Slip distribution of the 2003 Tokachi-oki earthquake estimated from tsunami waveform inversion

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(Received December 3, 2003; Revised February 17, 2004; Accepted February 29, 2004)

The slip distribution of the 2003 Tokachi-oki earthquake is estimated from the 11 tsunami waveforms recorded at 9 tide gauges in the southern Hokkaido and eastern Tohoku coasts and two ocean bottom tsunami-meters (pressure gauges) off Kamaishi, Tohoku. The largest slip of 4.3 m is estimated on the subfault located off Hiroo. A large slip of 2.1 m is also estimated on the subfault located near Kushiro. The total seismic moment of the 2003 Tokachi-oki earthquake is 1.0×10^{21} Nm. The slip distribution estimated from the tsunami waveform inversion is similar to the slip distribution deduced by Yamanaka and Kikuchi (2003) from the inversion of the teleseismic body waves. The rupture area of the 2003 Tokachi-oki earthquake is similar to the western part of the rupture area of the 1952 Tokachi-oki earthquake estimated by Hirata *et al.* (2003).

Key words: The 2003 Tokachi-oki earthquake, slip distribution, tsunami waveform inversion.

1. Introduction

On 26 September 2003, a large Tokachi-oki earthquake occurred off the southern coast of Hokkaido, Japan. Source parameters provided by the Japan Meteorological Agency (JMA) are as follows: origin time, 4:50:07.5 (Japanese Standard Time (JST)); epicenter, 41°46.7′N, 144°04.7′E; the JMA magnitude, M_{JMA} 8.0. The focal mechanism of the earthquake determined by Yamanaka and Kikuchi (2003) indicates the thrust type faulting with a shallow dip angle (strike=230°, dip=20°, rake=109°) (Fig. 1). This earthquake generated large tsunamis causing damage along the southern coast of Hokkaido. A tsunami run-up height survey was conducted immediately after the earthquake (Tanioka *et al.*, 2003). Their results show that the largest tsunami height is about 4 m. The aftershock distribution of this event (Takahashi *et al.*, 2004) shows that the source region of the 2003 event is slightly smaller than that of the 1952 great Tokachi-oki earthquake. The slip distribution of the 2003 Tokachi-oki earthquake was estimated from the inversion of the teleseismic body-waves by Yamanaka and Kikuchi (2003). The tsunami source area of the 2003 Tokachi-oki earthquake was estimated from observed tsunami travel times by Hirata *et al.* (2004)

In this paper, we estimated the slip distribution of the earthquake from tsunami waveform inversion technique using waveforms recorded at tide gauges and ocean bottom tsunami meters. The result is compared with the slip distribution estimated by Yamanaka and Kikuchi (2003) using seismological data. The result is also compared with the slip distribution of the 1952 Tokachi-oki earthquake estimated by Hirata *et al.* (2003) using tsunami waveforms.

2. Data and Method

We used the tsunami waveform data recorded at 9 tide gauge stations, 6 in Hokkaido (Hanasaki, Akkeshi, Kushiro, Hiroo, Tomakomai (East), and Tomakomai (West)) and 3 in Tohoku (Hachinohe, Miyako, and Kamaishi) (Fig. 1). We also used tsunami waveforms recoded at 2 ocean bottom tsunami-meters (OBTMs) deployed at depths of 990 m and 1563 m off Kamaishi (Hino *et al.*, 2001). This study is the first attempt to invert tide gauge and OBTM data together. The tide gauge records were provided by JMA, the Hokkaido Regional Development Bureau of the Ministry of Land, Infrastructure and Transport, and the Hydrographic and Oceanographic Department of the Japanese Coast Guard. The tsunami waveforms at the OBTMs are particularly important because the waveforms are not affected by the complex wave response near the coast as the tide gauge waveforms are.

