Tsunami generated by the 2004 Kushiro-oki earthquake

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The 2004 Kushiro-oki earthquake generated a small tsunami that was observed at two tide gauge stations located on the Pacific coast of Hokkaido Province. Analysis of the tsunami waveforms shows that the slip amount of the fault was 2.1 m. The seismic moment was calculated to be 3.1×10^{19} Nm, which is consistent with the results of previous seismological studies. Tsunami simulation results indicate that a small first wave at Urakawa is caused by large shallow water off Cape Erimo. The tsunami generated from the source area off Kushiro circumvents the shallow area off the cape, propagates through the deep sea, and arrives at Urakawa as a small first wave. Larger tsunamis are propagated through the shallow region slowly and arrive at Urakawa as a later tsunami. These results suggest that a tsunami from a future large Nemuro-oki earthquake will also arrive at the west coast of Hidaka with a small first wave and large later phases.

Key words: 2004 Kushiro-oki earthquake, tsunami numerical simulation, tsunami disaster mitigation.

1. Introduction

On 29 November 2004, a large earthquake occurred off the coast of Kushiro (or Hamanaka). The Japan Meteorological Agency (JMA) estimated the source parameters as follows: origin time, 3:32 (JST); epicenter, 42.944°N, 145.280°E; depth, 48 km; JMA magnitude, Mj=7.1. The seismic moment obtained from the Harvard CMT catalog is 3.5×10^{19} Nm (Mw=7.0). The focal mechanism of the earthquake indicates the thrust type faulting (strike: 243°, dip: 27°, rake: 124°). Katsumata and Yamanaka (2006) also estimated similar results using the teleseismic body waves, the focal mechanism (strike: 238°, dip: 33°, rake: 117°), and a seismic moment of 3.4×10^{19} Nm.

The hypocenters of the mainshock and aftershocks were accurately estimated using the three-dimensional (3-D) velocity structure (Katsumata and Yamanaka 2006). The result indicates that the hypocenters were located on a plain dipping 22° toward the northwest (Fig. 1). The plain was located on the plate interface presented by Katsumata *et al.* (2003). These results clearly indicate that the earthquake was an underthrust event at the plate interface.

This earthquake generated the small tsunamis observed at a few tide gauge stations located along the Pacific coast of Hokkaido Province. In this paper, the tsunami waveforms are numerically computed using the fault model, which is consistent with the previous seismological studies. The computed tsunami waveforms are compared with the observed ones to estimate the slip amount of the fault. The tsunami generation of large later phases along the west coast of Hidaka is discussed for tsunami disaster mitigation of future large Nemuro-oki earthquakes.

2. Data and Method for Tsunami Computation

The tsunami waveforms were recorded at two tide gauge stations located along the Pacific coast of Hokkaido, Hanasaki, Kiritappu, and Urakawa (Fig. 2). A rectangular fault model (Fig. 1) that was used to compute the tsunami is located on a plain estimated from the aftershock distribution obtained by Katsumata and Yamanaka (2006). The depth of the top edge of the rectangular fault model is 44 km. Both the length and width of the fault are 15 km in order to cover the large slip area of the earthquake estimated from the teleseismic body wave analysis (Katsumata and Yamanaka, 2006) (Fig. 1). The strike, dip, and rake of the fault are 238°, 22°, and 117°, respectively.

The vertical seafloor displacement from the rectangular fault model is computed using Okada's (1985) equations and used as an initial condition of tsunami numerical simulation. Finite-difference computations of the linear long-wave equations (see Johnson, 1998) are carried out. The tsunami computational area is shown in Fig. 2. The total reflection boundary condition is used at the coast. The grid size is generally 20 s of the arc (about 600 m) except near the tide gauge stations where a finer grid size, 4 s of the arc, is used. The time step of the computation is 1 s to satisfy a stability condition. A slip amount of the rectangular fault model is estimated by comparing the observed and computed tsunami waveforms.

3. Results

The observed and computed tsunami waveforms at Hanasaki, Kiritappu, and Urakawa are compared in Fig. 3. The observed tsunami waveforms are well explained by the computed ones. The slip amount is estimated to be 2.1 m from a comparison of the amplitude of the observed and computed tsunami waveforms. The seismic moment is calculated to be 3.1×10^{19} Nm (Mw=7.0) by assuming that the rigidity around the fault is 6.5×10^{10} N/m^2. This was

