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RAPID SOURCE PARAMETER ESTIMATION OF GREAT EARTHQUAKES FOR TSUNAMI WARNING

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ABSTRACT: One of major problems in the tsunami warning for the 2011 off the Pacific coast of Tohoku Earthquake (*M*w 9.0) was a lack of awareness of underestimation of the earthquake magnitude at the time soon after the occurrence. Displacement magnitude, which is usually used for the first tsunami warning a few minutes after the earthquake occurrence, could not evaluate such large magnitude. Seismic moment could not be determined from the regional seismological network data due to over range of broadband sensor outputs. To overcome these difficulties in earthquake magnitude estimation, several methods are being developed to estimate proper magnitude roughly and to understand possible magnitude underestimation soon after such large earthquakes.

Key Words: rapid magnitude determination, great earthquakes, tsunami warning, area of strong shaking, strong motion duration

INTRODUCTION

The tsunami height of the first tsunami warning by Japan Meteorological Agency (JMA) is estimated based on earthquake magnitude. The first tsunami warning should be issued within a few minutes after the detection of the earthquake occurrence. Displacement magnitude (Katsumata, 2004) is used for the first tsunami warning. Seismic moment tensor is also estimated after the first tsunami warning to estimate size of the earthquake more accurately (Usui *et al.*, 2010). The tsunami height estimation is updated from data including the seismic moment tensor and sea level observations. At the time of the occurrence of the 2011 off the Pacific coast of Tohoku Earthquake (*M*w 9.0), the magnitude was not estimated properly due to too short cutoff period (six seconds) of the filter for the displacement magnitude compared with the rupture duration (about three minutes [Yoshida *et al*., 2011a]). Seismic moment could not be estimated from the regional seismological network data due to over-range of broadband sensor (STS-1 and STS-2) outputs, and it took longer time to estimate it from global data. These caused a lack of awareness of underestimation of the earthquake magnitude at the time soon after the occurrence.

To overcome these difficulties in earthquake magnitude estimation, we are developing several methods to estimate proper magnitude roughly and to understand possible magnitude underestimation soon after such large earthquakes. A large earthquake causes strong shaking in a wide area, long strong motion duration, and large seismic amplitude in long period range as well as in short period range. These observations could be used for the magnitude estimation.

MAGNITUDE DETERMINATION FROM SPAN OF STRONG MOTION AREA

Large earthquakes cause strong motion in a wide area. Span of strong-motion area is related to earthquake magnitude. Seismic intensity distribution in Japan can be known in a few minutes after earthquake occurrence owing to a dense on-line network of seismic intensity meter in Japan. It is possible to estimate earthquake magnitude roughly from the area of strong shaking.

Figure 1 shows the distributions of seismic intensity of the 2011 off the Pacific coast of Tohoku Earthquake (*M*w 9.0) and the 2003 Off-Tokachi Earthquake (*Mw* 8.0). The span of 5-lower or the greater of the JMA seismic intensity scale of the 2011 off the Pacific coast of Tohoku Earthquake reached about 700 km. The span of the 2003 Off-Tokachi Earthquake was about 300 km, which was much less than that of the 2011 off the Pacific coast of Tohoku Earthquake.