We divided the source area of the 2003 Tokachi-oki earthquake into 14 subfaults (Fig. 1). The subfault coverage is designed to include both the source area of the 2003 event estimated by Yamanaka and Kikuchi (2003) and the source area of the 1952 Tokachi-oki earthquake estimated by Hirata *et al.* (2003). The subfault size is 40 km × 40 km. The strike of the subfaults is fixed to be 230° as estimated by Yamanaka and Kikuchi (2003). The depth of the shallowest edge and the dip angle and the rake angle of each subfault are shown in Table 1. The locations of the deeper subfaults, 1, 2, 3, 4, 5, 6, 7, and 8, are similar to the location of the fault model for the 2003 Tokachi-oki earthquake applied by Yamanaka and Kikuchi (2003). The locations of the shallower subfaults

Table 1. Subfaults and slip distribution.

Subfault number	Longitude of east edge (E)	Latitude of east edge (N)	Depth of top edge (km)	Dip angle (degree)	Rake angle (degree)	Slip (m)	Std error (m)
1	144°49′	42°37′	39	20	109	2.1	0.1
2	144°27′	42°23′	39	20	109	1.5	0.2
3	144°05′	42°09′	39	20	109	4.3	0.1
4	143°43′	41°55′	39	20	109	0.0	0.0
5	145°07′	42°21′	25	20	109	0.1	0.1
6	144°45′	42°07′	25	20	109	0.0	0.0
7	144°23′	41°53′	25	20	109	1.2	0.1
8	144°01′	41°39′	25	20	109	0.0	0.0
9	145°53′	42°10′	12	6	110	0.0	0.1
10	145°23′	42°05′	14	16	109	0.3	0.1
11	145°01′	41°51′	14	16	109	0.0	0.0
12	146°12′	41°55′	8	6	110	0.0	0.0
13	145°42′	41°49′	10	6	110	0.0	0.0
14	145°20′	41°35′	10	6	110	0.0	0.0

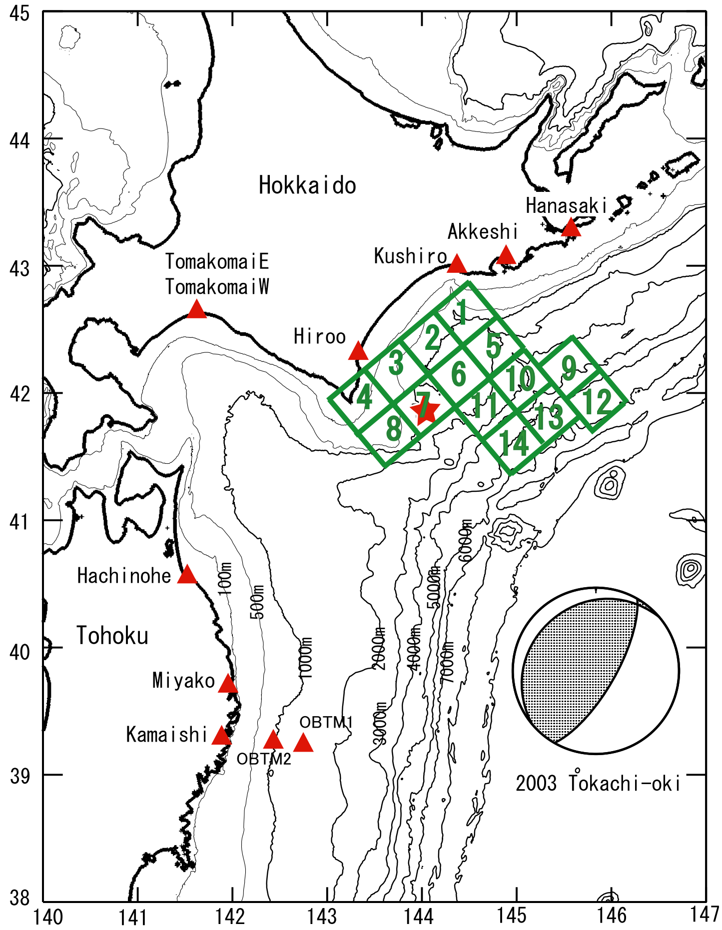

Fig. 1. Map of the source area of the 2003 Tokachi-oki earthquake. Green rectangles show subfaults. Red triangles indicate tide gauges and ocean bottom tsunami-meters where tsunami waveforms are recorded. A red star marks the epicenter of the mainshock. The focal mechanism of the mainshock estimated by Yamanaka and Kikuchi (2003) is also shown.

