DEVELOPMENT OF SITE-SPECIFIC EARTHQUAKE EARLY WARNING SYSTEM FOR HAZARD MITIGATION

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ABSTRACT :

We have developed a real-time hazard mitigation system using earthquake early warning to achieve (1) enhanced accuracy of seismic intensity estimation and (2) extension of interval from issuance of warning to arrival of strong tremors. Firstly, we have succeeded in reducing the error in seismic intensity estimation compared to that of the commonly used method based on an attenuation relationship and soil amplification factor by considering differences of source locations and propagation passes based on a site-specific empirical method. Secondly, the developed system utilizes a high-speed and reliable communication network for receiving information from JMA and quickly transmitting warning signals to users. In areas close to the epicenters of earthquakes, however, the warning may not be transmitted before strong tremors hit. We have therefore developed an on-site warning system using P-wave-pick-up sensors that can detect the arrival of P-waves at a site and predict the seismic intensity of ensuing ground motion to reduce the time until warning. We validated the prototype system based on vibration tests, numerical simulations and observations. Finally, we installed a practical system at a construction site in the aftershock source area of the 2008 Iwate-Miyagi inland earthquake and confirmed its applicability and accuracy.

KEYWORDS: Early Warning, On-site Warning, P-wave-pick-up Sensor, Seismic Intensity

1. INTRODUCTION

After an earthquake occurs, observation stations near the epicenter detect its magnitude and hypocenter and transmit the information faster than seismic waves to a site. The idea called “Earthquake Early Warning” (EEW) is effective in mitigating seismic hazard. This is an old concept, but it has not been implemented until recently. The Railway Technical Research Institute (Nakamura, 1988) developed an actual system to ensure the safety of bullet trains during earthquakes: UrEDAS (Urgent Earthquake Detection and Alarm System). Moroi et al. (1994) developed a similar system and installed five stations southeast of Tokyo in 1993 aimed at earthquakes in the Izu and Tokai regions, where great earthquakes are predicted to occur in the near future. We also studied its applications such as in structurally controlled buildings (Kanda et al., 1994). The system was on line for ten years. However, although it could not be put to practical use because of high communication and maintenance costs to ensure speed and reliability, we were able to accumulate technical knowledge related to it.

The Japan Metrological Agency (JMA) started formal operation of providing EEW information to organizations all over Japan in 2006. This system consists of about 1000 observation stations including JMA’s original network and “Hi-net” by the National Research Institute for Earth Science and Disaster Prevention (NIED). It issues basic information such as magnitude and source location, and it is necessary for users to establish post-process systems and to estimate shaking intensity and arrival time at their own risk. We have developed a warning system using this EEW information for construction sites, buildings and factories, utilizing our engineering knowledge and experience as a civil engineering and construction company (Kanda et al., 2006). However, some problems remain with the EEW from JMA, such as estimation error, false alarms and alarm timing. Our research is focused on two issues: 1) enhancing the accuracy of seismic intensity estimation and 2) extending the interval from issuance of warning to arrival of strong tremors on a user basis. The most important point in solving these issues is to analyze site-specific data and to customize the EEW system according to location.

2. DEVELOPMENT OF EARLY WARNING FROM JMA

2.1. System configuration for high speed communication

Figure 1 shows the system configuration, showing the flow of EEW information from JMA to in-house offices and construction sites. We have paid a lot of attention to communication speed and reliability. First, the original EEW information is transmitted from JMA through a closed IPv6 network of optical lines and is received by integrated servers connected to the in-house Local Area Network (LAN). The servers process EEW information and filter necessary information only. They can then quickly estimate probable seismic intensity and arrival time of major ground motions at every delivery point using site-specific data. The evaluation method is discussed in chapter 2.2. Furthermore, the system condition can be monitored and some error warning can be sent if necessary.

A construction site is one of the most important places to mitigate seismic hazard by using the EEW information, since it may suffer from various risks during strong shaking, such as falls of workers in high locations and accidents to temporary elevators and tower cranes. The Internet Protocol-Virtual Private Network (IP-VPN) is used for communication from in-house servers. We installed emergency blinking or rotating alarm lamps and character displays as warning devices at affected places at construction sites. The contact signal is used to control all the devices. Furthermore, E-mails are sent to workers' cellular phones through the Internet.

