ShakeAlert: Using early warnings for earthquakes along the US West Coast

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In 2016, the ShakeAlert earthquake early warning (EEW) system for the US West Coast progressed from demonstration to production prototype operations. This progress has been funded by the US Geological Survey and the Gordon & Betty Moore Foundation. 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. During the demonstration phase, beta-test users from critical industries and institutions in US West Coast states were recruited for the EEW system, to observe the alerts produced, think about actions their organization could take and provide feedback for improving the system. With the advent of the prototype production system, some users are developing and implementing actions - planned responses to an alert that would protect lives and reduce losses. We also continue to test and develop alert 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 both the 2014 South Napa (M6) earthquake and a M5 earthquake near The Geysers, CA, the BART operations center received EEW alerts from ShakeAlert and their automatic actions worked as planned. Most recently, PG&E, a northern California gas and electrical power company has begun a pilot project to explore and implement personal and automatic actions to ensure staff safety and improve resilience. Other pilot project participants include additional mass transit organizations and utilities, emergency management offices at various levels of government, school districts, pipeline operators, mass media organizations such as radio and television, and medical centers.

Keywords: Earthquake Early Warning, Seismology, earthquakes and society, rapid earthquake information

Real-Time Risk Reduction Through Early Warning, Earthquake and Volcano Monitoring in Southern California, USA

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More than 20 million people live in southern California, astride the Pacific and North America plate boundary. Caltech and USGS operate the Southern California Seismic Network (SCSN) to provide timely disaster mitigation in the form of early warning, event notification, ShakeMap, and other data products.

The earthquake early warning (EEW) project (ShakeAlert) analyzes SCSN data to identify the P-waves of earthquakes and issue warnings. The ShakeAlert prototype production system has been operating in a test mode for more than a year. Two point source algorithms report rapid earthquake magnitude and location that are received by UserDisplay and cell phone apps operated by pilot users. In the future, finite source algorithms will be added to the system to improve performance for the largest events.

Real-time processing provides accurate magnitudes and hypocenters within two minutes. Within 5 minutes, an accurate ShakeMap of the peak amplitudes of shaking provides a geographical view of potential damaging shaking for emergency responders. In the same time frame, a seismic moment tensor to identify the causative fault and evaluate tsunami hazards is available. In the case of unusual activity, seismologists provide near real-time situational awareness to warn civic authorities of increased hazards levels. We also operate seismic swarm detectors to identify possible onset of volcanic activity, alerting civic authorities.

The SCSN processes data real-time and routinely archives more than 15,000 earthquakes every year; in case of a large sequence, it may archive more than 60,000 events per year. The Southern California Earthquake Data Center (SCEDC) archives the data and facilitates the use of the SCSN data for scientific research, earthquake engineering, and public communication. All 80TB of data produced by the SCSN are freely distributed via the SCEDC; waveform data are made available online within minutes of the occurrence of an earthquake. The magnitude completeness level since 1981 is M1.8, on average, within the SCSN reporting region. The template-matching catalog that is being constructed for the SCSN will have a completeness level of approximately M0.0, as template matching detects 20 to 30 times more events than the regular catalog.

The performance goals of the SCSN are to deliver data for earthquake early warning (EEW) processing within 0.5 sec as well as a continuous stream of data for archiving and future processing. The SCSN records real-time seismic data from more than 500 stations. To capture data on scale, these stations have 24-bit digitizers with a variety of sensors, including strong motion, broadband, and short-period sensors. By using two sensors at each station, the SCSN has the capability of recording data on scale for a magnitude range from < M0 to > M8. To ensure timely data delivery and redundancy in data communications the SCSN uses cell modems, microwave, radio, and satellite links for data communications. We use various tools to monitor the state of health of stations, primarily to detect data latency, and sudden changes in data quality. To ensure data integrity the SCSN uses virtual private networking (VPN) to secure data delivery from remote stations. For data processing we use AQMS and earthworm software, and parametric data are stored in an Oracle database. Metadata are maintained in

the Station Information System Database (SIS), which is a relational database designed to store equipment inventory and produce metadata information in a variety of formats, including dataless SEED and station XML metadata information.

To take advantage of publicly available cloud computing facilities, we have already migrated some of our operations into the Amazon web services cloud (AWS). We plan to distribute products from the AWS and maintain a long-term archive in the AWS Glacier facility. This will significantly reduce the vulnerability of SCSN and SCEDC operations during future earthquakes in southern California.

