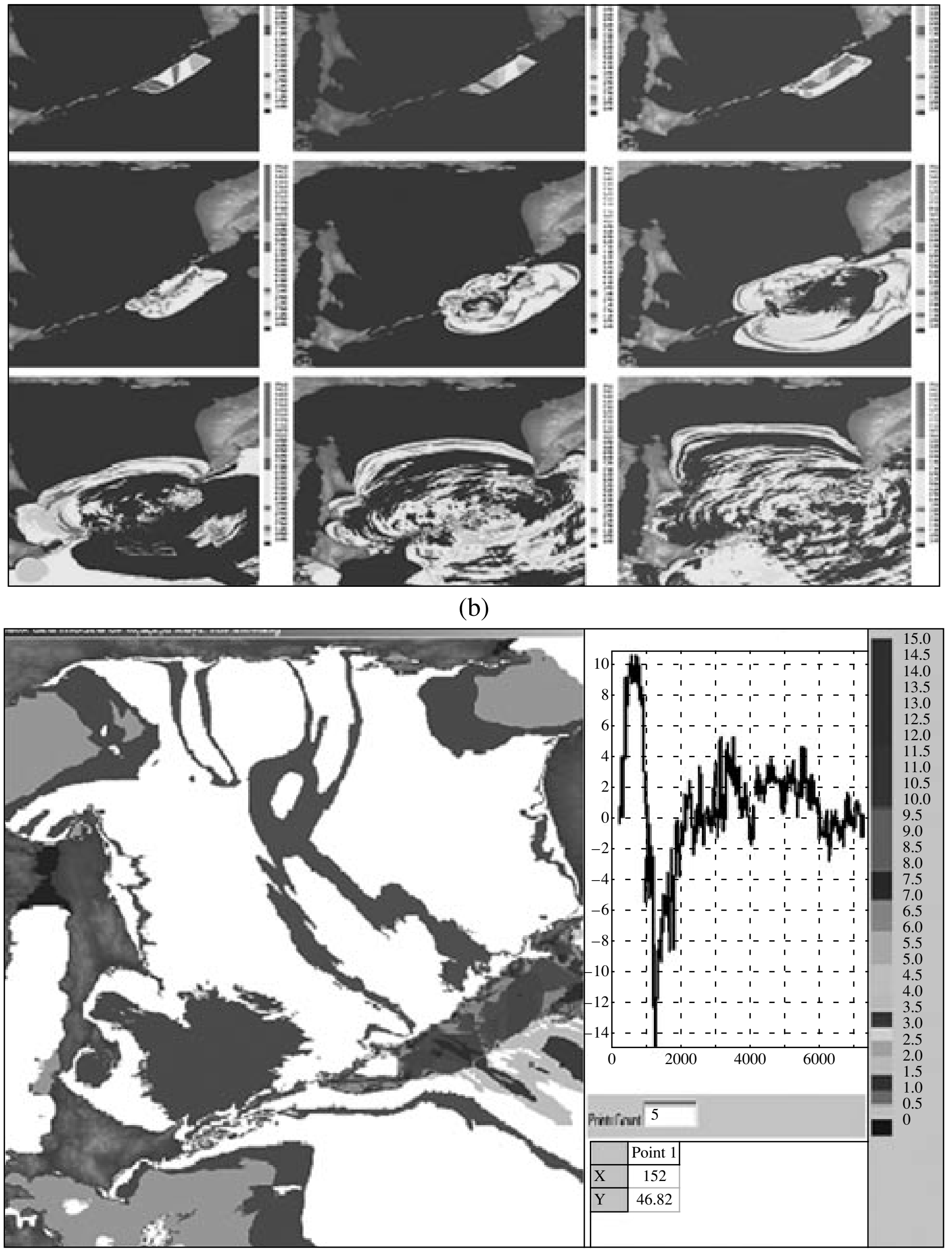

Fig. 3. (a) Generation and propagation of tsunami wave in the basin of the Sea of Okhotsk from a source located in the region of the Middle Kuril Islands. The source consists of eight blocks. Blocks 1–8 rise to different heights with different velocities. The height of block uplift is 14, 10, 10, 14, 9, 9, 12, and 9 m. The time of uplift is 10, 10, 10, 30, 10, 30, 30, and 10 s, respectively. (b) Distribution of wave heights in the basin of the Sea of Okhotsk. The maximal height of wave along the eastern coast of Sakhalin reaches 8 m. Inset on the right shows an example of sea level fluctuation near Simushir Island (152° E, 46°49′ N).

upward and downward. The average velocity of the vertical motion of blocks depending on the characteristic time of motion in the source varied from 0.17 to 1.4 m/s. Horizontal motion of the blocks was not considered. The calculation of the propagation of the generated waves at the water surface was performed up to the 10-m isobath. We considered several calculation scenarios of the generation and propagation of tsunami waves from the hypothetical sources presented in Fig. 2.