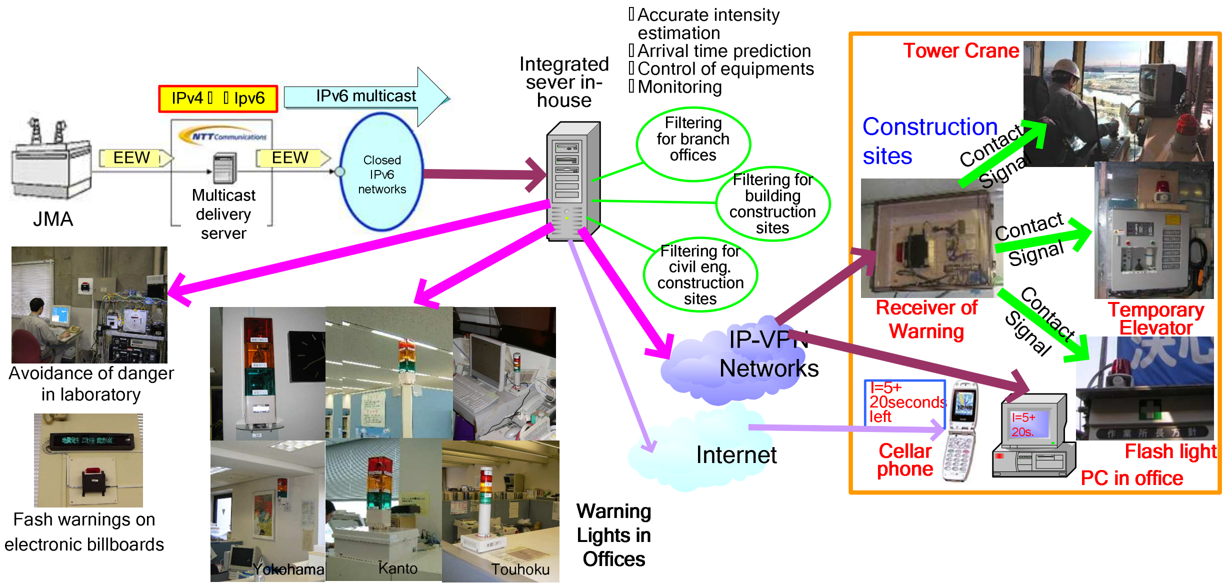


Figure 1 Flow of information of EEW from JMA to offices and construction sites

2.2. Improvement of seismic intensity estimation from EEW information

Seismic intensity in JMA scale is the most commonly used index of ground motion in Japan. JMA have been observing seismic intensity since 1926 and kept formal records in an annual seismological bulletin. Furthermore, seismic intensity data of major historical events have been evaluated from earthquake damage written in historical documents (e.g. Usami, 2003). Therefore, a lot of seismic intensity data covering more than 300 years are available in Japan. Figure 2(a) shows a flowchart of a proposed intensity estimation procedure using EEW information. First we analyze the JMA intensity data (JMA, 2008) near the site to evaluate a mean attenuation relationship and intensity residuals depending on the hypocenter. Secondly, we investigate the soil profile of the site and modify the attenuation relationship taking account of differences beyween surface soil amplifications at the site of interest and its nearest observation station. We can thus more accurately estimate the intensity by combining the mean intensity obtained from the attenuation relationship and intensity residuals. Figure 2(b) shows the relationship between observed and estimated intensity of the present method compared with the result from a commonly used attenuation relationship (Si and Midorikawa, 1999). It is indicated that the RMS of error is reduced to half by this method.

