Review of Earthquake Early Warning Operation in Japan for eight years from 2007

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It has been about eight years since the Japan Meteorological Agency (JMA) launched a nationwide Earthquake Early Warning (EEW) service for the general public on October 1, 2007. We describe details of the JMA EEW system and review its performance and improvements.

In the JMA EEW system, JMA seismic intensities in about 200 areas across the nation are predicted with hypocenter and magnitude estimated from several methods. EEW announcements are issued mainly based on predicted JMA seismic intensity. In order to assess EEW prediction accuracy, JMA reports annual EEW scores calculated from a percentage of areas where an error of predicted seismic intensity is within one degree (Figure 1).

The EEW operation started with about 200 seismometers of a JMA network and 800 of a National Research Institute for Earth Science and Disaster Prevention (NIED) network. In fiscal 2007 to 2009, the EEW scores remained at a high level (Note that fiscal year begins in April and ends in March in Japan). On June 14, 2008, JMA issued EEW announcements for the Iwate-Miyagi earthquake (M7.2), which contributed to disaster mitigation in various sites such as an airport and a kindergarten. Until March 1, 2011, 12 new stations, most of which were installed in islands, and five new ocean-bottom seismometers (OBS) in Tonankai were incorporated in the system.

On March 11, 2011, the 2011 off the Pacific coast of Tohoku Earthquake (the Tohoku earthquake) (M9.0) happened. An EEW warning was successfully issued for the Tohoku district, the nearest region from the epicenter, before S-wave arrival. The JMA EEW system worked well in Tohoku district, whereas the EEW system under-predicted seismic intensities of the Kanto district due to large extension of the rupture. After the Tohoku earthquake, highly-active aftershocks occurred and the system issued many warnings including false alarms. The score lowered down to 28% in fiscal 2010. Major causes for the false warnings fell into two factors: (1) confusion of multiple simultaneous earthquakes and a single large earthquake (2) lack of data from seismometers in disaster areas subject to blackout or disconnection of communication lines. JMA conducted improvement of an earthquake identification logic and reinforcement of the JMA seismometer network infrastructure. Owing to the countermeasures and decrease of the number of aftershocks, the number of false alarm decreased and the EEW score turned into an upward trend in fiscal 2011.

In fiscal 2012, JMA introduced site amplification factors estimated from actual observation. The score reached 79%. However, on August 8, 2013, a false warning was issued for very wide range of areas due to contamination of abnormal data from one of the Tonankai OBS. It caused serious impact on economic activities such as stopping trains. JMA took some actions for its measures. The score temporarily fell to 63% in fiscal 2013.

On March 31, 2015, the EEW system started to use 15 deep borehole seismometers (more than about 500 meters depth) of NIED, two OBS in DONET1 of Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and 50 new JMA seismometers. JMA plans to utilize about 180 OBS of JAMSTEC and NIED and about 410 seismic intensity meters of JMA in the future after checking data quality New prediction methods are going to be implemented within a couple of years for measures of multiple simultaneous earthquakes and a large rupture. Integrated Particle Filter (IPF) method is a new hypocenter determination algorithm with Bayesian estimation that can recognize occurrence of multiple simultaneous earthquakes more robustly. Propagation of Local Undamped Motion (PLUM) method

is a new seismic intensity prediction algorithm based on wave field prediction with real-time observed seismic intensity instead of hypocenter determination.

Keywords: Earthquake Early Warning, Integrated Particle Filter method, Propagation of Local Undamped Motion method

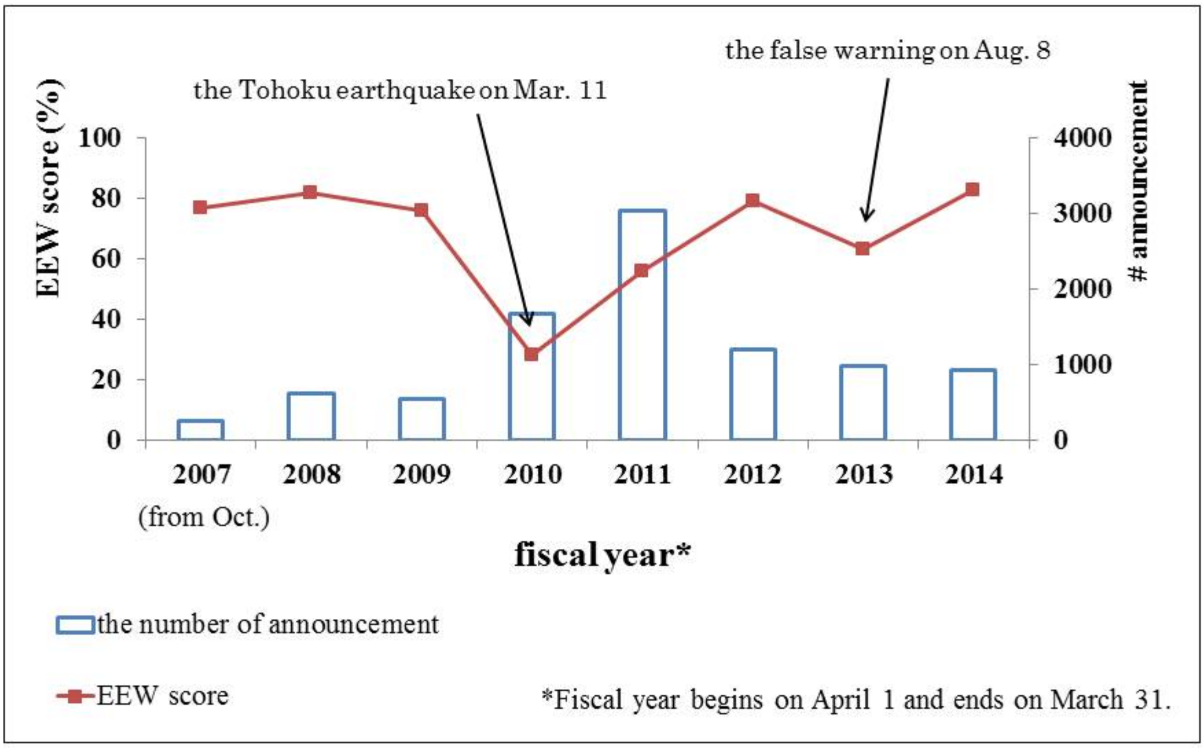

Figure 1. A time series graph of JMA EEW scores and the number of EEW announcement from fiscal 2007 to 2014.