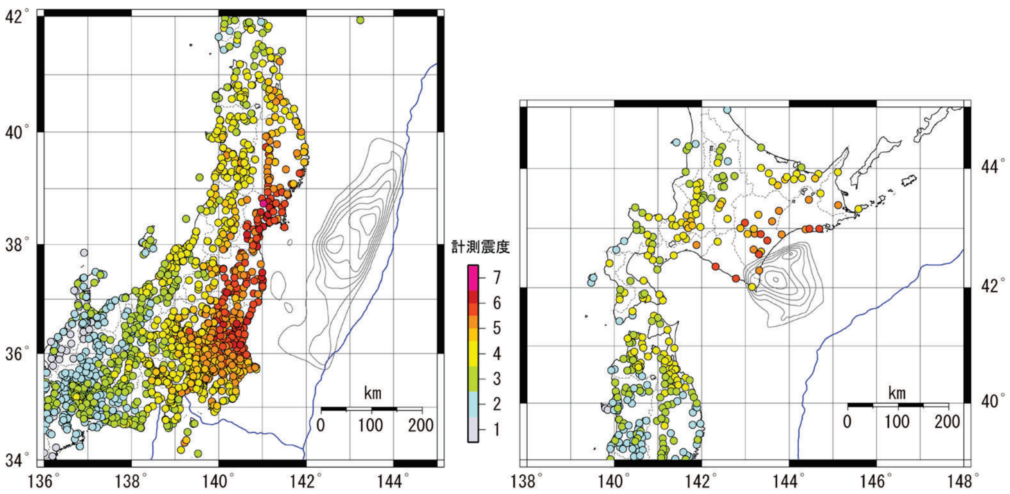

Fig. 1. Distributions of seismic intensity of the 2011 off the Pacific coast of Tohoku Earthquake and the 2003 Off-Tokachi Earthquake. The contours in maps denote slip distributions estimated by Yoshida (2005) and Yoshida *et al*. (2011a).

SOURCE AREA ESTIMATION FROM SEISMIC INTENSITY DISTRIBUTION

The place of observed strong motion would be close to the seismic source. Source area can be estimated from the area of strong-motion. At each station, distance from the fault is estimated from the seismic intensity with the formula by Si and Midorikawa (1999). To estimate the source area, grid points are set on the plate boundary. At each grid points, number of stations where the distance between the station and the grid point is larger than the estimated fault distance is counted. If the grid point is on the source area, the number of inconsistent stations (where the distance between the station and the grid point is larger than the estimated fault distance) should not exceed some number. Figure 2 shows the estimated source area of the 2011 off the Pacific coast of Tohoku Earthquake and the 2003 Off-Tokachi Earthquake from the number of the inconsistent stations. Whereas it is possible to estimate the close edge of a fault with this method, it is difficult to estimate the far edge of an offshore fault properly. A different color map is used for the area off the trench axis in Figure 2. When the seismic fault lies along the island arc, like the 2011 off the Pacific coast of Tohoku Earthquake, it is able to estimate length of the fault.

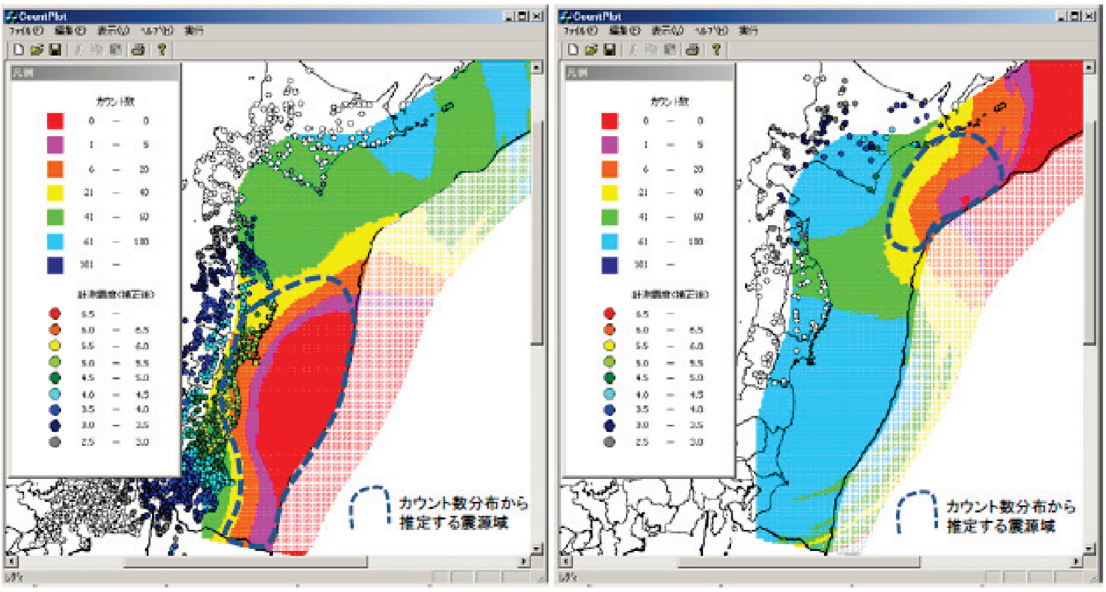

Fig. 2. Estimated source area of the 2011 off the Pacific coast of Tohoku Earthquake and the 2003 Off-Tokachi Earthquake from seismic intensity distribution [Yokota and Kaida, 2011].

