Estimation of extended source area from vertical PGA saturation during a great earthquake for upgrading the EEW system

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SUMMARY:
The present JMA Earthquake Early Warning system has some difficulties that the predicted seismic intensities might be underestimated in comparison with the observed ones for great earthquakes because seismic intensities are calculated assuming a point source. We proposed a methodology for estimating the rupture extent from vertical PGA before main motions of S waves are arriving when great earthquakes happen. The vertical PGAs at non-observation sites outside the source extent are calculated using the empirical attenuation-distance relationship of the vertical PGAs and shortest distances from sites to the source fault without determining seismic magnitude. The seismic intensities there are estimated using the empirical relationship between vertical PGA of P wave motions and seismic intensity. We estimated the seismic intensity during 2011 Tohoku earthquake using this method. As a result, the calculated seismic intensities agreed well with the observed ones at stations around the epicenter and far from epicenter.

Keywords: the Earthquake Early Warning, assumed rupture extend, vertical PGA

1. INTRODUCTION

The earthquake early warning (EEW) system was developed by Japan Metrological Agency (JMA) and was launched nationwide in October 2007. The goal of the early warning system is to provide the maximum expected seismic intensity and the earliest S-wave arrival time in each subprefectural area (about a quarter to a third of one prefecture) before the strong motion arrival (Kamigaishi et al., 2009).
This system had its first true test on March 11, 2011, during the M9 Tohoku earthquake off the Pacific coast of northeastern Japan. The system issued a warning before the S-wave arrived onshore, a great achievement for the seismological community in Japan. It looked successful, but exposed severe difficulty at the same time (Hoshiba et al., 2011).
The EEW system by JMA provides source information consisting of the hypocenter coordinate, the origin time and the magnitude of target earthquakes based on a point source assumption. The seismic intensity at each site is calculated by using an attenuation distance relation and site amplification from the magnitude and hypocentral distance provided from the EEW. Therefore, there is high possibility that the predicted seismic intensity is underestimated in comparison with the observed one for great earthquakes.
The calculated seismic intensity distribution during the assumed Tonankai earthquake whose hypocenter is Shionomisaki-oki by Central Disaster Prevention Council (2003) is shown in Figure 1. Figure 1 (a) shows result calculated by EEW. Figure 1 (b) shows result calculated by predicted strong motion. The calculated seismic intensity by EEW is lower than the calculated seismic intensity by predicted strong motion in Aichi Prefecture. It is caused to the fact that the attenuation-distance relationships of PGV and PGA for such earthquakes are well expressed as a function of not epicentral distance but shortest distance from site to source fault.
We have found that the attenuation-distance relationships of both horizontal and vertical PGAs tend to have some saturation near the source faults during large inland earthquakes more than Mw 6.5 using the strong motion data from the K-NET and KiK-net data by the National Research Institute for Earth

Science and Disaster Prevention (NIED) in Japan. We have also found that the time of the saturation of the vertical PGA is generally earlier than that of the horizontal PGA. Based on the above results, we can provide the information about the rupture extension before the arrival of the main motions (Kurahashi et al., 2011).
We examined the saturation of the vertical PGAs near the source of the 2011 Tohoku earthquake. In this study, we try to check the applicability of our methodology to the EEW information for megathrust earthquakes.