ShakeAlert: Implementing Public Earthquake Early Warning for the U.S.

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The ShakeAlert Earthquake Early Warning (EEW) is a practical use of earthquake science that can reduce injuries, deaths, and property damage by giving people and systems up to a minute to take protective actions before the heaviest shaking arrives. The U.S. Geological Survey (USGS) and its many partners are working to implement ShakeAlert in the three states of the West Coast of the U.S., Washington, Oregon, and California. The partners include Caltech, UC Berkeley, the University of Washington, the University of Oregon, state emergency services organizations, private companies, and the Gordon and Betty Moore Foundation. ShakeAlert is built on the extensive monitoring infrastructure of the USGS Advanced National Seismic System.

The ShakeAlert demonstration system has successfully sent hundreds of test notifications to selected beta users in California since 2012 and began sending messages for Washington and Oregon in 2015. It has alerted on several significant earthquakes and has demonstrated its ability, in some cases, to send alerts less than 4 seconds after an earthquake begins.

On February 1, 2016 the USGS, along with its partners, rolled-out the next-generation ShakeAlert early warning test system in California. This next-generation “production prototype” does not support public warnings but will allow qualified early adopters to develop and deploy pilot implementations that take protective actions triggered by the ShakeAlert warnings in areas with sufficient station coverage.

To reach full public operation the system needs about 1,000 more sensors in California, Oregon and Washington, more reliable telecommunications paths, and a campaign to educate the public about earthquake early warning alerts and how to respond to them. Progress is being made in all these areas; however the project is not yet fully funded. The USGS ShakeAlert implementation plan estimates it will cost $38.3 million in capital funding to complete the system on the West Coast to the point of issuing public alerts and $16.1 million each year to operate and maintain it. This is in addition to current support for seismic networks from other sources.

Completion of the system to the point of public alerting will require a whole-community effort which is gaining momentum. The USGS budget is now $8.2 million per year for the project. A recent White House summit focused attention on ShakeAlert and announced new commitments from a variety of stakeholders. There is a bill in the California legislature for $23 million to build that state’s part of the system and the state of Oregon, as well as various utilities, have funded stations. University partners and the USGS are implementing and testing new algorithms that will speed up and improve the system, incorporate high-precision real-time GPS data, and characterize evolving fault ruptures, including megathrusts, in real-time. Use of data from low-cost sensors and cell phones is also being explored. Private partners are co-developing commercial applications to receive and act on ShakeAlert notifications. The telecommunications industry is taking steps to develop the standards and technological enhancements needed to broadcast alerts to cell phones with minimum delay.

While significant progress is being made, a fully functional ShakeAlert system will require additional funding and further collaborative work before full West Coast public alerting will be possible.

Keywords: ShakeAlert, earthquake early warning, alert

Improving earthquake early warning in the U.S. and around the world: ShakeAlert, MyShake and beyond

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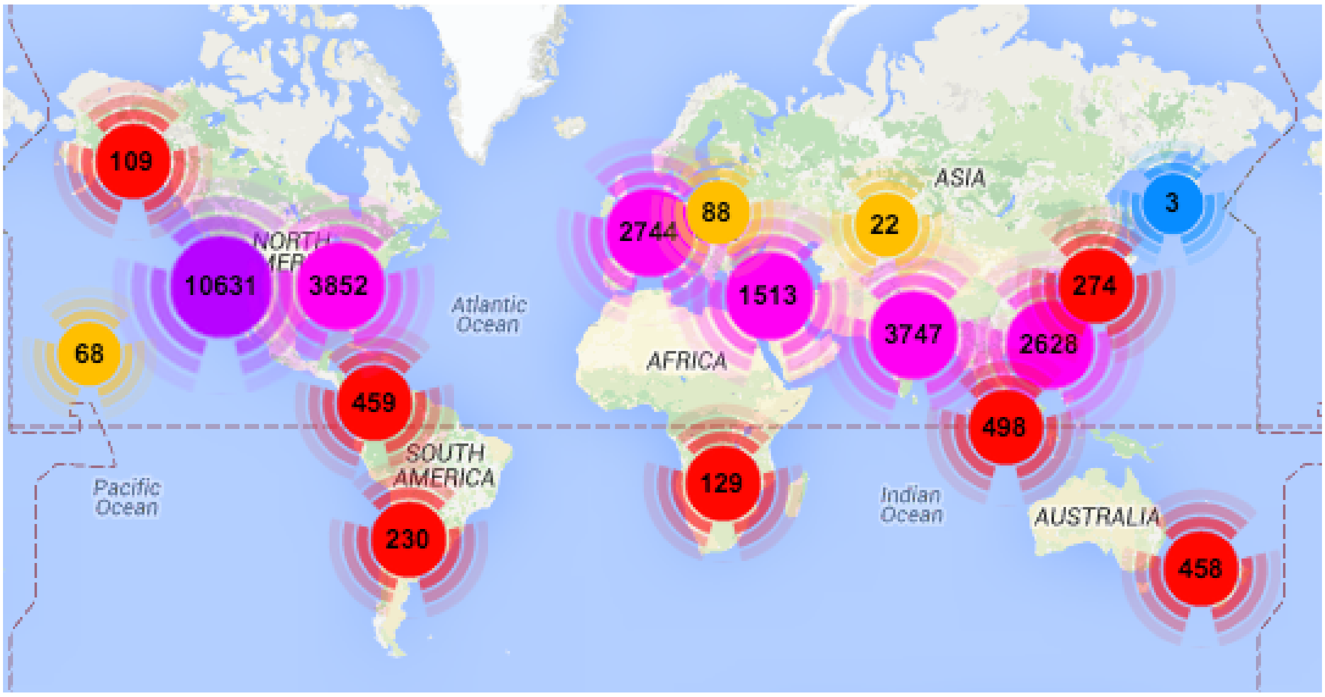
ShakeAlert is the U.S. earthquake early warning system that is now in the process of being rolled out across the U.S. west coast. it uses traditional networks of seismic and geodetic stations to provide seconds to minutes of warning. The newly operational ‘production prototype’ system is now available for pilot projects in which selected users make automated responses and warn personnel of forthcoming shaking. Improved methodologies are also under evaluation for inclusion in the system. New approaches focus on providing better information in the biggest earthquakes by assessing the finite extent of the rupture and updating the warning accordingly.
MyShake is a new experimental approach to earthquake early warning that harnesses the accelerometers in personal smartphones to detect the earthquake and assess the hazard. In the first two days of the public release 50,000 people installed the app on their android phones around the world (see map). We will report on the performance of this system and its potential to contribute to early warning in regions with and without traditional seismic networks.