DURATION OF STRONG MOTION

The duration of the strong motion becomes also longer for larger earthquakes. Durations of strong motion were investigated for large earthquakes in and around Japan.

Figure 3 shows distribution of strong-motion durations for the 2003 Off-Tokachi Earthquake. The colors denote strong-motion duration at stations. Data from K-NET [Kinoshita, 1998] and KiK-net [Aoi *et al*. 2000] is used for this analysis. The durations in the north of the epicenter are shorter than those in the other directions in the figure. The duration difference is considered due to directivity effect. Figure 4 shows azimuthal distribution of the duration, which shapes a sinusoidal curve. It is possible to estimate fault length and rupture direction from the distribution (Izutani and Hiraswa, 1987). The arrow in Figure 3 indicates estimated fault length and rupture direction. When the faulting is simple unilateral, this method is useful for rapid estimation of the fault parameters.

Figure 5 shows relationship between moment magnitude and strong-motion duration of earthquakes which occurred in and around Japan. Good correlation is seen between strong-motion duration and earthquake magnitude. The duration of the earthquake in March, 2011 exceeded eighty seconds, which was the longest among those of the large earthquakes. It is difficult to estimate the accurate moment magnitude on the basis of the duration due to the large scatter. We can, however, judge possible magnitude underestimation by the duration.

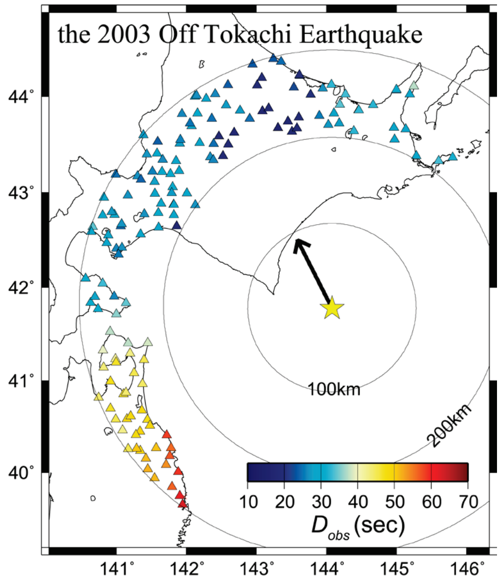

Fig. 3. Distribution of strong-motion duration of the 2003 Off-Tokachi Earthquake [Aoki *et al.*, 2011]. The star indicates the epicenter of the earthquake, and the arrow indicates estimated fault length and rupture direction by the method of Izutani and Hirasawa (1987).

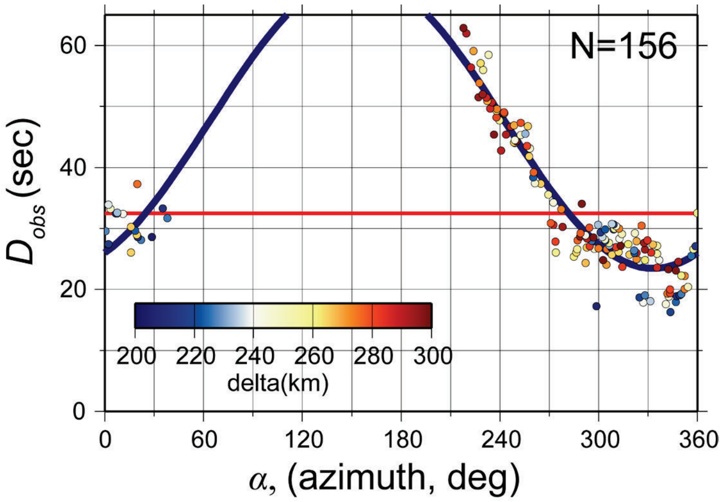

Fig. 4. Azimuthal distribution of strong-motion duration of the 2003 Off-Tokachi Earthquake [Aoki *et al.*, 2011]. Blue curve indicates the theoretical distribution of the estimated fault.