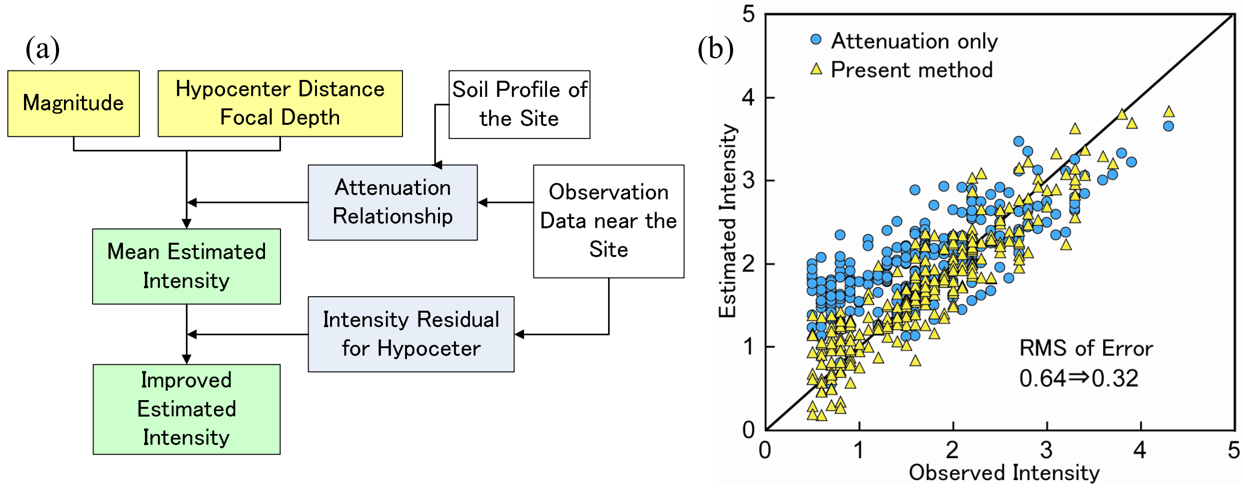


Figure 2 Improved intensity estimation. (a) Flowchart of procedure. (b)Comparison of accuracy.

This improved method is applied to facilities requiring accuracy and reliability of EEW, such as the Imperial Hotel in Tokyo and NHK broadcasting station (Nasu et al., 2007, 2008).

3. ON-SITE WARNING SYSTEM FOR NEAR-FIELD EARTHQUAKES

3.1. Concept of on-site warning

In general, the EEW observation stations near an epicenter can pick up P-wave arrival and send the analyzed information to users in far-field before a strong tremor reaches them. For near-field earthquakes, however, the EEW information may not reach the user before the S-wave with strong shaking. This is because the EEW system takes several seconds to process and transmit the information and S-waves propagate faster than EEW information near the epicenter. In Japan, it is well known that there are many active faults in large urban areas such as Tokyo and Osaka. Thus, EEW information may be useless in such events. Figure 3 shows the concept of "on-site warning" (OSW) (Wu and Kanamori, 2005). The OSW can detect P-wave arrival using seismometers installed at the site using the automatic earthquake recognition procedure (Allen, 1978) and estimate the intensity of impending strong shaking in a few seconds. The intensity estimation method is based on the empirical amplitude relationship between P and S waves. The warning can be issued before S-wave arrival taking advantage of the difference between the velocities of P and S waves.

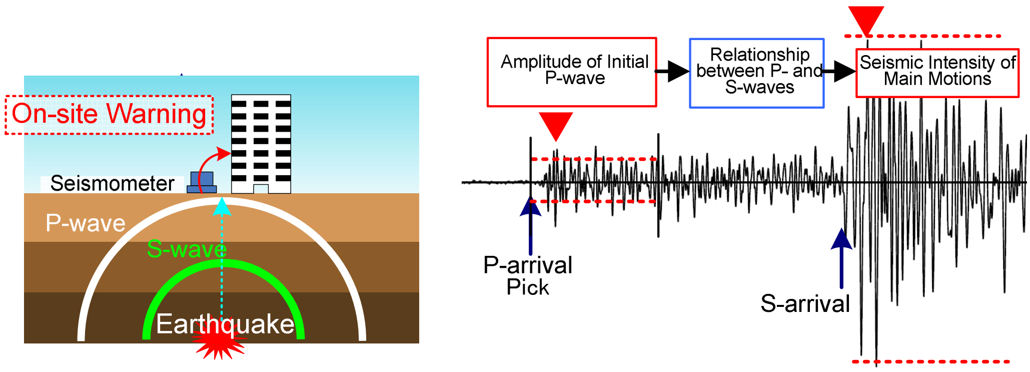
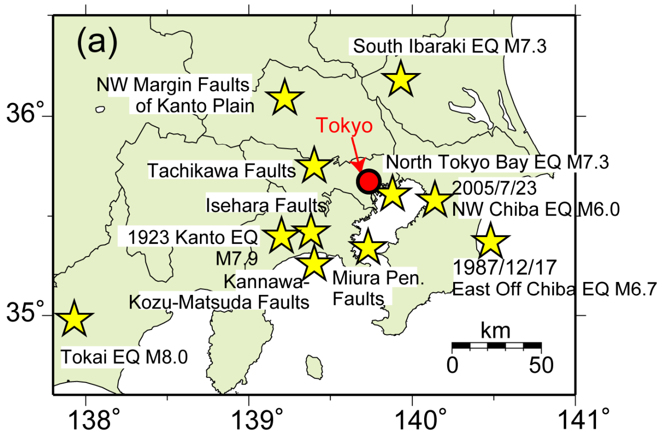


Figure 3 Concept of on-site warning

It is important to compare the interval between warning and S-wave arrival in the discussion on the efficiency of each system. Figure 4 shows the case of a major scenario and observed earthquakes around the Tokyo metropolitan area. The user's site is assumed to be located in Tokyo. The OSW is faster than EEW from JMA for earthquakes within about 50km epicentral distance. In particular, within about 30km, the EEW information may not be transmitted before S-wave arrival. However, EEW from JMA is more effective for distant huge interplate earthquakes such as the Tokai earthquake. Thus, the combination of OSW and EEW from JMA covers each other's shortcomings and can be applied to a wide range of distant earthquakes. Figure 5 shows the configuration of the proposed integrated system. It consists of three parts: 1) a receiver of the EEW information from JMA, 2) an on-site warning device and 3) a server for information integration. Each part is assembled into a small box-type computer. The integrated system is designed especially to control important facilities and equipments.