Keywords: earthquake early warning, ShakeAlert, MyShake



The Mexican Seismic Alert System, its public service since 1993

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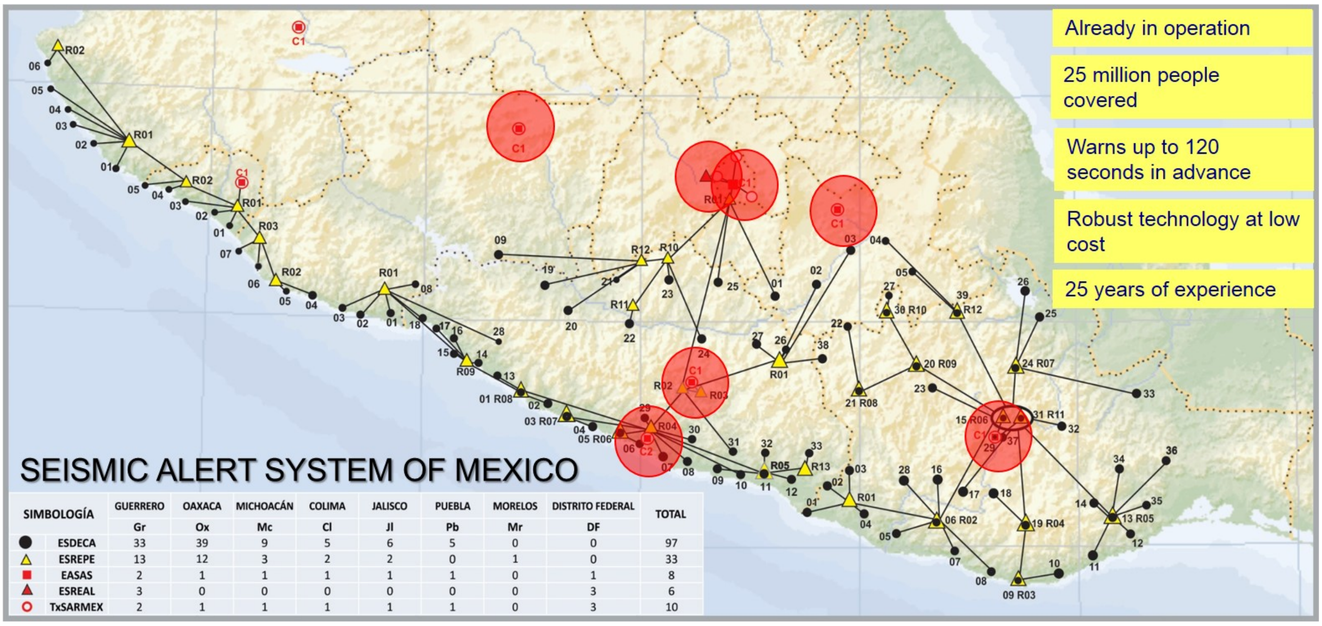
With the aim to mitigate future seismic disasters in the metropolitan region of Mexico Valley, Mexico City Authorities required from CIRES in 1991 the experimental development of a *Sistema de Alerta Sísmica* (SAS), originally with 12 strong motion seismic detectors in the Guerrero Gap, capable to detect and forecast danger generated by strong seismic events, and broadcast warning signals in the Mexico City Valley, distant 320 km, bringing the population opportunity to reduce the seismic vulnerability with near to beneficial 60 s, prior to perceive the strong “s” wave effects. With the same objective during 2002 the Oaxaca State Authorities also required from CIRES the development of another EEW system which started operating 36-field seismic sensors in 2003. After the 2010 Haiti Caribbean disaster, with the agree of the Mexico Ministry of Government, the Civil Protection States Authorities decided the integration of the SAS developments and also shared their services, extending the sensors coverage over seismic active regions in the Pacific coast from Jalisco to Oaxaca, also over the South of the Neovolcanic axis in Guerrero and Puebla. Today, integrated as the SASMEX is operating 97 field stations from 130 originally programmed. SASMEX warning performance has been capable to detect and forecast seismic danger issuing 58 public alerts that announced strong seismic effects and 90 preventive ones, when they were estimated moderate. The SASMEX data catalog accumulates more than 9300 seismic records, generated by near than 4700 seismic events. SASMEX warning services broadcasts signals in Acapulco, Chilpancingo, Morelia, Oaxaca, Puebla, Toluca and Mexico City. To reduce any time delay to reach people under seismic risk, SASMEX automatically controls the signals to modulate the carriers broadcasted by the commercial Television and Radio stations integrated in this social service, also the signals of the NWR SAME international NOAA protocol and EAS-Public Alert, now issued to operate especial receivers SARMEX, which have the capability to operate with the SASMEX warning and more natural hazards or emergencies. Mexico City Government and Federal Government Ministry invested to buy little more than 88 thousand SARMEX receivers to provide the SASMEX seismic warning mainly inside the classrooms of public elementary schools as well as other public services: Metro, Hospitals, etc. The real seismic threaten and good SASMEX results motivated the local governments, and the federal one, to deem relevant expand geographic coverage of the sensors in seismic regions of the south of México, as well as the dissemination capacity of other alert notices trough the SARMEX receivers, useful to mitigate the vulnerability to populations under risk by other natural hazards. The SASMEX performance is notified across such diverse Internet platforms like Web, Blog, E-mail, Facebook, Twitter, RSS and web-socket protocols, emphasizing that due to the uncontrolled delays of these media and Apps, they should not be used to warn seismic alert signals.