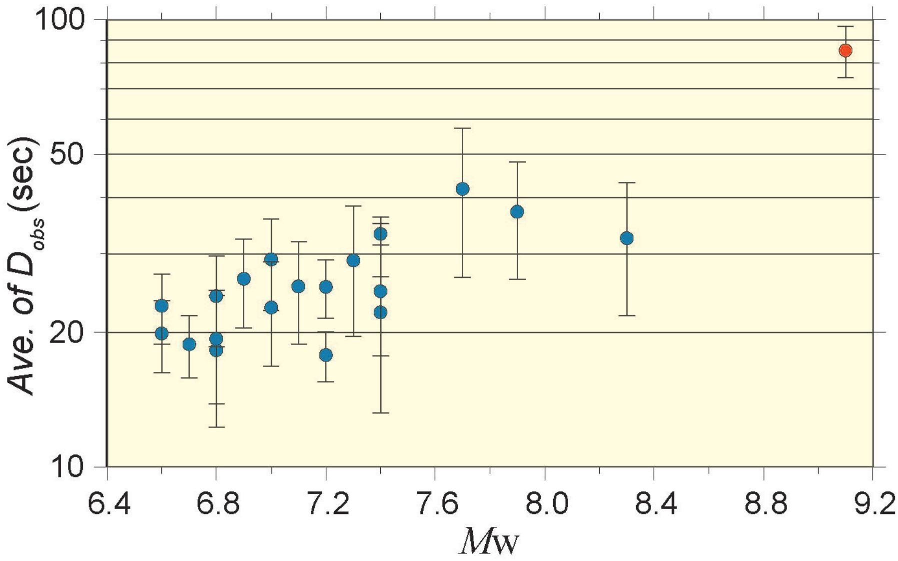

Fig. 5. Relationship between moment magnitude (after the Global CMT Project) and strong-motion duration D_{obs} of earthquakes which occurred in and around Japan [Aoki, *et al*., 2011]. The red circle denotes that of the 2011 off the Pacific coast of Tohoku Earthquake.

MAGNITUDE ESTIMATION FROM P-WAVE

Some magnitude determination methods from P-wave have been proposed. Yoshida (1995) proposed a magnitude determination method from P-wave displacement amplitude, *Mp*. Figure 6 shows the station magnitude *Mp* of the 2011 off the Pacific coast of Tohoku Earthquake. The horizontal axis of Figure 6 denotes time of magnitude determination from the origin time of the earthquake which corresponds to S-wave arrival time at the station. The magnitude grows before about four minutes. This reflects the extension of the rupture area.

Tsuboi *et al.* (1995) developed a method of estimating moment magnitude, *Mwp*, from integrated P-wave. Figure 7 shows the magnitude *Mwp* of the 2011 off the Pacific coast of Tohoku Earthquake.

Ogawara *et al*. (2004) showed a magnitude determination method, *Mwliss*, based on squared amplitude of broadband seismic wave. Figure 8 shows the magnitude *Mwliss* of the 2011 off the Pacific coast of Tohoku Earthquake.

These magnitudes show similar variation along the time from the origin time, and reach about nine in five minutes. It is possible to determine the magnitude of this earthquake properly in five minutes with these methods. Dispersion of *Mwp* is smaller compared with other P-wave magnitudes.