Keywords: earthquake monitoring, earthquake early warning, seismicity & seismic network, data processing, security & cloud computing, ShakeMap, Reducing risk from natural hazards

An International Platform on Earthquake Early Warning Systems under the aegis of UNESCO

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The Sendai Framework for Disaster Risk Reduction 2015-2030 recognizes the need to "substantially increase the availability of, and access to, multi-hazard early warning systems and disaster risk information and assessments to the people by 2030" as one of its global targets (target "g"). While considerable progress has been made in recent decades, early warning systems continue to be less developed for geo-hazards and significant challenges remain in advancing the development of these systems for specific hazards, particularly for sudden onset hazards such as earthquakes. An earthquake early warning system helps in disseminating timely information about potentially catastrophic earthquake hazards to the public, emergency managers and the private sector to provide enough time to implement automatized emergency measures. In recent years, earthquake early warning systems have been developed independently in few countries. Provided that, in many instances, the development of such a system still requires further testing, increased density coverage in seismic observation stations, regional coordination, and further scientific understanding, there is a strong need to enhance the technical and operational capacities required for these systems and to further understand their implications for policy. In an effort to address this gap, in December 2015, UNESCO launched the "International Platform on Earthquake Early Warning Systems". The main objective of the Platform is to assess the current state of the art in the development and implementation of earthquake early warning systems worldwide, and to foster dialogue and international cooperation for capacity building around these systems. Here we will discuss the opportunities and challenges for the establishment of earthquake early warning systems around the world, as well as the aim, objectives and expected contributions of this newly established Platform.

Keywords: Earthquake, Early Warning, Geo-hazards

Testing a real-time GNSS-based earthquake and tsunami early warning system

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The goal of GNSS-based earthquake early warning (EEW) is to estimate magnitude, without saturation, and fault finiteness for the largest, most damaging earthquakes. This is especially important for tsunamigenic earthquakes, where slip on a finite fault can be used to guide local tsunami hazard warning in real-time. Because large events (M>6.5) are infrequent, geodetic algorithms are not regularly exercised and tested. It is therefore necessary to assess the performance of such algorithms using synthetic earthquakes and geodetically-recorded earthquakes worldwide. We will discuss the testing and performance of the Geodetic Alarm System (G-larmS) using both real and synthetic earthquake data. G-larmS has been in continuous operation since 2014 using event triggers from the ShakeAlert EEW system and real-time position time series from a triangulated network of GPS stations along the west coast of the United States. G-larmS uses high rate (1 Hz), low latency (<~5 s), accurate positioning (cm level) time series data from a regional GPS network and P-wave event triggers from the ShakeAlert EEW system. It extracts static offsets from real-time GPS time series upon S-wave arrival and performs a least squares inversion on these offsets to determine slip on a finite fault. During its 3 years of operation, G-larmS has only been tested in real-time by the 2014 M6 Napa, California earthquake. We therefore develop a catalog of 1300 Cascadia megathrust scenarios and 4000 individual ruptures on 25 faults in California built from realistic 3D geometries in order to test the system. Synthetic long-period 1Hz displacement waveforms were obtained from a new stochastic kinematic slip distribution generation method (Fakequakes). Waveforms are validated by direct comparison to peak P-wave displacement scaling laws, peak ground displacement GMPEs obtained from high-rate GPS observations of large events worldwide, and NGA-West2 spectral acceleration GMPEs at 10s period. In addition to the synthetic catalog, we also run real-time simulations for the recent M7.6 Melinka, Chile earthquake and the 2011 M9 Tohoku-Oki earthquake. We use the resulting finite fault sources to simulate tsunami hazards and demonstrate the usefulness of geodetic-algorithms for tsunami early warning.

Keywords: Earthquake Early Warning, Tsunami Early Warning

Numerical Shake Prediction for Earthquake Early Warning: Introduction of attenuation relation consistent with empirical GMPEs

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Numerical Shake Prediction proposed by Hoshiba and Aoki (2015) is a promising method for prediction of ground shaking. The method is different from conventional methods of Earthquake Early Warning, source information such as hypocenter location and magnitude is not required. Instead current wavefield of ground motion is estimated using data assimilation technique and then future wavefield is prediction using simulation of seismic wave propagation: the basic idea is the same as that used in Numerical Weather Prediction is meteorology.
Although Numerical Shake Prediction enabled more precise prediction than the conventional methods for near future (that is, near target location), it does not necessarily so for distant future (far location) because 2D space was used for simulation of seismic energy propagation in Hoshiba and Aoki (2015): attenuation of seismic energy (~amplitude^2) is proportional to (distance) $^{-1}$ in 2D, and (distance)$^{-2}$ in 3D. In many empirical Ground Motion Prediction Equations (GMPEs), the attenuation relation is between (distance) $^{-1}$ and (distance)$^{-2}$ for seismic energy propagation. For sample, -1.72 power is used for the Earthquake Early Warning of JMA. Introduction of 3D space into the simulation is not so difficult, but seismic observation is usually limited to the ground surface (2D) in which the data assimilation is applicable only at near ground surface.
To overcome the difference between 2D and 3D space, and realize virtually the arbitrary attenuation relation between (-1) and (-2), we introduce an adjust parameter in the seismic energy attenuation, which enables the prediction to be consistent with attention relation of the empirical GMPEs. It makes the prediction to be more precise even for distant future.
We will show results of predictions of the attenuation relation using crustal earthquakes such as the 2004 Mid-Niigata Earthquake and the 2016 Kumamoto earthquakes.