9, 10, 11, 12, 13, and 14, are close to the subfaults used by Hirata *et al*. (2003).

To calculate the tsunami Green's functions, finite difference approximation of the linear long-wave equations (see Satake, 1995) is computed in the area shown in Fig. 1. The grid size is 20 sec of arc (about 600 m) in deep water; a finer grid (4 sec) is used around the tide gauge stations. The time-step for the computation is 1 s to satisfy a stability condition. The initial condition for tsunami propagation is coseismic ocean bottom displacement, which is computed using the equations of Okada (1985). The rise time of the tsunami initial wave is assumed to be 30 sec. Green's functions for

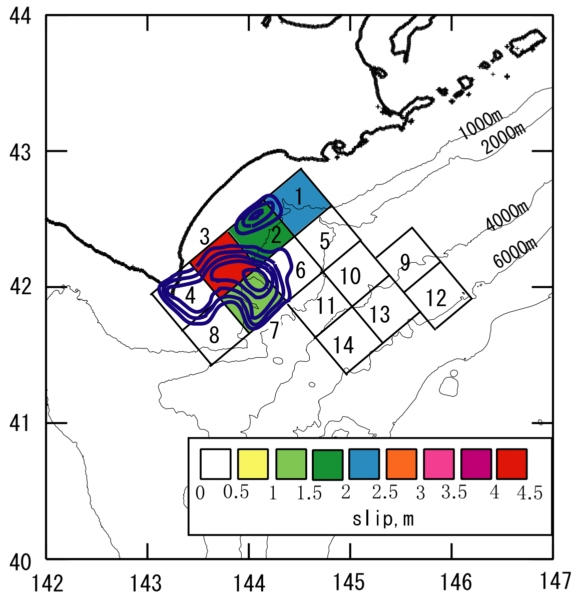

Fig. 2. Coseismic slip distribution of the 2003 Tokachi-oki earthquake estimated from the tsunami waveform inversion. Blue contours designate the slip distribution estimated by Yamanaka and Kikuchi (2003). The contour interval is 1 m.

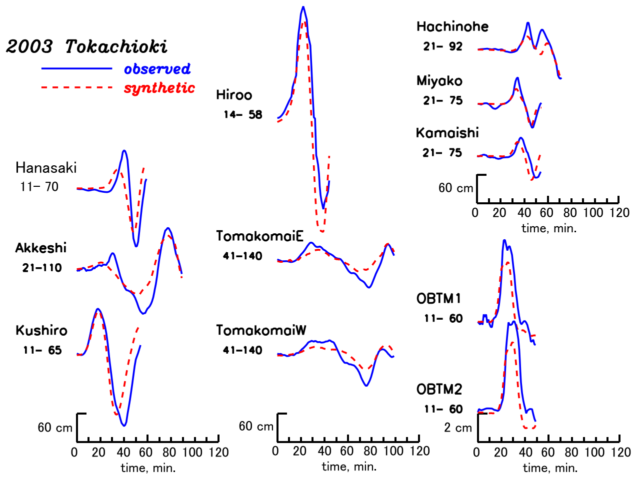

Fig. 3. Comparison of the observed (blue solid lines) and computed (red dashed lines) tsunami waveforms at tide gauges and ocean bottom tsunami-meters (OBTMs). See Fig. 1 for tide gauge and OBTM locations. Numbers below the station name indicate the time (in minutes) after the earthquake origin time.