Keywords: SASMEX, Mexican , SAS, Alert, early , warning



SIMBOLOGÍA		GUERRERO Gr	OAXACA Ox	MICHOACÁN Mc	COLIMA Cl	JALISCO Jl	PUEBLA Pb	MORELOS Mr	DISTRITO FEDERAL DF	TOTAL
●	ESDECA	33	39	9	5	6	5	0	0	97
△	ESREPE	13	12	3	2	2	0	1	0	33
■	EASAS	2	1	1	1	1	1	0	1	8
▲	ESREAL	3	0	0	0	0	0	0	3	6
○	TxSARMEX	2	1	1	1	1	1	0	3	10

The Performance of Earthworm Based Earthquake Alarm Reporting system in Taiwan

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The Central Weather Bureau of Taiwan has operated an earthquake early warning (EEW) system and issued warnings to schools and government agencies since 2014. Because the real-time seismic data streams are integrated by the Earthworm software, some EEW modules were created under the Earthworm platform. The system is named Earthworm Based Earthquake Alarm Reporting (*e*BEAR) system, which is currently operating. The *e*BEAR system consists of new Earthworm modules for managing P-wave phase picking, trigger associations, hypocenter locations, magnitude estimations, and alert filtering prior to broadcasting. Here, we outline the methodology and performance of the *e*BEAR system. The online performance of the *e*BEAR system indicated that the average reporting times afforded by the system are approximately 15 and 26 s for inland and offshore earthquakes, respectively. Comparing to the earthquake catalog, the difference of the epicenters are less than 10 km for inland earthquakes; the difference of the magnitude are about 0.3. No false alarms generated by the system, but there were three false alarms issued by human. Due to the wrong operations, the EEW information created by off-line test were sent. However, we have learned from it and improved the standard operation procedure in the EEW system.

Keywords: real-time, earthquake early warning, earthworm

Local Tsunami Warnings and the role of high-rate GNSS in Earthquake Early Warning

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Local tsunami warning requires rapid assessment and communication of the tsunami hazard for communities immediately adjacent to large earthquake. Here, the warning times are typically of minutes to tens of minutes. Local warning remains a challenging problem with very few systems worldwide capable of issuing such alerts. Here, we demonstrate a flexible strategy for local tsunami warning that relies on regional geodetic and seismic stations. Through retrospective analysis of four recent tsunamigenic events in Japan and Chile, we show that rapid earthquake source information, provided by methodologies developed for earthquake early warning, can be used to generate timely estimates of maximum expected tsunami amplitude with enough accuracy for tsunami warning. We validate the technique by comparing to detailed models of earthquake source and tsunami propagation as well as field surveys of tsunami inundation. Our approach does not require deployment of new geodetic and seismic instrumentation in many subduction zones, and could be implemented rapidly by national monitoring and warning agencies. We illustrate the potential impact of our method with a detailed comparison to the actual timeline of events during the recent 2015 Mw8.3 Illapel, Chile earthquake and tsunami that prompted the evacuation of 1 million people.

For tsunami warning and for rapid assessment of large events high-rate GNSS observations are a fundamental tool. We will discuss the Geodetic Alarm System (G-larmS) tool. A software system developed in collaboration between the Berkeley Seismological Laboratory (BSL) and New Mexico Tech (NMT) for real-time Earthquake Early Warning (EEW). It currently uses high rate (1Hz), low latency (< ~5 seconds), accurate positioning (cm level) time series data from a regional GPS network and P-wave event triggers from the ShakeAlert EEW system. G-larmS has been in continuous operation at the BSL since 2014 using event triggers from the California Integrated Seismic Network (CISN) ShakeAlert system and real-time position time series. We evaluate the performance of G-larmS for EEW by analyzing the results using a set of well defined test cases to investigate the following: (1) using multiple fault regimes and concurrent processing with the ultimate goal of achieving model generation (slip and magnitude computations) within each 1 second GPS epoch on very large magnitude earthquakes (up to M 9.0) and (2) the use of Precise Point Positioning (PPP) real-time data streams of various operators, accuracies, latencies and formats along with baseline data streams. We will also discuss the recent expansion and performance of the G-larmS algorithm along the U.S. West Coast on a regional network basis for Northern California, Southern California and Cascadia.

We will further highlight ongoing collaboration between the National Seismological Center (CSN) in Chile and the Berkeley Seismological Laboratory. This strategic partnership’s goal is to share data and warning algorithms between the two institutions with the end goal of enabling CSN to issue and disseminate early warning alerts to the country at large.

ShakeAlert: Using early warnings for earthquakes in California and the US West Coast

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With funding from the USGS and the Gordon & Betty Moore Foundation, a prototype production system for earthquake early warning, ShakeAlert, is now operating in California. Earthquake early warning (EEW) is the ability to detect an earthquake quickly and provide a few seconds of warning before destructive shaking starts. Alerts from an EEW system can improve resilience if their recipients have developed plans for responding and act on them. We are working with a suite of perspective users from critical industries and institutions throughout California to identify information they require, as well as delivery mechanisms, procedures and products. Our most effective collaboration has been with the Bay Area Rapid Transit District (BART). Since 2012 the BART system has been using EEW information to automatically slow trains. BART receives alerts via the internet and feeds them into the train operating system. In the 2014 South Napa (M6) earthquake, the BART operations center received the EEW alert 8 s before shaking began at their site, 5 s after the earthquake started. The automatic processing worked. Had trains been running at 03:21 local time when the quake occurred, they would have slowed automatically. Other recipients of EEW alerts from California's EEW system include the emergency managers of San Francisco and Los Angeles, the California Office of Emergency Services, UC Berkeley's police department, and other organizations like the LA School District, Google, Amgen and the major power companies in California, PG&E and SoCal Edison. These organizations currently receive the alerts to enhance their situational awareness. We are also supporting their efforts to determine and implement appropriate responses to EEW alerts, and to assess possible uses and especially benefits to themselves and to society. More recently, the ShakeAlert system has begun operating in the Pacific Northwest, where our partners are also reaching out to perspective users. With the recent step to the production prototype system in California, we are encouraging our users to develop and implement automated and personal actions suitable to their applications, as further demonstrations of the benefits of EEW toward enhancing society's resilience.

Keywords: Earthquakes, Earthquake early warning, earthquakes and society

On-Site Earthquake Early Warning System

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In Japan, Semiconductor industry aimed at a strong factory to an earthquake after the Great Hanshin/Awaji Earthquake in1995.
We have carried out the correspondence by earthquake-resistant reinforcement of factory, fixing of equipment, shaking stop of the pipes, using expansion joint, etc.
On the other hand, as effective use of JMA-EEW this information is adopted as life safety and factory production continuation.
In our company, an earthquake prediction like JMA-EEW is being carried out using On-Site seismometer. This On-Site system has functioned effectively, when we did not received a prediction of JMA-EEW and we received a wrong prediction.
At present, We use this system combined by JMA-EEW, On-Site EEW and the actual measurement.
We pile up much improvement after introduction in 2005 and have obtained many results. The secondary disaster by leakage of dangerous chemicals and special gases is prevented and the reduction in operation loss by early re-operation was achieved.
In 2011 The Great East Japan Earthquake, this function is done effectively and early re-operation was achieved.
Using this outcome, we aimed at practical use expansion of On-Site EEW System.
We developed a MEMS seismometer and the exclusive controller which does the announcement and the external equipment control and use. The Development aiming at effective use of neighborhood information system is expanded by network building of On-Site EEW System as the next stage.