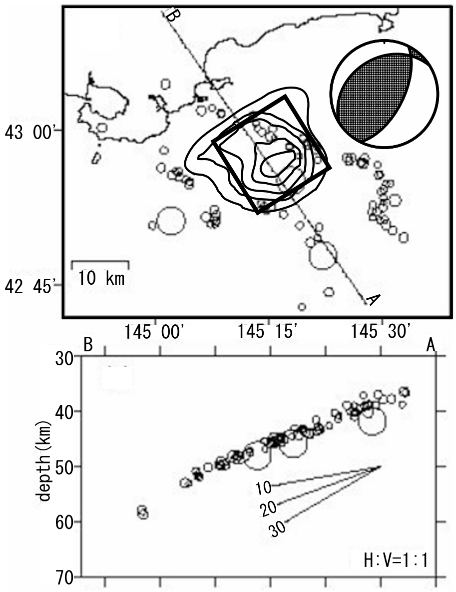

Fig. 1. Aftershocks of the 2004 Kushiro-Oki earthquake relocated using the three-dimensional velocity structure of Katsumata and Yamanaya (2006). The time period is from 29 November 2004 to 29 January 2005, and the magnitude is 3.5 or larger. The contours show the slip distribution estimated using teleseismic body waves of Katsumata and Yamanaka (2006). The contour interval is 0.5 m. A rectangle shows the fault model used for the tsunami computation. The focal mechanism of the mainshock is also shown.

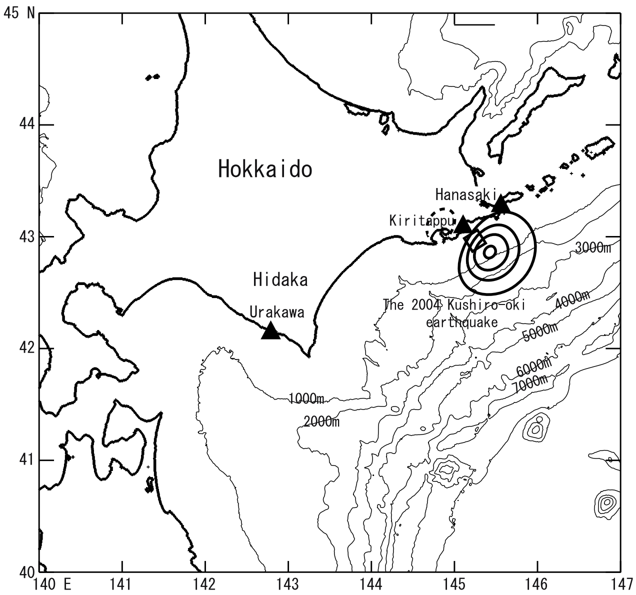

Fig. 2. Tsunami computational area. Triangles show three tide gauges where the tsunami waveforms were observed. A rectangle shows the fault model used for the tsunami computation. Closed contours show the coseismic vertical displacement (solid curves for uplift and dashed for subsidence with a 0.5-cm interval).

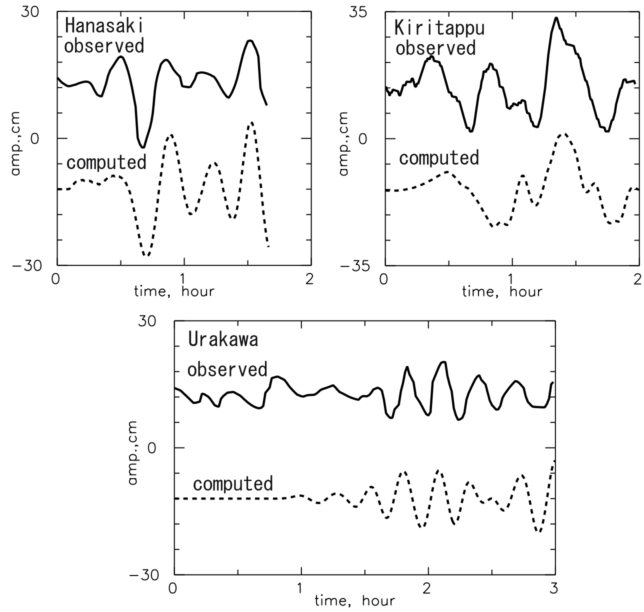

Fig. 3. Comparison of the observed (solid lines) and computed (dashed lines) tsunami waveforms at Hanasaki, Kiritappu, and Urakawa.

the rigidity used by Hirata *et al*. (2003) and at the deepest part of the plate interface ruptured by the 1952 Tokachi-oki earthquake. This seismic moment is consistent with the result using the teleseismic body wave data of Katsumata and Yamanaka (2006) or that in the Harvard CMT catalog.

We see in Fig. 3 that a tsunami was observed at Urakawa about 110 min after the origin time of the earthquake. The computed tsunami waveform shows that these waves are not a first tsunami wave but later waves. The first tsunami is much smaller and arrives about 50 min before those later and larger tsunamis. The first tsunami at Urakawa was not observable because the amplitude of the wave was smaller than the noise level.