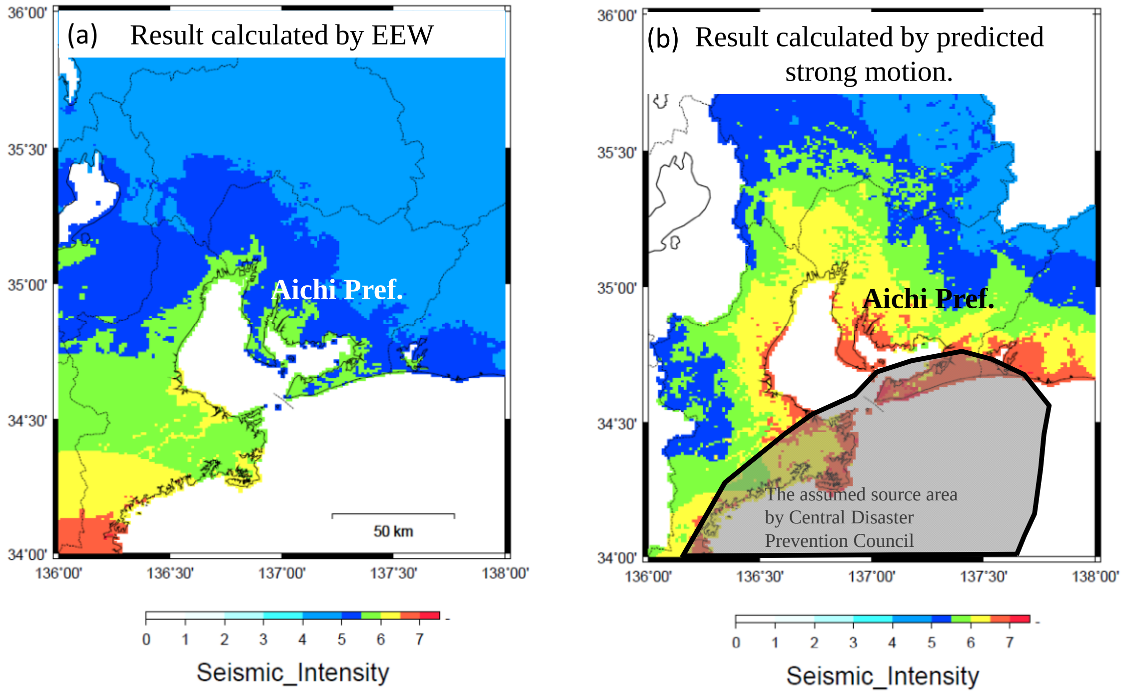

Figure 1. Calculated seismic intensity distribution during the assumed Tonankai earthquake whose hypocentre is Shionomisaki-oki by Central Disaster Prevention Council (2003). (a) Result calculated by EEW. (b) Result calculated by predicted strong motion.

2. ESTIMATION OF RUPTURE EXTENT FROM VERTICAL PGA

The present EEW system is not fully available for megathrust earthquakes. The problems come from the assumption of a point source for estimating seismic magnitude and then the estimation of seismic intensity based on the attenuation-distance relations without rupture extent. Ground motions are not generated from a point but source area especially for large earthquakes. Kurahashi et al. (2009) tried to obtain range of the rupture areas of large earthquakes from observed records using the attenuation-distance relationship of the maximum amplitudes of P wave motions without assuming the point sources.
The attenuation-distance relationships of peak ground acceleration (PGA) and peak ground velocity (PGV) of S wave motions have a certain saturation level near the fault distance as well known (e.g. Fukushima and Tanaka, 1990; Si and Midorikawa, 1999). The range of this saturation might be related to length of the rupture area of the large earthquake. They found that the attenuation-distance relationship of peak ground acceleration (PGA) and peak ground velocity (PGV) of P wave motions also has certain saturation near the fault distance as well as the S wave motions using 2004 Chuetsu earthquake (Mw6.6) and 2008 Iwate-Miyagi nairiku earthquake (Mw6.9) as shown in Figure 2. For the EEW system, the PGAs of vertical components of P wave are best because the saturation of the PGAs appears earlier than that of the PGVs.
Further, they examined the attenuation-distance relationship of the PGAs of P wave motions in which site effects were excluded at each site for 4 inland earthquakes. The saturation levels of the PGAs of P wave motions are about 200 gals, independent of seismic magnitude, as shown in Figure 3. They find

that the PGAs of P wave motions for such great large earthquakes have also a certain saturation level as well, as long as all portions of vertical components before the main S wave motions are used.
We can obtain seismic magnitude from the diameter of the saturation area of the PGAs of P wave motions. Moreover, the information about the saturation area is useful for estimating the seismic intensity distribution considering the source areas of great earthquakes.
On the other hand, the attenuation-distance relationship of observed vertical PGAs during 2011 Tohoku earthquake is shown in Figure 4. We adopt the geometry of the source-fault model based on the aftershock distribution in the first 24 hours by Japan Meteorological Agency (JMA) the JMA to calculate shortest distance from each station to the source fault. The attenuation-distance relationship of observed PGAs of vertical motions seems to be similar to those of horizontal S-wave ones, although the saturation levels are different between vertical and horizontal motions. There are some stations where exceptionally large accelerations were observed near the rupture area. This is caused to local site effects, i.e. amplifications due to surface layers related to P wave velocities. The saturation level of the vertical PGA in Figure 4 is about 200 – 300 gals, a little larger than the saturation level for the inland earthquake so far done.
We evaluated the rupture extent of this earthquake assuming that the saturation level is 250 gals. The seismic intensities at sites outside the assumed rupture zone are estimated using the empirical attenuation-distance relationship as a function of distance from the edge of the rupture zone.

