2000 Uglegorsk earthquake

A Yu Polets
Institute of Marine Geology and Geophysics Far Eastern Branch of Russian Academy of Science, Yuzhno-Sakhalinsk, 693022, Russia

E-mail: aypolec@gmail.com

Abstract. The paper presents the results of waveform inversion of the Mw 6.8 August 4 (5), 2000 Uglegorsk earthquake (Sakhalin Island, Russia). The detailed rupture process of the 2000 Uglegorsk earthquake was simulated using the waveform inversion method. The average parameters were calculated for both nodal planes. Waveform inversion was carried out on the basis of Global Seismographic Network (GSN) data. Only P-waves from BHZ channels of all stations from the GSN were used. The simulated source parameters included a double-couple source, the scalar seismic moment, the source time function, and the slip directions. The performed studies made it possible to investigate the features of the rupture development and the amplitude of displacements along the east and west-dipping nodal planes of the August 4 (5), 2000 Uglegorsk earthquake. The obtained P-slip model for the 2000 Uglegorsk earthquake source area is in good agreement with the surface manifestations of the rupture according to the field geology data and the results of geodetic inversion.

1. Introduction

A strong Mw 6.8 earthquake occurred on Sakhalin Island (48.786° N, 142.246° E) on August 4, 2000, at 21:13 pm (August 5 at 8:13 am, local time) and caused a swarm of earthquakes. The magnitude of the largest aftershock was MLH 5.5.

The earthquake occurred in a sparsely populated area of the Uglegorsk district, under the Western Sakhalin mountain range. The event caused significant damage and destruction of buildings and structures in the settlements located close to the epicentre. By lucky chance, there were no casualties. The earthquake was named Uglegorsk or Uglegorsk-Ainu earthquake [1].

The earthquake has confirmed that the Uglegorsk district is one of the most earthquake-prone areas of the Sakhalin Region. Before the devastating Neftegorsk earthquake (the Mw 7.0 Neftegorsk earthquake occurred in Northern Sakhalin, killed almost 2000 people [2]), this part of the island, like the entire Sakhalin Region, belonged to the moderate seismic zone.

Some strong earthquakes occurred earlier in the area: 1924 Lesogorsk-Uglegorsk earthquake (epicentral intensity I0 8 – 9); 1928 Lesogorsk earthquake (I0 7 – 8), 1931 Lesogorsk earthquake (I0 6), 1956 Uglegorsk earthquake (I0 6 – 7), 1970 Lesogorsk earthquake (I0 6), 1973 Uglegorsk earthquake (I0 7). There are only 6 earthquakes with Mw > 5 for the period 1924 – 2000. Four of them were realized outside the island, in the Tatar Strait, and only two on the island (1924 Lesogorsk-Uglegorsk and 1970 Lesogorsk earthquakes). All earthquakes within the island, including 2000 Uglegorsk earthquake, are characterized by the high magnitudes – Mw 6.7 (1924 Lesogorsk-Uglegorsk earthquake), Mw 7.0 (1970 Lesogorsk earthquake), Mw 6.8
(2000 Uglegorsk earthquake). It should also be noted that the 2000 Uglegorsk earthquake was localized much to the south of all previous events [3].

On September 13, 2020 (20 years after the 2000 Uglegorsk event), an earthquake with a moment magnitude Mw = 4.8 occurred in the study area. The focal mechanism of the earthquake is a reverse fault type (table 1). The epicentral intensity was I₀=5 according to MSK-64. The seismic process lasted for about 2 days, the most of the aftershocks were recorded during the first 7 hours [4]. The epicenters of the earthquakes are located within the Western Sakhalin fault structure.

It should be noted that in the seismic history of the region there are irregular phases of intensification and decline of seismic activity, replacing each other in about 20 years [1]. However, today it is difficult to say whether this earthquake is associated with a new phase of intensification of seismic activity or not, more research is needed in this area.

Present study aims to simulate the rupture process of the 2000 Uglegorsk earthquake using a waveform inversion method [5].

2. The tectonic position and the main 2000 Uglegorsk earthquake fault parameters

The tectonic position of the 2000 Uglegorsk earthquake is determined by three main orographic elements: the Western Sakhalin Mountains (represented by the Kamyshev Ridge), the Uglegorsk-Ainu Plateau near the western border of the Kamyshev Ridge, the Lomanon volcanic massif, separated from the plateau by one of the main branches of the Western Sakhalin Ridge. The 2000 Uglegorsk earthquake occurred under the horizontal compressive sublatitudinal stresses. The focal mechanism of the earthquake is a reverse fault type (table 1).

| T | N | P | Nodal planes | Focal mechanism solution |
|---|---|---|--------------|-------------------------|
| NP1   | NP2   |
| PL | AZM | PL | AZM | PL | AZM | STK | DP | SLIP | STK | DP | SLIP |
| Mw 6.8 Uglegorsk earthquake | 69 | 134 | 177 | 353 | 13 | 259 | 328 | 36 | 60 | 183 | 60 | 110 |
| Mw 4.8 Uglegorsk earthquake | 60 | 345 | 29 | 151 | 6 | 244 | 3 | 47 | 132 | 130 | 57 | 55 |

The tectonic position of this reverse in the structure of the northwestern part of the transition zone from the Asian continent to the Pacific Ocean is the following: on the one hand, the earthquake is located near the western boundary of the Sakhalin fold area with the deep-water Japan Basin which is pinching out to the north. Therefore, the concentration of compression stresses can be associated with the Japan Basin expansion. On the other hand, the fault orientation coincides with the strike of numerous echeloned region folds, which can be considered as a manifestation of shear deformations, then the formation of the fault should be associated with the release of stresses on the reverse fault in the meridionally oriented right-side shearing zone [6].