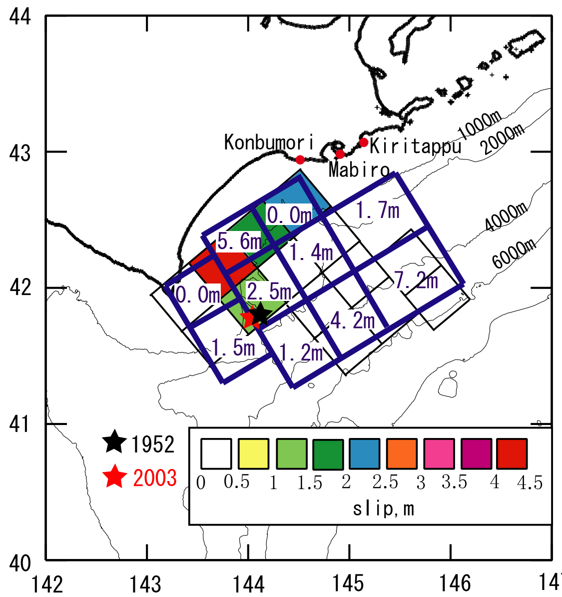

Fig. 4. Comparison of the slip distribution of the 2003 Tokachi-oki earthquake estimated in this study and the slip distribution of the 1952 Tokachi-oki earthquake estimated by Hirata *et al.* (2003). Blue numbers in blue rectangles indicate the slip distribution of the 1952 Tokachi-oki earthquake estimated by Hirata *et al.* (2003). The black star marks the epicenter of the 1952 Tokachi-oki earthquake. The red star marks the epicenter of the 2003 Tokachi-oki earthquake.

the 11 stations are computed for each subfault with a unit amount of slip. This method of tsunami inversion is the same as Tanioka and Satake (2001). For error analysis, the jackknife technique (Tichelaar and Ruff, 1989) is applied.

The tsunami waveform records for each tide gauge and OBTM are 45 to 100 minutes in length with a sample interval of 1 minute. The tsunami amplitudes observed at the OBTMs in the deep ocean off Kamaishi are much smaller than those observed at tide gauges on the coast. However, the tsunami waveforms at the OBTMs have more direct information of the source than those at tide gauges suffering from complex wave effects from the nearshore bathymetry. Therefore, we need to weight the OBTM data for the tsunami waveform inversion in order to treat the OBTM data as significant as the tide gauge data. The peak to trough tsunami amplitudes at tide gauges in Hanasaki, Akkeshi, and Kushiro are 204 cm, 182 cm and 249 cm, respectively, but the peak to trough amplitudes at two OBTMs are only 6.7 cm and 6.9 cm. The OBTM data are weighted 30 times for the inversion, so the peak to trough amplitudes at the OBTMs is treated as 201 cm and 207 cm for the inversion, respectively. This means that the OBTM waveforms are treated as significant for the inversion as the waveforms at three tide gauges in Hanasaki, Akkeshi and Kushiro.

3. Slip Distribution

The result of the tsunami waveform inversion is shown in Fig. 2 and Table 1. The largest slip of 4.3 m is estimated on subfault 3 located off Hiroo. The largest slip of 2.1 m is also estimated on subfault 1 located near Kushiro. The slip of 1.5 m is estimated on subfault 2 located between subfault 1 and 3. The slip of 1.2 m is estimated on subfault 7 located southeast side of subfault 3. On the subfaults located southeast of the source area (subfault 9, 10, 11, 12, 13, 14), the slip amount is less than 0.3 m. Essentially, those subfaults located south-east of the source area are not ruptured by the 2003 Tokachi-oki earthquake. The slip distribution estimated in this study is similar to the slip distribution estimated by Yamanaka and Kikuchi (2003) using teleseismic data (Fig. 2) although they estimated the maximum slip of 5.8 m within subfault 7 and a large slip of more than 3 m within subfault 4. The total seismic moment is calculated to be 1.0. $\times$ 10^{21} Nm (Mw 8.0) by assuming that the rigidity is 6.5 $\times$ 10^{10} N/m^2. This seismic moment is the same as the seismic moment estimated by Yamanaka and Kikuchi (2003). The observed and computed tsunami waveforms are compared in Fig. 3. The observed tsunami waveforms are well matched by the computed tsunami waveforms. The variance reduction for the inversion is 74%, and the correlation coefficient between the observed and computed waveforms is 0.86.