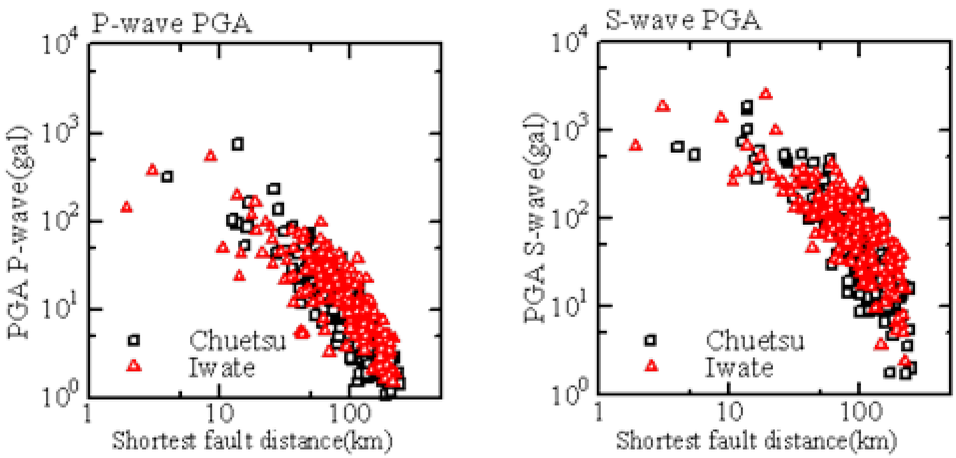

Figure 2 The attenuation-distance relationship of observed PGAs P-wave and S-wave using 2004 Chuetsu earthquake (Mw6.6) and 2008 Iwate-Miyagi Nairiku earthquake (Mw6.9).

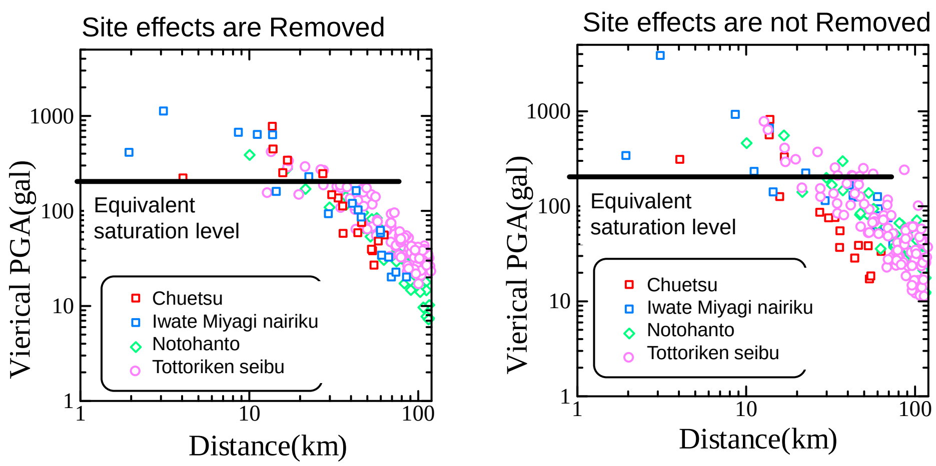

Figure 3 The attenuation-distance relationship of vertical PGA using 4 inland earthquakes. (a):vertical PGA by removing the site amplification from the observed vertical PGA. (b) vertical PGA by not removing the site amplification from the observed vertical PGA.