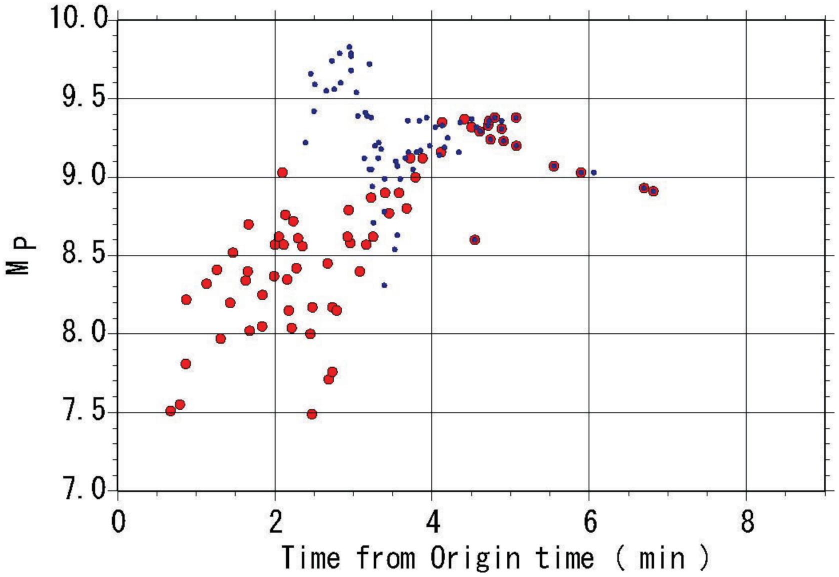

Fig. 6. *Mp* of the 2011 off the Pacific coast of Tohoku Earthquake (*M*w 9.0) [Yoshida *et al.*, 2011b]. The red circle denotes station magnitude calculated from seismic wave between P and S arrivals at each station. The blue small dot denotes that calculated from seismic wave contaminated with S-wave. The horizontal axis shows the time when the magnitude is estimated at each station measured from the origin time.

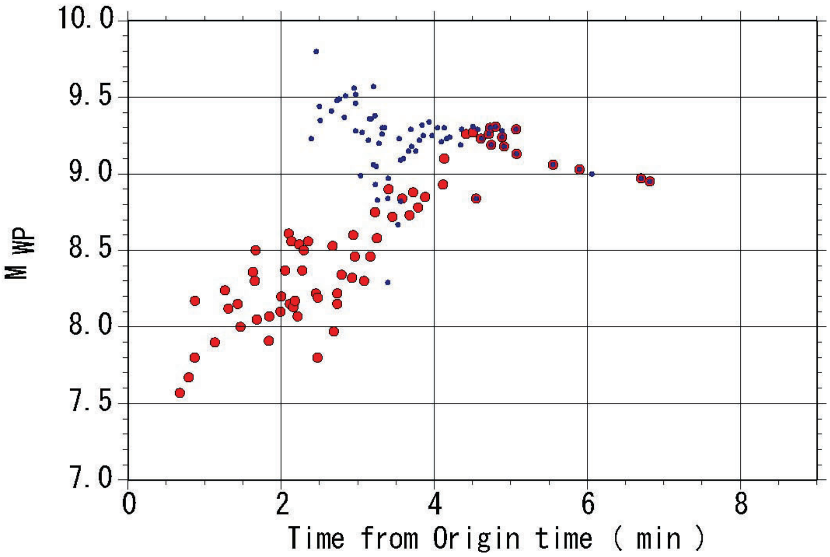

Fig. 7. *Mwp* [Tsuboi *et al.*, 1995] of the 2011 off the Pacific coast of Tohoku Earthquake [Yoshida *et al.*, 2011b]. The symbols are the same as those in Figure 6.