Figure 3 shows an example of the typical realization of the scenario of generation and propagation of tsunami waves when the seismic source consists of eight blocks located opposite to the Bussol and Kruzenshtern straits. Figure 3a shows the results of numerical modeling of a tsunami for nine moments of time: generation of tsunami waves (upper row of panels), propagation of tsunami wave through the Kuril Ridge (middle row of panels), and propagation of tsunami wave in the basin of the Sea of Okhotsk (lower row of panels). Figure 3b shows the distribution of maximum wave heights along the entire basin considered in this calculation. The inset demonstrates an example of pressure gauge time series simulation during propagation of a tsunami wave at an arbitrary point (46°49′ N, 152° E) close to Simushir Island. It is clearly seen that the maximum wave height is ~11m when the wave approaches the coast, while the negative amplitude is 15 m. The calculation of the sources (Fig. 2) shows that the character of wave propagation through the Kuril Islands and its propagation both beyond the Sea of Okhotsk basin and in the basin (for example, Fig. 3a) is practically the same for different versions of the motion of blocks in the source. During the first 150–240 s, part of the wave propagates to the open ocean in the direction to the Hawaiian Islands. At the same time, the Kuril Islands prevent the propagation of the tsunami wave toward the Sea of Okhotsk, leading to a greater wave height on the southeastern coast of the islands (up to 15 m at Simushir Island, 2 m at Kunashir Island, and 1.5 m at Shikotan Island, and so on (cf. [8, 9]). Part of the energy is reflected from the islands toward the open ocean, but the main part of the wave propagates through the deep Kruzenshtern and Bussol straits, which play the role of natural waveguides. Two wave fronts formed after passing the Kuril Ridge govern the character of the joint wave front (middle row of panels). The further propagation of waves is strongly governed by the bathymetry of the basin: part of the wave that passed through Bussol Strait propagates along the Kuril Depression toward Sakhalin and Hokkaido (Japan) islands with a relatively high speed (V ~ 600 km/h) due to the great depth (approximately 3300 m) of this basin. The velocity of the propagation of the second wave passing through the Kruzenshtern Strait and propagating across the Kuril Depression decreases notably with time, because the wave spreads into the appreciably shallower Deryugin Depression. In 50–80 min (depending on the scenario), the joint front of the waves passing through the Kruzenshtern and Bussol straits reaches the southeastern end of Sakhalin Island (Cape Terpeniya) (lower row of panels). The modeling results show that the wave height on the eastern coast of Sakhalin Island is governed first of all by the wave that passed through the Kruzenshtern Strait. If the wave propagates toward the continental coast of the Sea of Okhotsk, the left part of the wave front gradually collapses on the eastern coast of Sakhalin from south to north. The wave height ranges from 2.5 to 8.5 m depending on the scenario considered. After passing Sakhalin, the wave front becomes almost flat and spreads with a relatively low velocity toward Okhotsk (northern coast of the Sea of Okhotsk), while the wave front on both sides of the island propagates with relatively high velocity to the west (Shantarskiye Islands) and east (Shelikhov Bay) and reaches the continental coast approximately in 3 h.

Analysis of this series of calculations for the same size of the earthquake source showed that the influence of the character of block motion in the source on the manifestation of tsunami on remote coasts is mainly reflected in the significant variation of the function of runup distribution along the coast rather than the general decrease (or increase) in the runup value. At the same time, the sequence of the motion of blocks in the source significantly influences the runup value on the nearest coasts (Kuril Islands). Thus, we have shown that, according to different scenarios of tsunami source formation by various seismic motions, the height of waves rolling along the coast of the Sea of Okhotsk can range from 15 m on the Kuril Islands to 8.5 m in some coastal sectors of Sakhalin Island.

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