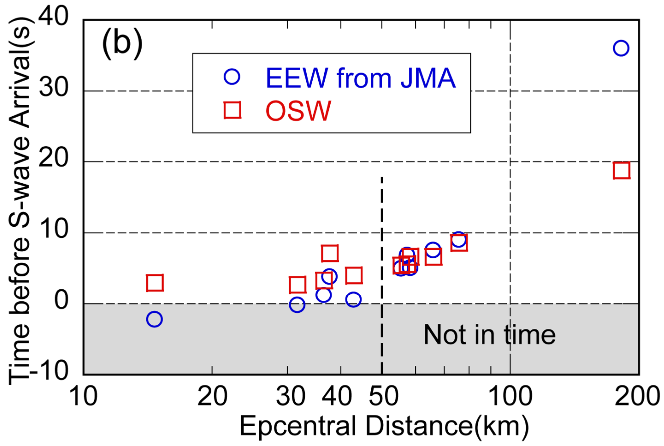


Figure 4 Comparison of warning timing between EEW from JMA and OSW: (a) Epicenters of possible major earthquakes and (b) their estimated interval from warnings to S-wave arrival in Tokyo.

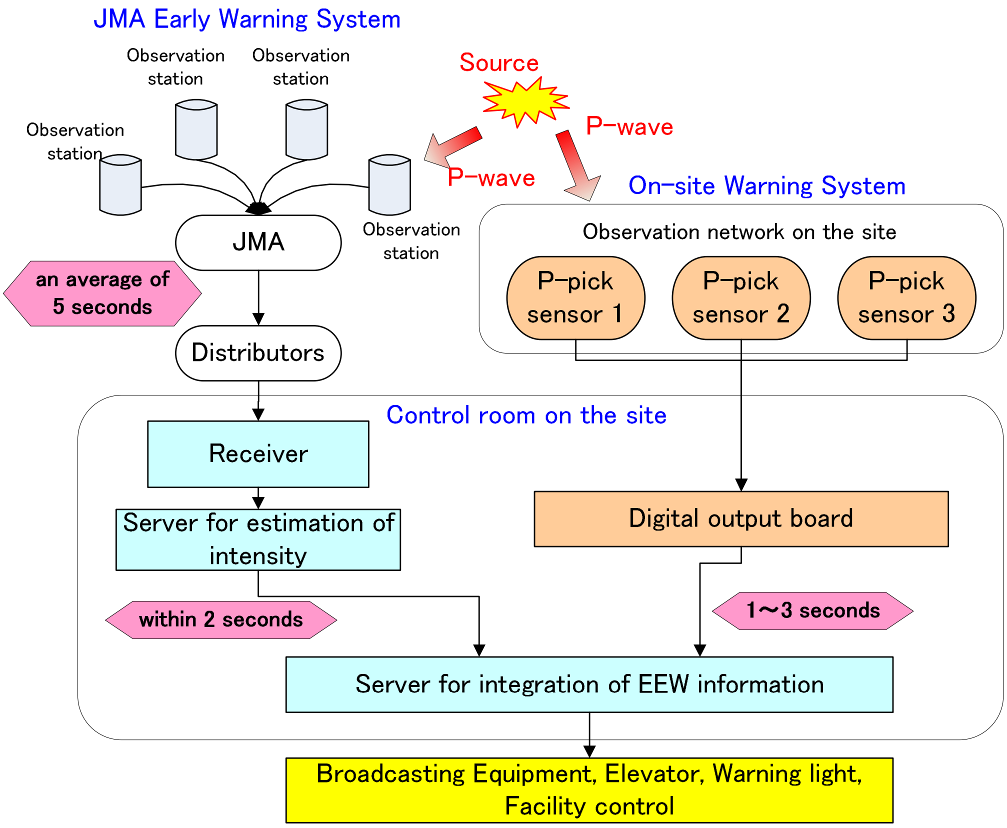


Figure 5 Configuration of integrated system for EEW information

3.2. Simulation study on intensity estimation method

The intensity estimation method used for OSW has been developed by means of analytical simulation using 210 time series of major recent earthquakes observed in “K-NET” (NIED) within 50km epicentral distance, as shown in Figure 6(a). There are two figures in Figure 6(b). One shows that the measured intensity has a linear relationship with root-mean-square (RMS) velocity V_{SD}, and the other shows maximum velocity V_{max} of 1-3 seconds time series after P-wave pick-up. The mean linear regression relationships, shown by solid lines, are given as:

$$I = 2\log(V_{SD}) + \alpha \tag{3.1}$$

$$I = 2\log(V_{\max}) + \beta \tag{3.2}$$

where α =6.12 and β=5.14 for 2 seconds of the P-wave shown in Figure 6(b). We find that the standard deviation σ is relatively large. Some adjustment of α and β may be required, depending on site location.

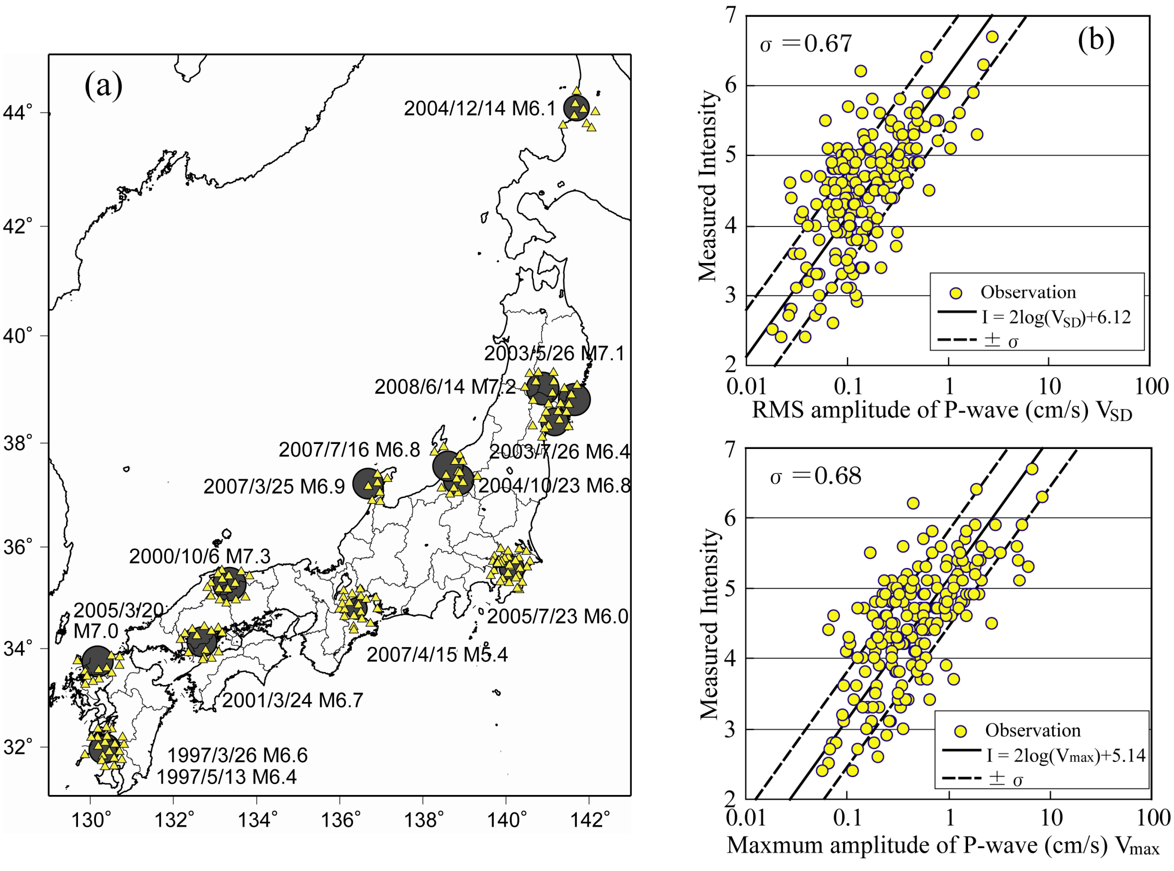


Figure 6 Preliminary simulation study using earthquake data observed within 50km in epicentral distance. (a) Epicenters of analyzed earthquakes (black circle) and K-NET stations (yellow triangle). (b) Measured seismic intensity in JMA scale vs P-wave velocity amplitude observed by P-wave sensor.