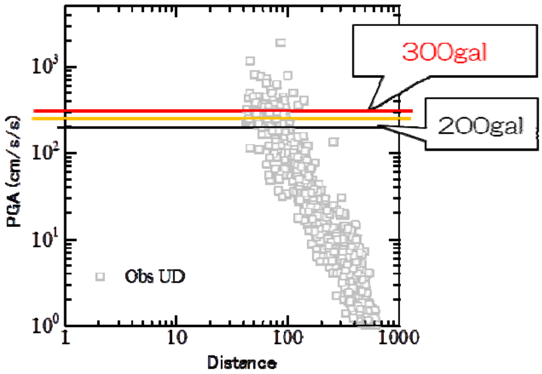

Figure 4. The attenuation-distance relationship of observed vertical PGAs during 2011 Tohoku earthquake.

3. PROCEDURE OF ESTIMATING SEISMIC INTENSITY FOR THE EEW

Procedure of calculating seismic intensity for the EEW is illustrated in Figure 5.
(1) The extent of the source fault is determined from the distribution of stations in which vertical PGAs of more than 250gal (in case of 2011 Tohoku earthquake) are observed. (2) The vertical PGAs at non-observation sites outside the source extent are calculated using the empirical attenuation-distance relationship of the vertical PGAs and shortest distances from sites to the source fault. (3) The seismic intensities there are estimated using the empirical relationship between vertical PGA of P wave motions and seismic intensity.

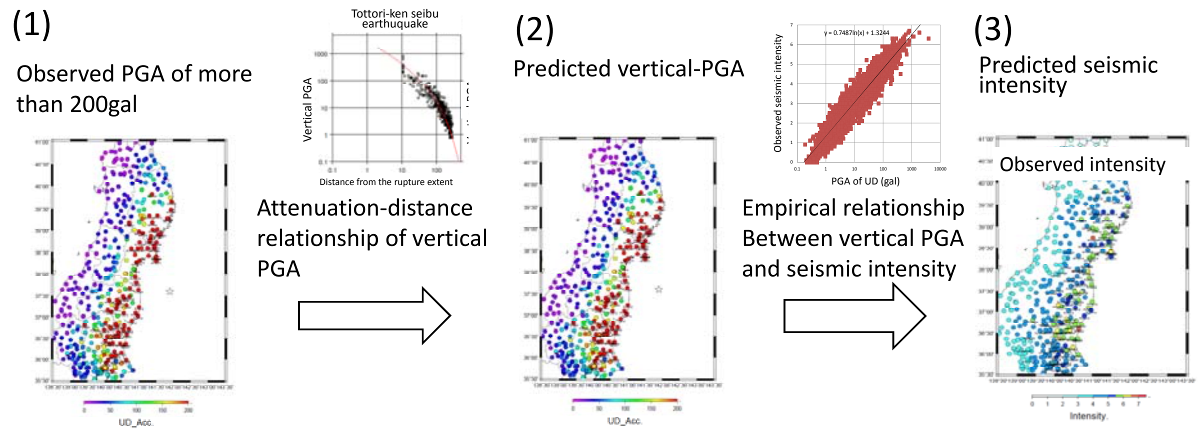

Figure 5 Illustrative procedure of obtaining predicted seismic intensity at each site.

4. VERIFICATION OF VALIDITY AND RELIABILITY OF THIS METHOD

4.1. COMPARISON BETWEEN SOURCE EXTENT ESTIMATED FROM SATURATION OF VERTICAL PGA AND RUPTURE AREA FROM INVERTED SOURCE MODEL

Rupture area obtained from the waveform inversion of strong motion data is related to seismic moment for inland earthquakes in Figure 6 (b) and for subduction-zone earthquakes in Figure 6 (c). We compared the relation between the rupture extent estimated from the saturation area of the vertical PGA and seismic moment with the empirical relationship for subduction-zone earthquake. The rupture extent from the saturation area was estimated in the following procedure.
First, we define an area inside which observed vertical-PGAs are beyond 200 gals at two adjacent stations as rupture extent. The length of the rupture extent was presumed as a line connecting both endpoints where vertical PGAs are over 250 gal. The width of the rupture extent is presumed to be 15 to 18 km for inland earthquakes taking account the thickness of seismogenic-zones. On the other hand,

the width is presumed to be half of the length for the subduction-zone earthquake, respectively. We estimated the rupture extents for five inland earthquakes (2000 Tottoriken-seibu, 2004 Chuetsu, 2005 Fukuokake-seihouoki, 2007 Notohanto and 2008 Iwate Miyagi nairiku earthquake) and for two subduction zone earthquakes (2003 Tokachi-oki and 2011 Tohoku earthquake).