4. Comparison of the 1952 and 2003 Tokachi-oki Earthquakes

The slip distribution of the 2003 Tokachi-oki earthquake estimated in this study is compared with the slip distribution of the 1952 Tokachi-oki earthquake estimated by Hirata *et al.* (2003) (Fig. 4). Two slip distributions of the 2003 and 1952 earthquakes are clearly different. For the 1952 Tokachi-oki earthquake, the largest slip was estimated on the south-east part of the source area, but almost no slip occurred on that part of the plate interface during the 2003 Tokachi-oki earthquake.

Ichiyanagi *et al.* (2004) compared the aftershock area of the 2003 Tokachi-oki earthquake with that of the 1952 Tokachi-oki earthquake. They show that the aftershock area of the 1952 Tokachi-oki earthquake extended east of the aftershock area for the 2003 Tokachi-oki earthquake. In addition, Tanioka *et al.* (2003) demonstrated that the tsunami height distribution of the 2003 Tokachi-oki earthquake was clearly different from that of the 1952 Tokachi-oki earthquake. The large tsunami heights, 4 m to 7 m, were observed between Kombumori and Kiritappu for the 1952 Tokachi-oki earthquake. However, the tsunami heights observed in the same region for the 2003 Tokachi-oki earthquake were less than 2 m except at Mabiro, where a large tsunami height of 4 m was locally observed. Yamanaka and Kikuchi (2003) estimated the slip distribution of the 2003 Tokachi-oki earthquake and also the slip distribution of an initial part of the 1952 Tokachi-oki earthquake by analyzing the nearby strong motion seismograms. The later part of the source processes of the 1952 Tokachi-oki earthquake was not estimated because waveforms of the strong motion seismograms went off-scale soon after the S-wave arrivals. They concluded that the slip distribution of the 2003 Tokachi-oki earthquake was almost the same as that of the initial part of the 1952 Tokachi-oki earthquake.

Those data, including slip distributions estimated from tsunami waveforms, aftershock distributions, tsunami run-up height distributions, and slip distributions estimated from seismic waveforms, suggest that the rupture processes of the 2003 Tokachi-oki earthquake was similar to the western part of the rupture processes of the 1952 Tokachi-oki earthquake. The 2003 Tokachi-oki earthquake did not continue to the south-east as in the 1952 earthquake probably because not enough strain has been accumulated in this part of the subduction zone since the 1952 rupture.

5. Conclusions

The slip distribution of the 2003 Tokachi-oki earthquake was estimated from the tsunami waveforms recorded at nine tide gauges and two OBTMs. The largest slip of 4.3 m was estimated on the subfault located off Hiroo. The large slip of 2.1 m was also estimated on the subfault located near Kushiro. The slip distribution estimated in this study was similar to that estimated by Yamanaka and Kikuchi (2003) using the teleseismic body waves. The rupture process of the 2003 Tokachi-oki earthquake is similar to the western half of the rupture processes of the 1952 Tokachi-oki near where both ruptures initiated. However, the 2003 Tokachi-oki earthquake did not rupture the south-east rupture area of the 1952 Tokachi-oki earthquake estimated by Hirata *et al.* (2003).

Acknowledgments. We would like to thank the Japan Meteorological Agency, the Hokkaido Regional Development Bureau of the Ministry of Land, Infrastructure and Transport, and the Hydrographic and Oceanographic Department of the Japan Coast Guard for providing us the digital tide gauge data. The article was significantly improved through constructive reviews by Eric L. Geist and an anonymous reviewer. This work was partially supported by Special Coordination Funds for Promoting Science and Technology, from the Ministry of Education, Sports, Culture, Science and Technology.

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