The fragments of the 2000 Uglegorsk earthquake fault (later they were named Ainu fault) were observed in three areas. During the initial observation of the epicentral zone, the fault fragments were located nearby Krasnova Mountains in two areas spaced about 5 km from each other. In the first one, north-east of the mountain, the fragment of seismic rupture is represented by a reverse fault. The fault plane has the north-northwest strike and dips to the west. The value of the vertical surface displacement was 70–80 cm (the western side of the fault was lifted). Approximately 300–400 m to
the south, the value of the vertical surface displacement sharply decreased and it does not exceed 10 cm. The size of the vertical cut of the road bed for each of them is 20–30 cm (the western wings are raised). The total vertical displacement of the Earth's surface along the fault fragments was about 60 cm.

In another area, at the eastern foot of Krasnova Mountain, two more fault fragments were discovered. The fault fragments differ sharply from each other. They have different morphokinematic properties and the values of vertical displacements. The eastern fault fragment, striking in the north-east direction, is similar to those discussed above. The value of the vertical displacement (the western fault side was raised) was 40 cm. Another western fault fragments with a total length of about 1 km is located at an insignificant distance to the west of the considered seismic fault. The western seismic rupture with the vertical plane of the displacer had a northeastern strike and a maximum amplitude of the vertical displacement of 2.5 meters (the eastern side was uplifted). At another point, this fault fragment had a vertical displacement of 2.2 m [1, 6].

The total length of the observed fault fragments was at least 5 km. It should be noted, that signs of horizontal displacements were not found.

Initially, it was impossible to distinguish exactly which of the nodal planes was a fault plane and the west dipping plane was chosen as the fault plane. Additional study of the earthquake has shown that the east-dipping plane is preferred since it fits the data significantly better, it is more consistent with the aftershock distribution and the location of the surface rupture, and the resulting geodetic moment is closer to the seismically determined value [7, 8].

3. A waveform inversion method

Recent developments in waveform inversion method for inferring earthquake source behaviour, together with the establishment of high-quality digital seismograph networks and advances in computer technology, have led to great progress in understanding earthquake source behaviour. Using waveform inversion methods, the detailed rupture process of the earthquake can be retrieved from observed data. Also moment tensors for many moderate and large earthquakes can be determined in a routine way [9].

The waveform inversion method was used to construct a source model and study the features of the development of the seismic process in the source area of the Uglegorsk earthquake [5]. The method allows us to determine the source mechanism and estimate its parameters, the orientation of the seismic rupture in the source area, the form of the source time function, the value of the seismic moment, the velocity of rupture propagation, etc. The method allows calculating synthetic seismograms for the current source model, comparing them with the observed waveforms and calculating corrections to the model in order to bring the synthetic seismograms closer to the observed ones.

The inverse problem solution is to compare the observed and calculated waveforms to obtain the best match. Source data – broadband seismograms of body waves recorded by the stations of the GSN (http://www.iris.edu/). The working data include seismic records, characteristics of seismic channels, coordinates and names of stations, as well as information about the event (coordinates, time, magnitude).

4. The results of waveform inversion for the 2000 Uglegorsk earthquake

The azimuthal network of the stations in the source area was inhomogeneous. Only P-waves recorded by broadband stations of the GSN in the range of epicentral distances from 20 to 100°, on the vertical channels (BHZ) were used. The boundaries of the aftershock area were taken as the boundaries of the August 4 (5), 2000 Uglegorsk earthquake. In the process of waveforms selecting one or several records that significantly differ in amplitude and oscillation forms at closely spaced stations were removed. In the final analysis, 69 P-wave seismograms were selected (figure 1). The deviation between real and synthetic waveforms for both nodal planes was about 0.4. The resulting P-slip models for two nodal planes of the 2000 Uglegorsk earthquake are shown in figure 2.

The waveform inversion was performed using a grid of 10x5 nodes (along strike and dip, respectively), with a grid step of 8 km. The arrows show the displacement direction, the color reflects their magnitude.
Figure 1. Station distribution used for P-slip inversion of the August 4(5), 2000 Uglegorsk earthquake: (a) the east-dipping nodal plane; (b) the west-dipping nodal plane.

The average parameters were calculated for both planes. Thus, for the east-dipping nodal plane (STK 328 DP 36 RAKE 73), the average displacement was about 2 m (the maximum displacement was about 4 m), the rupture time was about $T = 28$ s, and the seismic moment was $M_0 = 3.1 \times 10^{19}$ N·m ($M_w = 6.93$). The time source function has peaks at the $8^{th}$ and $12^{th}$ seconds. For the west-dipping nodal plane (STK 183 DP 60 RAKE 119), the average displacement was about 3 m (the maximum displacement – 5 m), the seismic moment was $M_0 = 3.6 \times 10^{19}$ N·m ($M_w = 6.97$).

Figure 2. Horizontal axis is a distance along the strike and vertical axis is a distance along the dip of the fault planes. Red star marks the hypocentre location. (a) the east-dipping plane; (b) the west-dipping plane.

5. Conclusion
Direct observations of the source area of a strong earthquake are possible only in the cases, when the rupture reaches the surface. Therefore, the indirect remote sensing methods in various combinations and modifications are the most acceptable. The carried out waveform inversion made it possible to simulate the development of the seismic process of the August 4 (5), 2000 Uglegorsk earthquake source zone and to study the features of the rupture development and the amplitude of displacements. The simulated source parameters included a double-couple source, the scalar seismic moment, the
source time function, and the slip directions. The obtained dislocation model for the 2000 Uglegorsk earthquake source area is in good agreement with the surface manifestations of the rupture according to the field geology data and the results of geodetic inversion.

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