An example of the length of the rupture area estimated from the vertical PGA at stations during the 2011 Tohoku earthquake was shown in Figure 6(a). The length of the rupture area for this earthquake is about 450 km. The relationship between the seismic moment and rupture area for inland crustal earthquakes by Matsushima et al. (2010), including the five earthquakes, are summarized as shown Figure 6(b). The relationship between the seismic moment and rupture area for subduction-zone earthquakes by Murotani et al. (2008), including the two earthquakes, are summarized as shown Figure 6(c). The rupture areas estimated from vertical PGAs agree well with the ruptures from the empirical relationship between seismic moments and rupture area within 1 standard deviation (sigma).

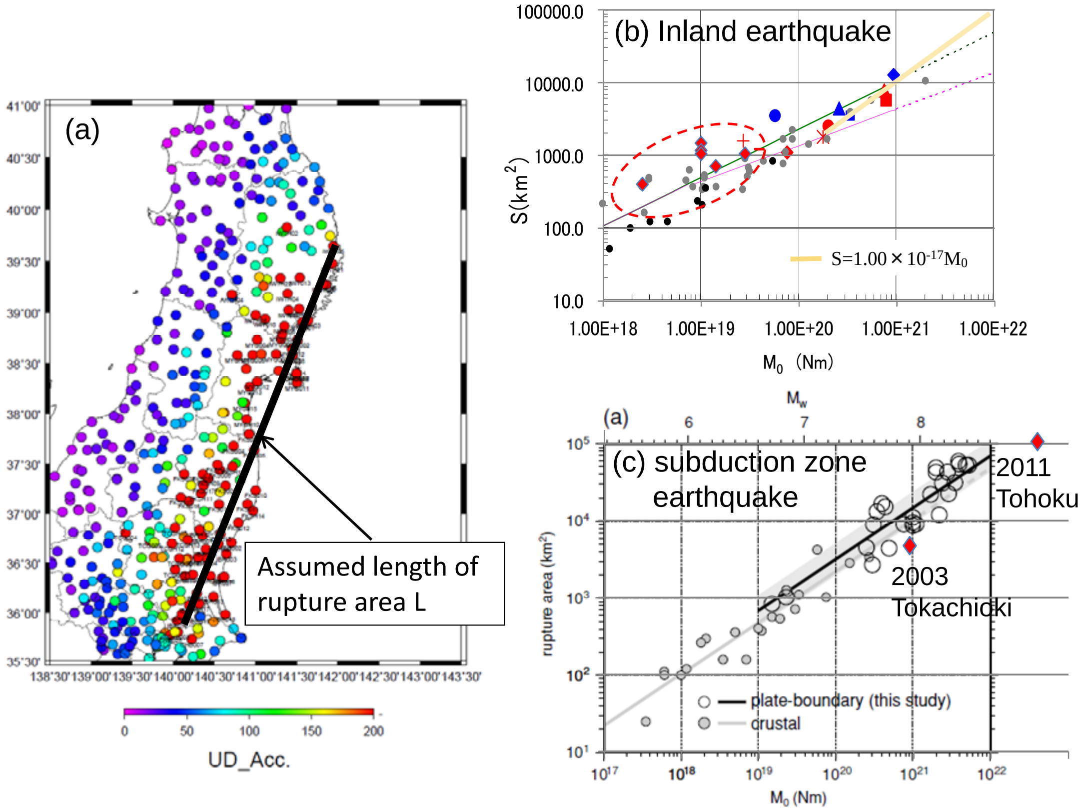

Figure 6 (a): Map showing the vertical PGA at stations in the 2011 Tohoku earthquake and the length of assumed rupture extent. (b): Empirical relationship between seismic moment and rupture area for inland earthquakes (Matsushima et al., 2010). (c): Empirical relationship between seismic moment and rupture area for subduction zone earthquakes (Murotani et al., 2008). The red diamonds indicate the result of the present study.