3.3. Validation of prototype system by earthquake observation

We made a prototype of the OSW system and installed it on the 5th floor of an office building in Tokyo. The system detected 5 events in three months, as shown in Table 1. The measured intensities were also observed by an accelerometer placed nearby for validation of the OSW system. The OSW system adopted the evaluation method described in chapter 3.2 and estimated the intensity using 2-second records after P-wave pick-up. The estimation is found to be very accurate. Figure 7 shows a time series of the No.1 event, which consists of two horizontal components of the accelerometer and a vertical component of the OSW sensor. The interval between S and P arrivals was 8 seconds. This means that 6 seconds remained from warning to S-wave arrival. Note that

Table 1 Experimental observation (April – June, 2008) at 5th floor of building in Tokyo.

No.	Date	Time	Depth (km)	M_J	Epicentral Distance (km)	Measured Intensity	Estimated Intensity from on-site warning	Time from warning to S-wave (s)
1	2008/4/4	19:01	53	5.0	50.6	2.5	2.5	6
2	2008/5/8	1:02	60	6.4	209.1	2.6	2.0	20
3	2008/5/8	1:45	51	7.0	179.7	3.4	2.9	17
4	2008/5/9	7:43	74	4.6	27.9	2.2	2.8	6
5	2008/5/26	4:41	53	3.8	22.4	1.4	2.3	4

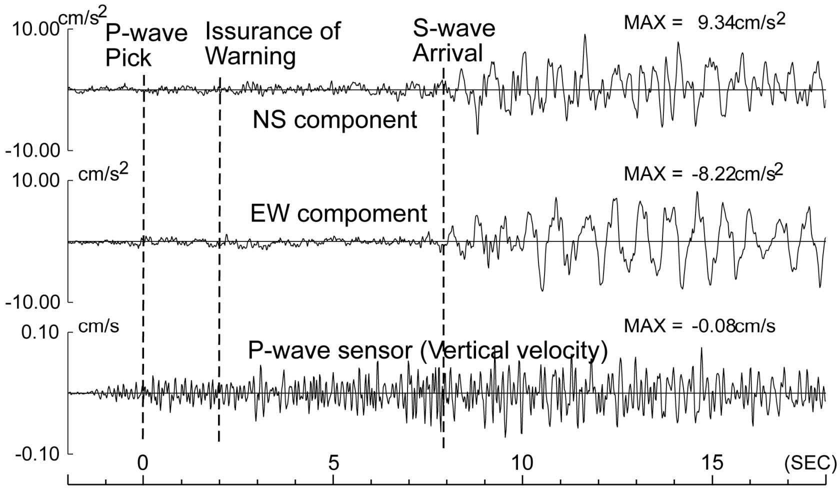


Figure 7 Time series (No.1) observed in office building in Tokyo.

the OSWs of No.1, 4 and 5 events were earlier than EEWs from JMA, since their epicentral distances were short.

3.4. Application to construction site in aftershock area

The Iwate-Miyagi inland earthquake (M_J7.2, depth 8km) occurred in the northern part of Japan on June 14, 2008. 26 people were dead or missing. The Isawa Dam construction site is located near the epicenter. The EEW from JMA has been operating at the site since the end of 2007. Unfortunately, the EEW information was output to the site after the arrival of the S-wave in the main shock. It was indicated that the EEW from JMA was not very effective for such a near earthquake. Since the aftershocks were quite active, especially in the vicinity of the site, as shown in Figure 8, we installed the OSW system and a normal 3-component seismometer for practical use as well as validation of the system. The system can issue alert signals from EEW or OSW, whichever comes first. The safety and announcing systems installed at hazardous places at the site can receive these signals and start to operate instantaneously.

Figure 9 shows an example of time series recorded in the system. In this case, one second after P-wave pick-up is used for the estimation of intensity, considering the characteristics of targeted near-field events whose S-P time is quite short. Figure 10(a) compares the measured and estimated intensities of all the events, depicted as red circles in Figure 8. It is indicated that intensity can be predicted quite accurately using this OSW system, except the event on 7/12 8:06, which occurred outside the presumed fault of the main shock. Figure 10(b) shows the interval between P- and S-wave arrivals over epicentral distance. P-wave arrival was detected automatically by the system, but S-wave arrival was manually determined from the time series. S-P intervals of observed aftershocks were around 2 seconds. This means that one second remained before the onset of strong shaking. Site workers often do not notice a tremor until it becomes quite strong. It is therefore important to transmit the occurrence of an earthquake as soon as possible, even if it is after P-wave arrival. This is effective not only in keeping workers safe but also in raising workers' awareness of disaster prevention