Keywords: Earthquake Early Warning, On-Site

Development of the Earthquake Early Warning System for Railway in Japan

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Since Japan is located in one of the highest seismicity zones, to improve countermeasures against earthquake is a significant issue for railway. An earthquake early warning system is one of those countermeasures, particularly for high-speed trains. The first EEW system was in operation in 1982. This was a front-detection system, in which a seismometer located along coastlines remote from the rail monitors a large shaking from subduction zone earthquakes. The second system called Urgent Earthquake Detection and Alarm System (UrEDAS) had been installed since 1992. UrEDAS estimates magnitude and epicenter of an earthquake in several seconds by the initial phases of P-wave observed at single station, and issues a warning signal when a large shaking is expected along the rail. The present system, which has upgraded algorithms for a warning using single station data, has been operated since 2004. At present all the high-speed trains in Japan use this EEW system.The present EEW system consists of track-side seismometers, front-detection seismometers and a central server. Basically each seismometer can issue warnings by itself, but at the same time it can issue warning by using the information from other seismometers. The seismometer has two kinds of warnings, which are a S-wave warning and a P-wave warning. The S-wave warning is issued by threshold excess of acceleration and the P-wave warning is issued by analyzing the P-wave data. In order to issue the P-wave warning, the seismometer firstly estimates epicentral distance by the B-D method from 2-second P-wave data and also estimates back-azimuth to the epicenter by the Principal Component Analysis from 1.1-second P-wave data. Secondary it determines magnitude by using the epicentral distance and observed amplitude. Finally P-wave warning is issued for the potential damaging area which is determined from an empirical relation using the estimated epicenter and magnitude.The present system is reported to have worked well during large earthquakes. A successful train control by the EEW system during the 2011 Great Tohoku earthquake (Mw=9.0) is one of those examples. However to improve the rapidness, accuracy and reliability of the warnings is expected so as to enhance the safety of railway during earthquakes. Now all the high-speed trains in Japan use EEW information from JMA as an additional EEW source. Further, two other approaches are considered for safety. One is improvement of P-wave warning algorithms, the other is usage of external data such as data from ocean bottom seismometers. For the former approach, the C-D method and variable time window method are developed. These methods shorten the data length for estimation to 0.5-1.0 second and improve the estimation accuracy at the same time. For the latter approach, a simple warning logic using ocean bottom seismometers is proposed though an advanced study to understand the characteristics of OBS data is still necessary. The redundancy of warning logics as well as redundancy of system configurations is essential for a reliable EEW.

Keywords: Earthquake Early Warning, Railway, P-wave warning, S-wave warning

Numerical shake prediction for Earthquake Early Warning: Introduction of attenuation structure

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In many strategies of the present EEW systems, hypocenter and magnitude are determined quickly, and then the strengths of ground motions (PGA, PGV, seismic intensity) are predicted based on a ground motion prediction equation (GMPE) using the hypocentral distance and magnitude, which usually leads the prediction of concentric distribution of ground shaking. However, actual ground shaking is not always concentric, even when the difference of site amplification is corrected. Even after correction of site amplification factor, the strengths of shaking may be much different at stations having the same hypocentral distances. For some cases, PGA differs more than 10 times, which leads to imprecise prediction of ground shaking in EEW.
Recently, innovative approach was proposed for EEW (Hoshiba and Aoki, 2015), that is Numerical Shake Prediction. In the method, the present ongoing wavefield of ground shaking is estimated using data assimilation technique, and then future wavefield is predicted based on physics of wave propagation. Information of hypocentral location and magnitude is not required. Because future is predicted from the present condition, it is possible to address the issue of the non-concentric distribution. Once the heterogeneous distribution is actually monitored in ongoing wavefield, future distribution is predicted accordingly to be non-concentric. We will indicate examples of M6 crustal earthquakes occurred at central Japan, in which strengths of shaking were observed to non-concentrically distribute. We will show their predictions using Numerical Shake Prediction method.
The heterogeneous distribution may be explained by inhomogeneity of attenuation/velocity. If attenuation/velocity structure is introduced, we can predict the future shaking more rapidly and precisely. The information of attenuation/velocity structure leads to more precise and rapid prediction in Numerical Shake Prediction method for EEW. We will show examples of precise predictions of the M6 crustal earthquakes at central Japan using the attenuation structure.

Keywords: Earthquake early warning, ground motion , real-time , prediction

Near-field tsunami forecast system based on near real-time seismic moment tensor estimation in the regions of Indonesia, the Philippines, and Chile

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We have developed a near-field tsunami forecast system based on an automatic centroid moment tensor (CMT) estimation using regional broadband seismic observation networks in the regions of Indonesia, the Philippines, and Chile. The automatic procedure of the CMT estimation has been implemented to work for tsunamigenic earthquakes. A tsunami propagation simulation model is used for the forecast and hindcast. A rectangular fault model based on the estimated CMT is employed to figure the initial condition of the tsunami height. The forecast system considers uncertainties due to two possible fault planes and two possible scaling laws, and shows four possible scenarios with the uncertainties for each estimated CMT. The system requires approximately 15 minutes to estimate the CMT after earthquake occurrence, and approximately another 15 minutes to make tsunami forecast results available, including the maximum tsunami height and its arrival time at the epicentral region and near-field coasts. The retrospectively forecasted tsunamis were evaluated by the deep-sea pressure and tide gauge observations, for the eight past tsunamis (Mw7.5-8.6) that occurred around the regional seismic networks. The forecasts were shown to range from half to double the amplitudes of the deep-sea pressure observations, and range mostly in the same order of magnitude of the maximum heights of the tide gauge observations. It was found that the forecast uncertainties become larger for greater earthquakes because the tsunami source is no longer approximated as a point source for greater earthquakes (e.g., Mw>8). The forecast results for the coasts nearest to the epicenter should be carefully used because the coasts often experience the highest tsunami with the shortest arrival time (e.g., <30 minutes).