4.2. PREDICTION OF VERTICAL PGA AT SITE OUTSIDE SATURATION OF VERTICAL PGA

The vertical PGAs at sites outside the source extent are calculated using the empirical attenuation-distance relationship of the vertical PGAs and shortest distance from the sites to the source fault. We found that the decay coefficients with distance in the vertical attenuation-distance relationship are independent of magnitude (Ueda et al., 2008). Then we used part of attenuation term by the vertical attenuation-distance relation by Nishimura and Horike (2003). The Nishimura and Horike's equation of attenuation-distance relations for vertical PGAs was shown as equation (1).

$$\mathrm{LogA} = a - Log(r + Const.) - 0.0025D^{0.263}r \quad (1)$$

The A and r are amplitude of vertical PGA and shortest distance from site to the rupture extent, respectively. The D is depth of earthquake. The a is a constant amplitude of vertical PGA independent of distance.

The vertical PGAs observed during three earthquakes are compared with those calculated from the attenuation relationship in Figure 7. The agreement between the observed vertical PGAs and the empirical attenuation-distance relationship is satisfactory for most of sites.

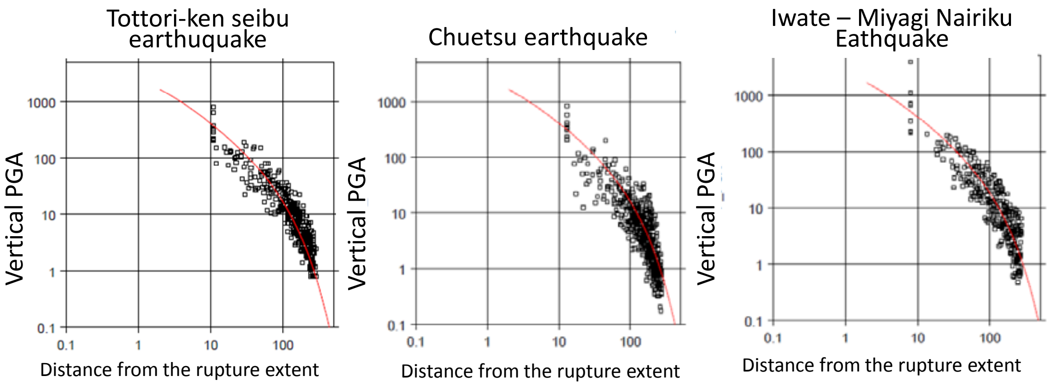

Figure 7 Comparison of observed vertical PGA and the attenuation relationship of part of attenuations term in the three earthquakes. The x axis and y axis are shortest distance from each site to the assumed rupture extent and vertical PGA, respectively. The red solid line indicates the attenuation relationship of part of attenuations term.

4.3. EMPIRICAL RELATIONSHIP BETWEEN VERTICAL PGA AND SEISMIC INTENSITY

The relationship between vertical PGA and observed seismic intensity is shown in Figure 8. The solid line indicates the estimated relation by the method of least-squares. The correlation between vertical PGA and observed seismic intensity is satisfactory for the most part., although, there is considerable variation.

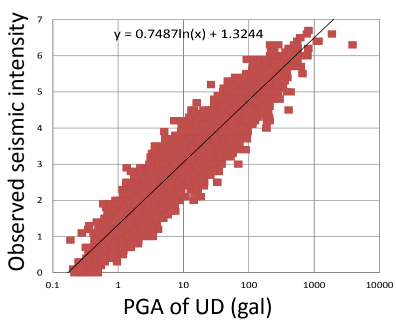

Figure 8 The relationship between vertical PGA and observed seismic intensity. The solid line indicates the estimated relation by least-square method.

5 . SEISMIC INTENSITY MAP PREDICTED FROM VERTICAL PGA

The observed records vertical PGA and the calculated vertical PGA by this study in the 2008 Iwate Miyagi nairiku earthquake and 2011 Tohoku earthquake are shown in Figure 9. The observed results agree well with the calculated ones at stations around the epicenter as well as far from epicenter.