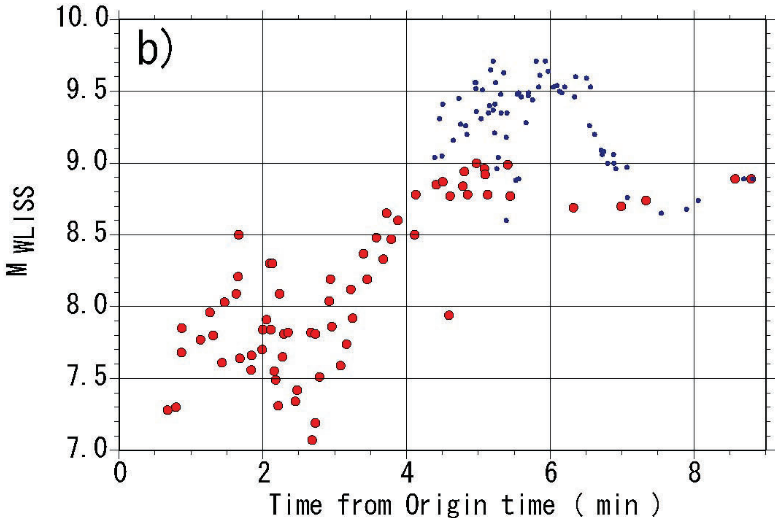

Fig. 8. *Mwliss* [Ogawara *et al*., 2004] of the 2011 off the Pacific coast of Tohoku Earthquake [Yoshida *et al*., 2011b]. The symbols are the same as those in Figure 6.

MAGNITUDE DETERMINATION FROM LONG-PERIOD SEISMIC WAVE

It takes a long time to complete a rupture of a large earthquake. Excitation of long-period seismic wave is one of features of large earthquakes. The cutoff period (6 s) for the displacement magnitude used for the first tsunami warning was too short for the 2011 off the Pacific coast of Tohoku Earthquake. Usage of long period components of seismic wave would help to estimate earthquake magnitude properly.

Figure 9 shows seismic waves processed with filters of different frequency responses. The figure shows seismic waves of the 2011 off the Pacific coast of Tohoku Earthquake (the left) and the 2003 Off-Tokachi Earthquake (the right). The upper of the figure shows seismic waves with the same response for the displacement magnitude. The lower shows those processed with a filter of 200-1000 second pass-band. While amplitudes of short-period seismic wave are not so different between the two earthquakes, those of long-period seismic wave differ very much. This is one method to distinguish the difference of these magnitudes.

Magnitude determination methods from various frequency ranges are developed. Peak displacements of seismic waves of 1, 2, 5, 10, 20, 50 and 100 second cutoff periods are used to determine magnitude. Phase type is not cared in this method, and peaks are possibly those of S-waves. Figure 10 shows estimated durations to determine magnitude only from P-wave and from S-wave. It is necessary to wait for the completion of fault rupture to get enough length of data. At a station close to source area, S-P time would be shorter than the rupture duration. It is considered that magnitude determination from S-wave peak is more rapid than that only from P-wave peaks when local seismic data are available. Figure 11 shows growth of the magnitude with time from the origin time on the horizontal axis. The averaged magnitudes calculated from closest ten stations are shown in the figure. The magnitudes from long-period seismic wave reach the final values within three minutes for the earthquake.

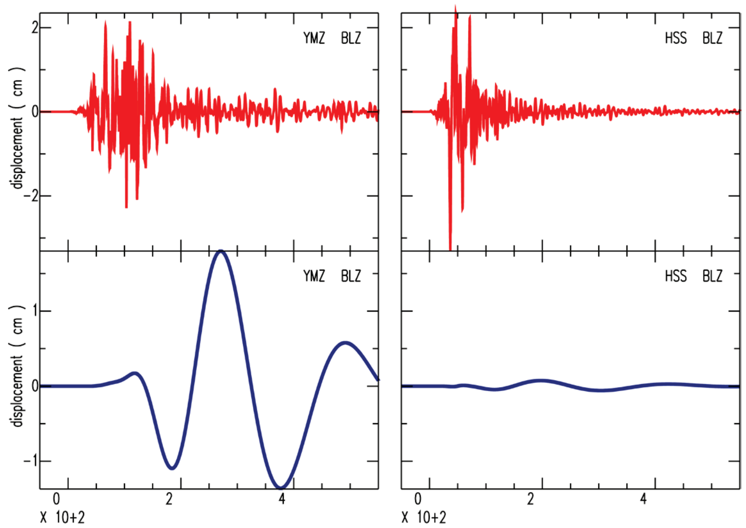

Fig. 9. Filtered Seismic waves of the 2011 off the Pacific coast of Tohoku Earthquake (the left) and the 2003 Off-Tokachi Earthquake (the right) [Yoshida *et al.*, 2011b]. The upper shows seismic waves for the displacement magnitude used for the tsunami warning, and the lower shows those processed with a filter of a 200-1000 second pass-pand.