Keywords: tsunami forecast, seismic centroid moment tensor, forecast accuracy, forecast uncertainty

Brief History of Effective EEW Systems

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A first EEW was proposed by Dr. J. D. Cooper on San Francisco Daily Evening Bulletin dated 3rd November 1868 after a failure of an earthquake prediction. Around 100 years later, Dr. M. Hakuno et al. proposed “A system 10 seconds before a strong motion” for Tokyo metropolitan area in 1972, independently from the concept above. Although many scientific research institutes in Japan tried to realize this without image of effective usage and some research papers were produced, they finally failed for practical use. On the other hand, Japanese National Railways at that time recognized strongly the necessity of EEW for the safety of the high-speed railways with a concrete image of disaster prevention.

The earthquake damage is caused mainly by the earthquake motion more than Ijma 5, JMA intensity, so the conventional instruments was triggered by acceleration corresponding to Ijma 4 to issue before reaching Ijma 5 and to omit unnecessary warning caused by the other vibration. Because of the dilemma that lower alarm to get longer leading time caused increasing over warning, we tried various measures as restricting the observing frequency range or observing the large event at the area close to the occurrence zone.

UrEDAS, Urgent Earthquake Detection and Alarm System, was developed in 1983 and used practically for Tokaido Shinkansen since 1992. UrEDAS detects the initial P-wave motion and estimates the earthquake parameters. Then it estimates the damage area from the parameters and issues proper warning. Because only a basic seismological knowledge is applied for UrEDAS methodology and then the physical meaning is clear. The estimation is done continuously at every 1/100 seconds as sampling time using three components waveform data at a single station. The estimation terminates almost at the same time of the detection, but only the estimation of the initial motion period requires three seconds as one period corresponding to over 10 km of the fault length. And later we confirmed that the initial motion period can be estimated with 1/4 period and can be determined in one second.

At the time of the 1995 Kobe Earthquake, we faced a situation that UrEDAS issued warning properly but it could not reach the damaged area because of communication breakdown. And we recognized strongly a problem for the processing the warning to take three seconds especially for an earthquake just below the epicenter. So we developed Compact UrEDAS in 1997 for the warning at least one second after the detection even for a near earthquake and it was used practically in 1998 for Shinkansens of JR East. It monitors the realtime intensity, defined by us and its maximum value RI is almost same as Ijma, and issues a needed warning by estimated maximum intensity on detecting the initial P-wave. The processing time for warning was shortened to 0.1 seconds from initially one second.

For the 2004 Niigata-Ken-Chuetsu Earthquake, Compact UrEDAS detected it just above the hypocenter and alarmed one second after the P wave detection. The warning made the high-speed running Shinkansen train close to epicenter apply the emergency brakes and succeeded to keep safety of 154 passengers and staffs without injury despite a derailment.

UrEDAS and Compact UrEDAS have been integrated to FREQL, Fast Response Equipment against Quake Load, as the advanced small-sized-portable P-wave warning device in 2004. FREQL has been adopted presently not only for railways but also for a nuclear power plant, stadiums and factories. And it is equipped as an emergency device for hyper-rescue teams.

An on-site FREQL at a hard rock site on foot of Oshika peninsula issued an EEW properly and quickly

with maximum RI 5.5 for the 2011 Tohoku Earthquake. After this, we advanced some technics for more quick and reliable warning.
Finally I’d like to emphasize that EEW is only a supplement for disaster prevention mainly as reinforcement to avoid overvaluations of EEW effect.

Proposal of earthquake early warning system estimating damage assessment of buildings and structures in metropolitan area

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< >
An earthquake of magnitude 5.2 with focal depth of 57 km occurred beneath Tokyo bay on September 12, 2015. Shaking intensities by this earthquake are ranging from 2 to 5- in a small areas of nearly same hypocentral distances. This observation suggests that it is almost impossible to predict accurate shaking intensity by the present EEW system operated by JMA, which determines hypocenters and magnitude and transmits them for the estimation of shaking intensity at user's location, because the spatial large change in observed shaking intensity is originated to the existence of very strong lateral heterogeneity in the site amplification factors and the complexed deep structure but not in the estimation errors of hypocenter location or magnitude. We proposed to install a new EEW system specialized for the metropolitan areas.
2. Why we need a new EEW system specialized for metropolitan areas
1) The present EEW system has about 30 km of blind zone in focal areas where most of earthquake damages occur, owing to the limitation of the number of seismic stations. 2) There are large estimation errors of seismic intensity owing to the large lateral heterogeneity of site amplifications. It is shown that estimated values of site amplifications with 250m mesh do not able to greatly decrease estimation errors. 3) Each building has different strength and the natural period. Estimation of earthquake damage should be done based on the response of building to the earthquake shaking. 4) Because the earthquake damages are huge in metropolitan areas, which is limited in a small area in general, specialized earthquake early warning system for urban area seems to be effective.
3. Proposed EEW system in metropolitan areas
1) Install seismometers with an interval of several hundred meters which send observed real-time waveform data to their data center. 2) Register data of user's buildings or structures to the data center, such as the location, dumping factor, and strength of buildings. 3) At a time of strong shaking, the data center predicts shaking intensity using real-time P wave data transmitted from the closest station. It also calculates response of buildings associated with the ground shaking and estimates damage assessment of individual buildings. 4) The data center sends these computed results to each owner of building or users so as to do something for the mitigation of earthquake damage. Since there are seismic stations closed to each building in the proposed EEW system, we can consider that shaking at each building are approximated by the shaking recorded at the closest station. Therefore, we can consider that the proposed system can issue accurate EEW information to individual users. It is also pointed out that shaking intensity is predicted by the use of near-by stations, there are almost no blind zone.

4. Effectiveness of the proposed system
We checked the accuracy of shaking intensity estimation by the proposed system. We estimated values of shaking intensity using 1800 P wave data recorded by K-net station and found that the average estimation error of shaking intensity is 0.5. Since the shaking intensity is predicted by the use of waveform data at near-by station in the proposed system, we are able to consider that the average estimation error obtained by K-net data is approximated to that by the proposed system. We also calculated estimated errors of shaking intensity estimation from the attenuation equation with

putting parameters of hypocenter location and magnitude used in the present EEW system. The average error in this case is 0.91, which is much larger than the value of 0.51. The proposed system compute the response of each building associated with ground shaking. it may be possible to issue warning about the fall down of unfixed furniture.