Figure 10 shows the observed seismic intensity and the calculated seismic intensity by this study in the 2008 Iwate Miyagi nairiku earthquake and 2011 Tohoku earthquake. The predicted seismic intensities by EEW were underestimated in Kanto area in the 2011 Tohoku earthquake. However, it would not be underestimated if our method were applied.

The relationship between observed calculated vertical PGAs and between observed and calculated seismic intensities during the 2008 Iwate-Miyagi Niriku earthquake (inland) and the 2011 Tohoku earthquake (subduction-zone) are shown in Figure 11. The variation of the relationship between observed and calculated seismic intensities is larger than that of the relationship between observed and calculated vertical PGAs. There are seen considerable variations caused by variation of the empirical relationship between vertical PGA and observed intensity.

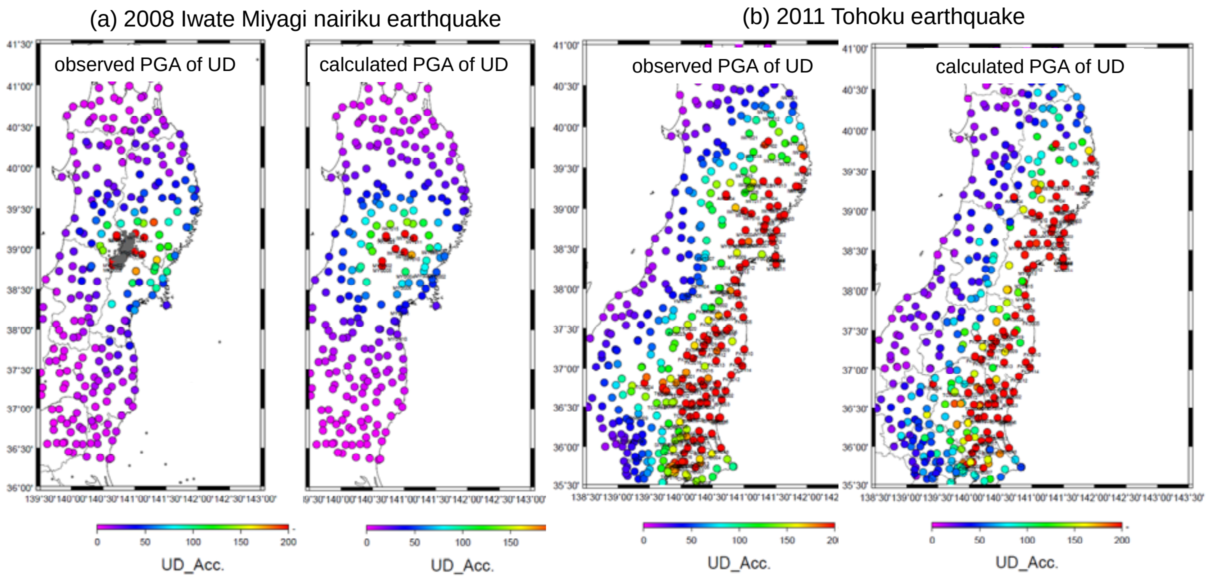

Figure 9 Comparison of the observed vertical PGA and calculated vertical PGA by this study method. (a) :2008 Iwate Miyagi Naririku earthquake. (b):2011 Tohoku earthquake.