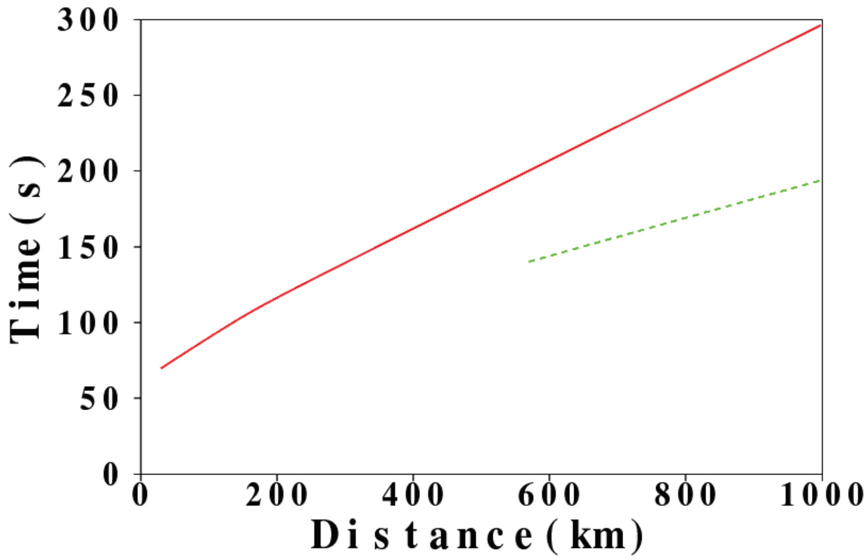

Fig. 10. Assumed time to estimate earthquake magnitude from P-wave (the green broken curve) and S-wave (the red solid curve) [Katsumata *et al.*, 2011]. The curves indicate relationships between epicentral distance and sum of travel time and assumed rupture duration. Sixty seconds is assumed as the rupture duration here.

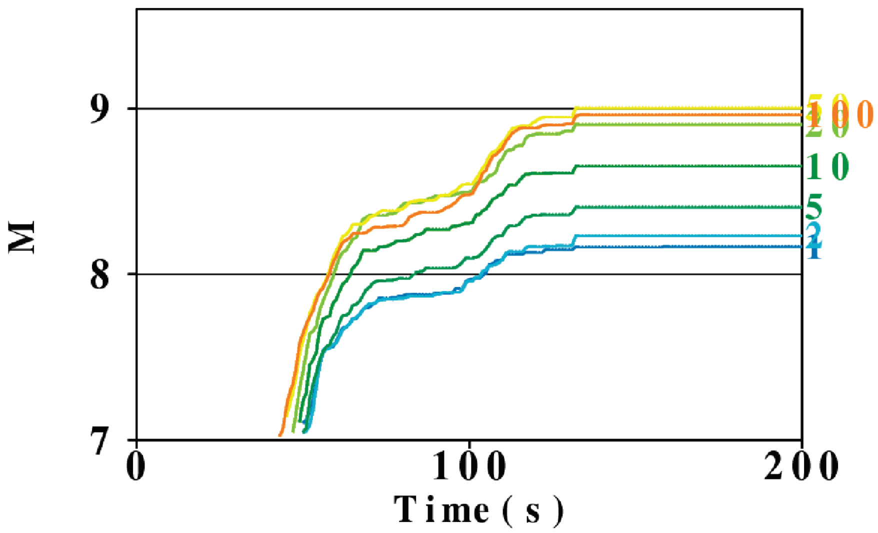

Fig. 11. Growth of magnitude from seismic waves of various cutoff-periods [Katsumata *et al*., 2011]. The horizontal axis shows time from the origin time of the earthquake. The numerals indicate cutoff periods of the filters.

CONCLUSIONS

Several magnitude determination methods are being developed to estimate earthquake magnitude soon after occurrence of a large earthquake for tsunami warning. Magnitude estimation from span of strong-motion area, strong-motion duration, P-wave, and S-wave amplitudes were examined. Combination of these methods is expected to help us to issue a proper tsunami warning for the next great earthquake.

ACKNOWLEDGMENTS

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