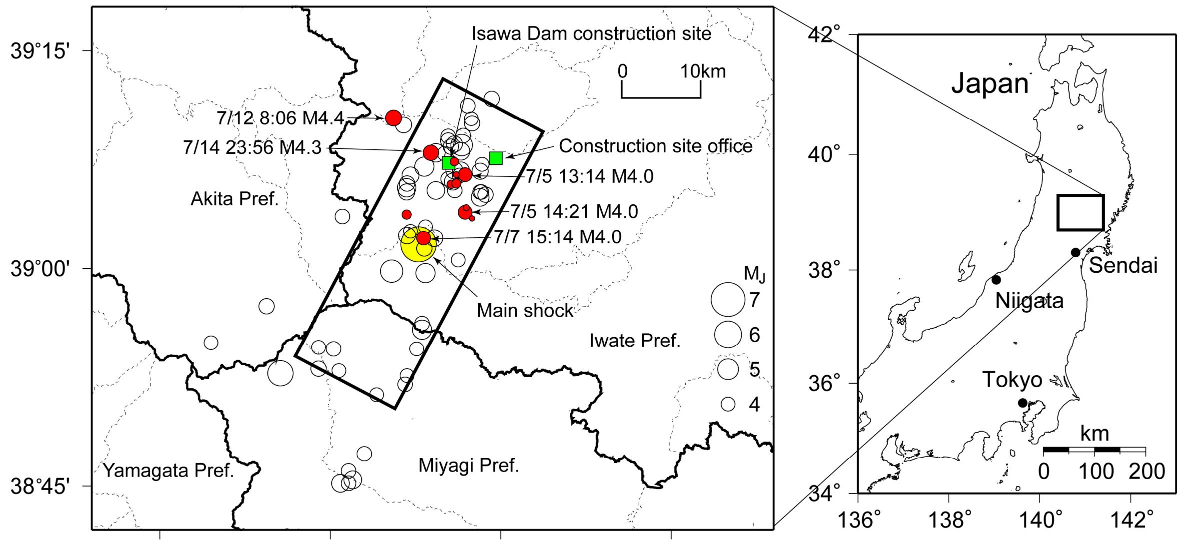


Figure 8 Epicenter map of 2008 Iwate-Miyagi inland earthquake (Blank circles: June 14 – July 4, $M_J \geq 4.0$. Red circles: events observed by the OSW at construction site office depicted by a green square, July 5–15). Rectangular area shows presumed fault model of main shock.

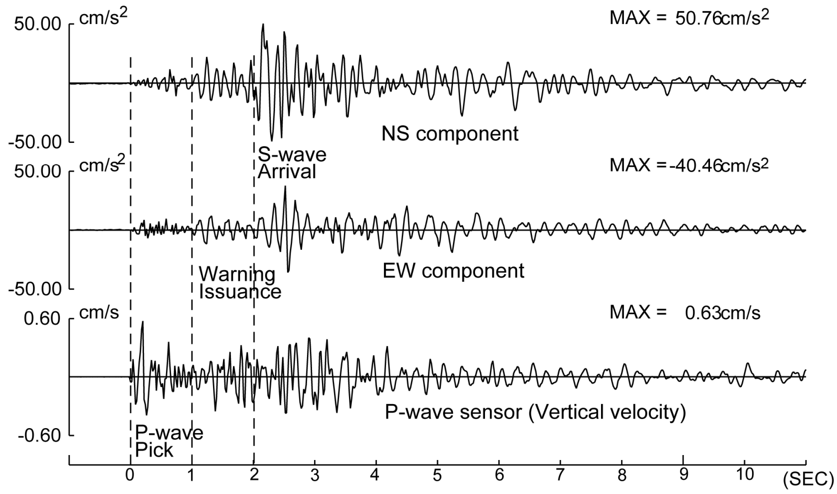


Figure 9 Time series of near-field event observed at construction site on July 14, 2008.