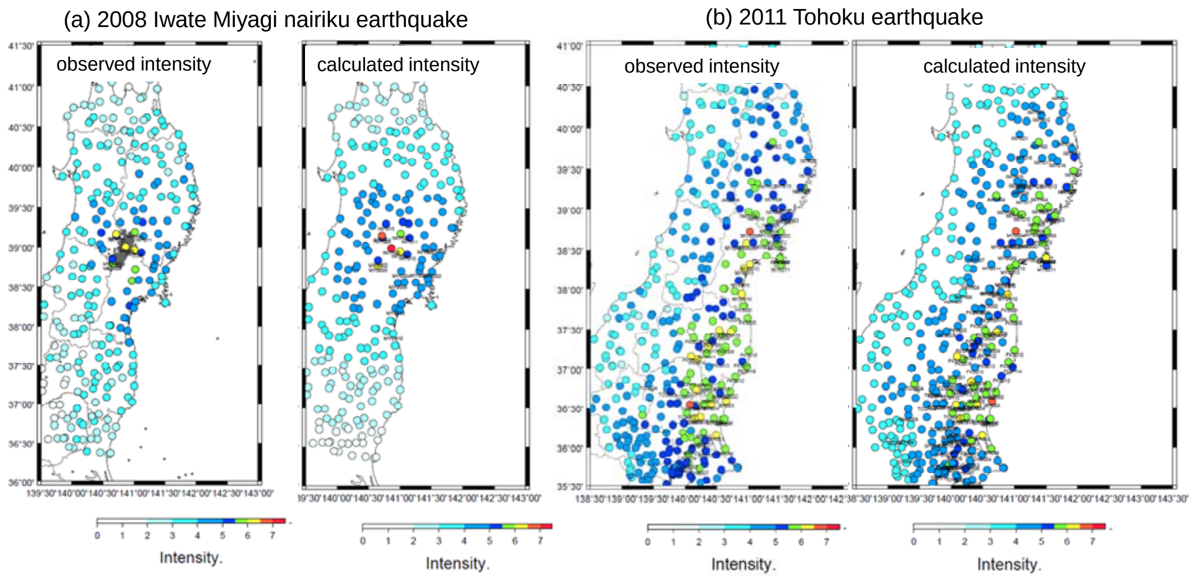

Figure 10 Comparison of the observed intensity and calculated intensity by this study method. (a) :2008 Iwate Miyagi nairiku earthquake. (b):2011 Tohoku earthquake.

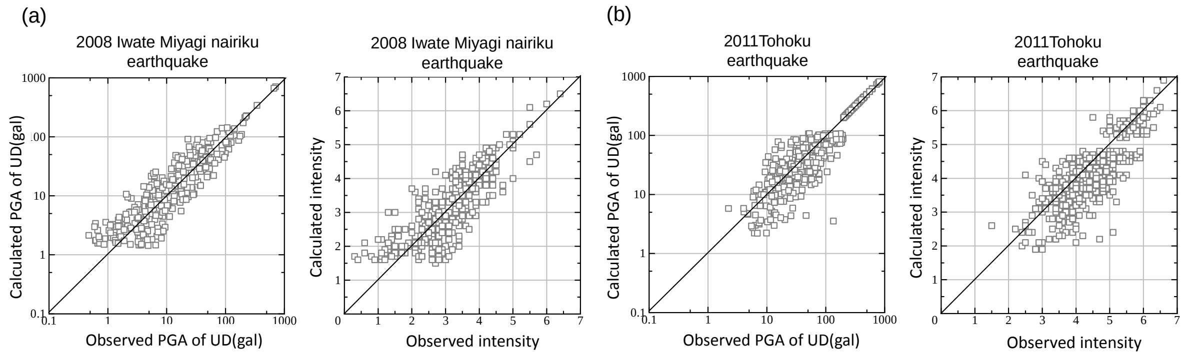

Figure 11 The relationship between the observed vertical PGA and calculated vertical PGA by this study method and between the observed intensity and calculated intensity by this study method. (a) :2008 Iwate Miyagi nairiku earthquake. (b):2011 Tohoku earthquake.

6 . CONCLUTION

We found that vertical PGAs at stations near the source fault during the 2011 Tohoku earthquake have some saturation, although the saturation levels are remarkably influenced by site effects of the stations. The extent of the source fault is estimated from the distribution of stations in which vertical PGAs of more than 250gal are observed in this earthquake.

The rupture areas estimated from vertical PGAs agree well with the ruptures from the empirical relationship between seismic moments and rupture area within 1 standard deviation (sigma)

The agreement between the observed vertical PGAs and the empirical attenuation-distance relationship is satisfactory for most of sites.

Seismic intensities at sites outside the saturation area are predicted using the empirical attenuation-distance relation of vertical PGA and shortest distance to the source fault and the empirical relationship between vertical PGA and seismic intensity. This methodology is available to provide correct seismic-intensities to public during megathrust earthquakes as one of updating EEW systems.

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We used the wave data provided by the K-NET and KiKnet of the National Research Institute for Earth Science and Disaster Prevention (NIED). We also used the hypocentral information from the Japan Meteorological Agency (JMA) and the moment tensor solution from the F-net (NIED).

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