Figure 4 shows the bathymetry off the Hidaka region and snapshots of the computed tsunami at 40, 50, 60, 70, 80, 90, and 100 min after the origin time of the earthquake. Forty minutes following the occurrence of the earthquake, we can see the first tsunami wave refracted around the shallow region off Cape Erimo. The tsunami propagated in the deep sea toward Urakawa becomes much smaller than the tsunami wave propagated in the shallow region off Cape Erimo. At 50 min post-earthquake, the first small wave is close to Urakawa and larger waves are slowly propagated in the shallow region near the cape toward Urakawa. At 60 min post-earthquake, the first wave has already arrived at Urakawa, representing the later large tsunamis propagating toward Urakawa from Cape Erimo. At 70, 80, 90, and 100 min after the earthquake, several larger tsunami waves are propagated from the south of Cape Erimo toward Urakawa, one after another.

These simulations show that due to the presence of Cape Erimo and a large shallow area off the cape, the tsunami wave from the Kushiro earthquake needs to first circumvent the shallow area, subsequently propagating through the deep sea, becoming small, and finally arriving at the west coast of the Hidaka region as a first wave. The larger tsunamis are propagated through the shallow region slowly and arrive at the west coast of the Hidaka as a later tsunami. This type of wave is called the edge wave and is trapped on a continental shelf or slope (Gonzalez *et al*., 1993). The same propagation effect was observed for the tsunami generated by the 2003 Tokachi earthquake (Tanioka *et al*., 2004).

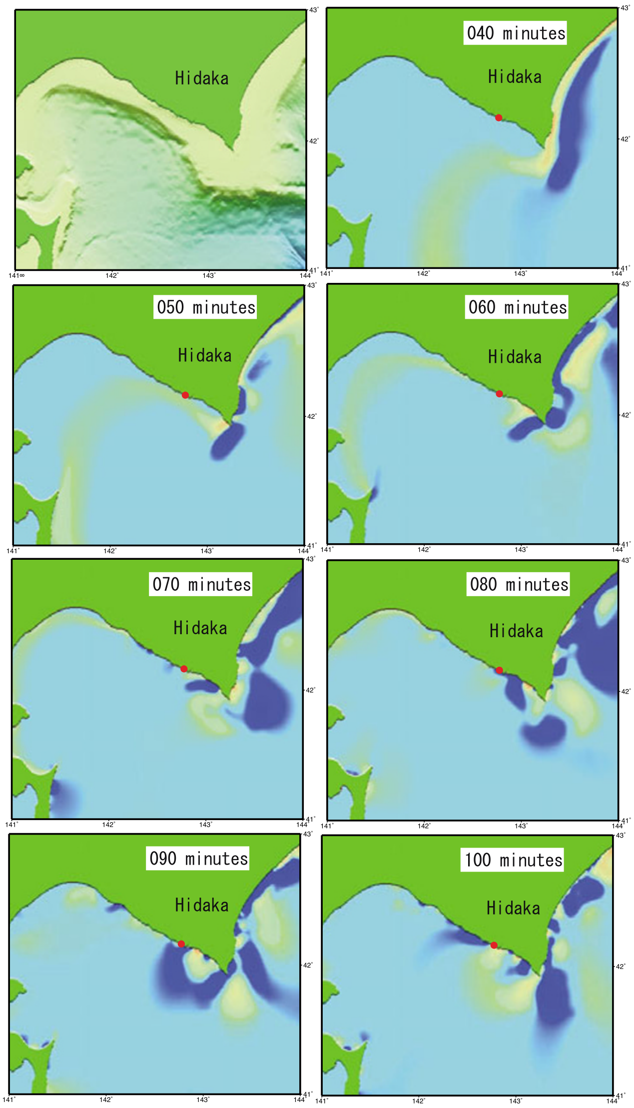

Fig. 4. The bathymetry off the Hidaka region and seven snapshots of the computed tsunami at 40, 50, 60, 70, 80, 90, and 100 min after the origin time of the earthquake. Yellow or red indicate the positive waves, and blue indicates the negative waves.

4. Discussion

In March 2003, the Japanese government made a long-term forecast for large earthquakes along the Kurile trench (Earthquake Research Committee, 2004). The estimated probability of a large earthquake occurring off Tokachi or Nemuro within the next 30 years (starting from March 2003) was reported to be 60% and 20–30%, respectively. Then the 2003 Tokachi-oki earthquake occurred in September of that same year. In this communication, we discuss a future Nemuro-oki earthquake. If the forecast great Nemuro-oki earthquake occurs, large tsunamis will be generated by the earthquake. When the large tsunami propagates toward the west coast of the Hidaka region, the propagation effect near Cape Erimo will be the same as that for the 2004 Kushiro-oki tsunami, although the amplitude of this future Namuro-oki earthquake may be much larger than that of the Kushiro-oki tsunami. We suggest that the large tsunami waves will arrive on the west coast of Hidaka as a later phase. Although the JMA may issue a tsunami advisory or warning along the west coast of the Hidaka with a tsunami arrival time, the tsunami arrival time from JMA is the arrival time of the first wave—not that of the later large tsunami waves. People living in that region have to clearly understand that there is a serious threat of later large tsunamis arriving more than 1 h after the JMA announced arrival time as a result of the future large Nemuro-oki earthquake.

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