Keywords: Earthquake early warning, metropolitan area, proposal

Real Time Strong Motion Prediction by High Dense Seismic Observation Network

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Most of the damages by shallow inland earthquakes are concentrated on the fault and surrounding areas. For instance, the highest level of intensity by an event of M7 class is often located within an area of 50-60 km from the source area. It is also noted that the shaking duration in the source area is approximately of 20-30 s. However, the current Earthquake Early Warning (EEW) in Japan has the difficulty to reach the strong motion prediction information in this area. In this study, we argue the possibility of using the peak ground accelerations (PGAs) and peak ground velocities (PGVs) obtained from P-wave amplitude for EEW. We investigated PGAs and PGVs in time step of 0.1 s (10 samples) of P-waves using 100,000 records from 2,000 events. The data were obtained from K-NET of National Research Institute for Earth Science and Disaster Prevention (NIED) from 1996 to 2016. Events were located in inland and coast regions, and records with a maximum epicenter distances of 20 km were included. In our results, the amplitude ratio of PGAs and PGVs obtained from S-wave to those obtained from P-wave has approximately a value of 5.9, which is close to the theoretical value (i.e., value of 5). The amplitude ratio shows a strong correlation with the time step when reach 0.5 s and follows, measured from the onset of P-wave. The PGAs and PGVs amplitude obtained from short period of P-waves are likely proportional to the scale of destruction, which it makes possible to estimate the microscopic seismic source parameters such as the inhomogeneity, strong motion generation area (i.e., asperity size), and the stress drop in the source area. We discuss the changes of the apparent velocity with different azimuthal angles of the source and surrounding areas. We also discuss the optimum network distribution for EEW using the proposed method. This study shows the potential of strong motion prediction obtained from short-period amplitudes by densely distributed seismic networks.

Keywords: Earthquake Early Warning , microscopic seismic source parameters , optimum network

Rapid Magnitude Estimation in Earthquake Early Warning with Seismogeodesy

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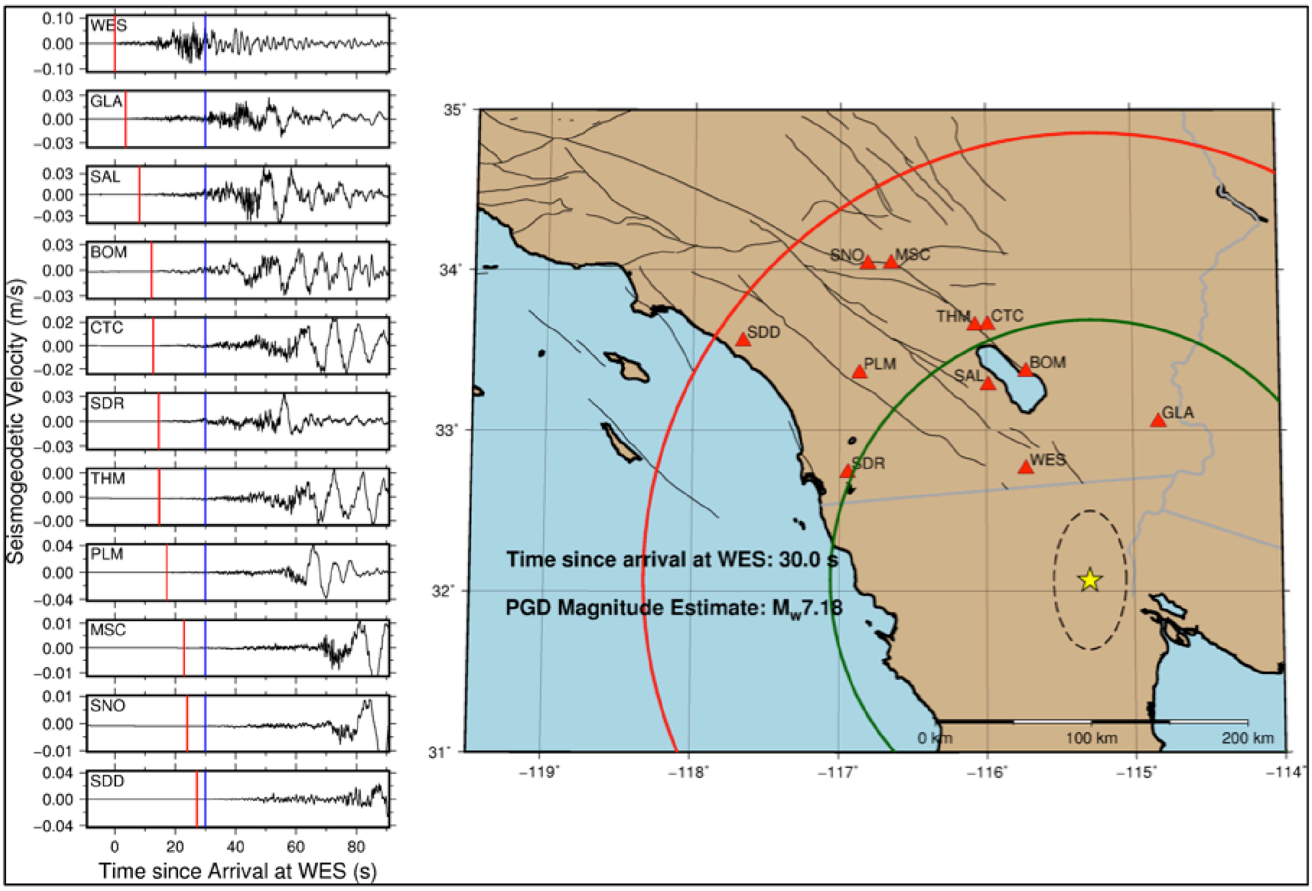
Earthquake early warning (EEW) is critical to reducing injuries and casualties in case of a large magnitude earthquake. Fault systems often coincide with populous cities, thus we require a P-wave detection method for effective early warning. Such a system must rely on near-source data to minimize the time between event onset and issuance of a warning. Current early warning systems typically rely on seismic instruments (seismometers and accelerometers). Global Navigation and Satellite System (GNSS) instruments are starting to be deployed, but are not yet fully exploited. Seismic instruments experience difficulty maintaining reliable data within close epicentral distance of large events. Large motions can exceed the dynamic range of broadband seismometers, and accelerometers conflate rotations and translations, causing spurious translational recordings that obscure the true nature of shaking. Moreover, the relation between ground motion amplitude and earthquake magnitude “saturates” for large earthquakes, causing magnitude underestimation that proved catastrophic for the 2011 M_w9.0 Great East Japan earthquake and resulting tsunami [*Hoshiba and Ozaki*, 2014; *Yun and Hamada*, 2014]. GNSS instruments capture the long period motions and have been shown to produce robust estimates of the true size of the earthquake source. However, GNSS alone is not precise enough to record first seismic wave arrivals, which is an important consideration for issuing an early warning. Our approach is to optimally combine direct measurements from collocated GNSS and accelerometer stations using a Kalman filter [*Bock et al.*, 2011] to estimate broadband coseismic displacement and velocity waveforms with complete spectral recovery from the static offset to the accelerometer Nyquist frequency, regardless of the intensity of shaking. This approach, referred to as seismogeodesy, includes the long period and static offset without interference from accelerometer errors or saturation for large magnitude events and, unlike GNSS alone, is precise enough to detect P-wave arrivals. We demonstrate the advantages of seismogeodesy for earthquake early warning via retrospective simulated real time examples for earthquakes in the western U.S., Japan and Chile. For event detection and location we use the seismogeodetic velocity. We also discuss the sensitivity of hypocenter location as a function of the distribution of monitoring stations near the source and demonstrate rapid magnitude scaling relationships [*Crowell et al.*, 2013; *Melgar et al.*, 2015]. The prototype early warning system developed at Scripps is being applied to local tsunami warning by the U.S. National Oceanic and Atmospheric Administration’s Tsunami Warning Centers. The critical input for tsunami warning is a rapid estimate of magnitude.