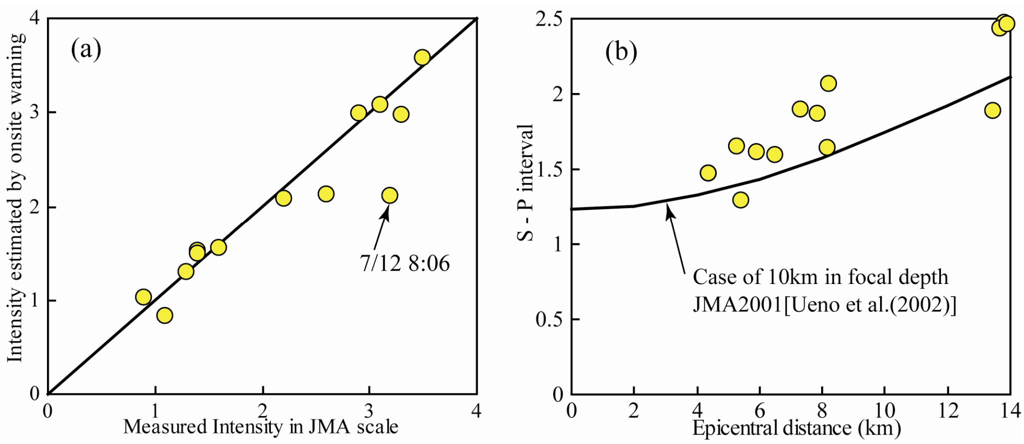


Figure 10 Results of OSW at construction site in fault zone. (a) Comparison between measured and estimated intensities, (b) S-P times read off time history vs epicentral distance.

4. CONCLUSION

We have developed a real-time hazard mitigation system using EEW information from JMA and OSW. Firstly, we succeeded in reducing the error in seismic intensity estimated from EEW information by considering differences of source locations and propagation passes using observed data. Secondly, since the EEW information may not be transmitted before strong shaking in areas close to the epicenter, we have developed an on-site warning system using P-wave-pick-up sensors that can detect the beginning of ground motion at a site and predict the seismic intensity of ensuing ground motion at the same site to increase the interval from warning to S-wave arrival. We made a prototype system, and verified it from vibration tests, numerical simulations and observations. We installed a practical OSW system combined with the EEW system from JMA at the Isawa dam construction site in the source area of the 2008 Iwate-Miyagi inland earthquake. It observed many aftershocks and was able to issue a warning before strong shaking. We hope that the developed integrated system will be widely adopted to mitigate seismic hazard at other construction sites and critical facilities.

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REFERENCES

Allen, R. V. (1978). Automatic Earthquake Recognition and Timing from Single Traces. *Bull. Seism. Soc. Am.* **68:5,** 1521-1532.

Kanda, K., Kobori, T., Ikeda, Y. and Koshida, H. (1994). The Development of a Pre-arrival Transmission System for Earthquake Information Applied to Seismic Response Controlled Structures. *Proc.1st World Conf. Structural Control*, **TA3**, 23-32.

Kanda, K. et al. (2006). Application of Earthquake Early Warning System to Construction Sites. *Proc. 4th World Conf. Structural Control and Monitoring*. 292.

Moroi, T., Miyamura, M., Ohbo, N., Kanda, K., Yamanaka, H. and Yamaya, H. (1994). Study on a Pre-Arrival Earthquake Detection and Information Transmission System. *Proc. 9th Japan Sympo. Earth. Eng*., 2281-2286 (in Japanese).

Nakamura, Y. (1988). On the Urgent Earthquake Detection and Alarm System (UrEDAS). Proc. 9th World Conf. Earth. Eng., **7**, 673-678.

Nasu, T., Miyamura, M. and Kanda, K. (2007). Application of Earthquake Early Warning System: Case of a Freese Warehouse and a Hotel. *Summaries Tech. Papers Annual Meeting, AIJ*, **B-2,** 657-658 (in Japanese).

Nasu, T., Miyamura, M. and Kanda, K. (2008). An Application of Earthquake Early Warning System: Application to Broadcasting Station and Office Buildings. *Summaries Tech. Papers Annual Meeting, AIJ*, **B-2**, 781-782 (in Japanese).

Si, H. and Midorikawa, S. (1999). New Attenuation Relationship for Peak Ground Acceleration and Velocity Considering Effects of Fault Type and Site Condition. *J. Struct. Constr. Eng*., AIJ, **524**, 63-70. (in Japanese).

Ueno, H. et al. (2002),. Improvement of Hypocenter Determination method – Modification of shallow velocity structure and weight function -. Quarterly Journal of Seismology, JMA, **65**, 123-134. (in Japanese).

Usami, T. (2003), *Conspectus of Damage Earthquakes in Japan* [416]-2001, University of Tokyo Press, 606pp. (in Japanese).

Japan Meteorological Agency (2008). *The Annual Seismological Bulletin of Japan for* 2006, CD-ROM.

Wu, Y-M. and Kanamori, H. (2005). Rapid Assessment of Damage Potential of Earthquakes in Taiwan from the Beginning of P Waves. *Bull. Seism. Soc. Am.* **95:3,** 1181-1185.