Keywords: earthquake early warning, seismogeodesy



Left: Seismogeodetic velocity waveforms at 11 GPS/seismic stations sorted by order of P-wave detection. Continuous blue vertical line denotes current epoch. Preceding red lines indicate when P-wave was detected from seismogeodetic velocity at each station.

Right: Once 4 stations have triggered, an estimate of the hypocenter can be made, denoted by the yellow star with one-sigma error ellipse on map. Hypocenter is updated with P-wave arrivals at additional stations. Propagation of P- and S-waves are shown by the partial circles (red and green, respectively), with the S-wave trailing the P-wave. In this scenario, it would take the S-wave front about 80-90s before arriving in the heavily populated areas of Riverside and Los Angeles Counties. Magnitude is estimated through Peak Ground Displacement (PGD) scaling relation using seismogeodetic displacement. Shown here is a frame 30s after P-wave detection at the first station.

Improvement of the P-wave detection method in real time by using kurtosis statistics

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The current the earthquake early warning system uses ST/lT algorithm (Allen, 1978), to detect seismic waves. Recently, Saragiotis et al,(2002) suggested a method to identify P-waves by using kurtosis statistics which was more robust than the STA/LTA. The method was used to create seismic catalogs, and designed for off-line process. To apply this method for an earthquake early warning, we need a modification to make the calculation acausal and enable the real-time processing by getting a little creativity with data length and noise rejection. Here, we propose a real-time P-wave detection method using kurtosis. an d We use strong motion records for earthquakes which record seismic intensity greater equal to 6 in the JMA scale between April,2005 and July, 2015. We selected the records with hypocentral distance within 100km. We tested various P-wave detection algorithm; STA/LTA, off-line kurtosis algorithm(Baillard et al,2014)), and real-time kurtosis algorithm (this study). We compared manual detected P-wave arrival times with P-wave arrival times detected by those methods, and evaluated the performance of our method. As a result, we can determine P-wave arrival time more precisely and earlier than STA/LTA and manual pick time by using kurtosis(this study) because our method is more robust and more sensitive to small changes in amplitude. Our approach will contribute to increase the accuracy of location determination of earthquakes, and improve the estimation of the shaking intensity of earthquake early warning.

Keywords: kurtosis, P-wave picking, earthquake early warning

Reduce False Alarm Due to Non-Earthquake Events for On-Site Earthquake Early Warning System in Schools

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An on-site earthquake early warning system (EEWS) can provide more lead-time at regions that are close to the epicentre of an earthquake since only seismic information of a target site is required. The on-site system extracts some P-wave features from the first few seconds of vertical ground acceleration of a single station and then predicts the intensity of the forthcoming earthquake at the same station according to these features. However, the system may be triggered by some vibration signals that are not caused by an earthquake or by interference from electronic signals, which may consequently result in a false alarm at the station. In order to reduce false alarms caused by non-earthquake events and at the same time keep earthquake alarms, an approach based on Support Vector Classification (SVC) and Singular Spectrum Analysis (SSA) is proposed. The established SVC model are employed to classify the vibration signals and then a SSA criterion is added for identifying earthquake events that are classified as non-earthquake events by the SVC model with increased accuracy. The proposed approach is verified by using data collected from earthquake early warning stations of the National Center for Research on Earthquake Engineering (NCREE). The results indicate that the proposed approaches effectively reduce the possibility of false alarms caused by unknown vibration events.

Keywords: On-Site Earthquake Early Warning, False Alarm, Non-Earthquake Events

Site Effective Earthquake Early Warning Outreach

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The earthquake early warning (EEW) concept is getting increasingly prevalent and somewhat replacing the expectation for earthquake prediction. An extensive real-time monitoring and EEW system installed in a wide region can detect an earthquake within seconds, and immediately issue alerts to affected areas through public media. On-site EEW systems developed for specific facilities may also detect an event and enable the facilities to take necessary actions before strong hits. Having timely warnings come accurate, EEWs can mitigate economy losses and save many lives. However, there are issues regarding EEWs provided by a big network and on-site monitoring systems that specialists in seismology know clearly, for which the general public has to be educated.
A big EEW system estimates seismic intensities using a conventional ground motion prediction equation (GMPE) as a function of distance that are not always in agreement with observed intensities. The actual intensity distributions in felt earthquakes show short-wavelength variation. The frequency band in which seismic intensities are determined is from about 0.5 to 10 Hz, and thus the response of subsurface structure is significant in the estimation. The ground motion at a specific site should be evaluated not only by a GMPE and a site amplification factor, but also accounting for the incident azimuth of incoming seismic waves. We have some exploratory studies to illustrate the local subsurface effects using data recorded by the dense network of strong motion instruments (with a station interval of less than 1.5 km) in Yokohama City. We used several small earthquakes of a similar magnitude (M~4.5) that are located at an epicentral distance of ~60 km from the network and provide different incident azimuths of incoming waves to the network. The observed ground motions at the stations show variations among the events reflecting 3D structural effects along the propagation paths. We also show the variation of amplification from a borehole to the surface using Kik-net data, and suggest that on-site calibrations are necessary for better intensity estimates. Should an earthquake occur directly beneath a crowded metropolitan area, e.g. Tokyo, the warning time is very short and cannot be extended by increasing the station density of a big network.

Keywords: Site Effective Earthquake Early Warning