Keywords: prediction of seimic ground motion, earthquake early warning, GMPE

Reducing risks from earthquakes: earthquake alert and site-effective action in industries

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Expectations for earthquake early warning (EEW) are somewhat replacing that for earthquake prediction in the past. Alerts of strong hits can be delivered from a big network system to areas that may be affected, but only seconds before arrivals. Nonetheless, people in public may overly expect a timely accurate warning, and criticize it when the actual ground motions turn to be different from EEW. There are many algorithm developments that attempt to resolve issues related to accurate prediction of ground-motions using big network operations with a station interval of ˜20 km in real-time. However, the spatial resolution covered by a big network is typically on the order of ˜10 km while the variation of actual ground motions can be in a much smaller scale. Our exploratory studies have shown short wavelength variation of ground motions recorded by a dense local network (˜1.5km) that also depends on the incident azimuths of seismic waves to sites. This situation evokes concerns about EEWs provided by a big network and issues of on-site monitoring systems. In high-tech industries buildings were generally built with a conventional earthquake-resistant design that meets a high standard building code and are supposed to have the strength to avoid structural collapses. In addition they are more concerned about how to protect the contents in the company buildings, expensive equipment and machines from strong ground shaking. Machines may be in operation with high speeds and/or high voltage current etc. that are vulnerable to strong shaking. It may take more than seconds to fully stop the operations after the switches are turned off with an alert. If the machines are damaged, they could leak hazardous chemicals. There are many other issues in addition to EEW to make earthquake safety in industries. I will discuss a case study of site-effective seismic safety configuration at a high-tech company.

Keywords: Earthquake Alert, Site Effective Action

A Rapid Earthquake Detection Algorithm for Earthquake Early Warning: A Bayesian Approach using Single Station Waveforms and Seismicity Forecast

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The utility of Earthquake Early Warning (EEW) relies on the robust and rapid classification of near-site earthquake source signals from noise and teleseismic arrivals. We propose a new method to achieve this, which uses the three-component acceleration and velocity waveform data and Epidemic-Type Aftershock Sequence (ETAS) seismicity forecast information in parallel, producing the posterior prediction by combining the predictions from the heterogeneous sources using a Bayesian probabilistic approach. We collected 2,446 three-component strong-motion records for training and testing. The rapid prediction is available as quickly as 0.5 s after the trigger at a single station, achieving a precision of 98% at the first prediction with the classification accuracy increasing with time. The leave-one-out validation method also demonstrates confidence of robust performance for future earthquake signal detections. Our new strategy has shown promising results and the implementation of this methodology could provide significantly faster and more reliable EEW warnings to regions near the earthquake’s epicenter where the strongest shaking is observed.

Identification of nonlinear response and estimation of S-wave amplifications at ocean bottom seismograph sites in Sagami Bay area, Japan

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Deployments of large scale ocean bottom networks that comprise seismometers and pressure gauges (e.g., DONET in the Nankai Trough area, S-net in the Japan Trench area) are expected to contribute to earthquake and tsunami early warnings by prompt detection of earthquakes at subduction zones. The amplification effects of soft sediments at the ocean bottom seismograph (OBS) sites on the overestimation of the displacement-amplitude-based magnitudes have already been discussed (Hayashimoto and Hoshiba 2013; Nakamura et al. 2015). On the other hand, Hayashimoto et al. (2014) analyzed nonlinear site effects at three Off-Kushiro OBS sites which showed that recordings having PGA 100 cm/s^2 or greater display the nonlinear site response. Because the OBS sites are located on soft sediments, the sites may undergo large deformations during major earthquakes causing unpredictable site response. In this paper, we investigated nonlinear site effects and site amplifications at six K-NET OBS sites namely KNG201, KNG202, KNG203, KNG204, KNG205, and KNG206 located in Sagami Bay area of Japan. We employed the method of Wen et al. (2006) to identify the nonlinearity and the equation proposed by Noguchi and Sasatani (2011) to quantify the degree of nonlinearity. The methodologies use horizontal-to-vertical spectral ratios of S-wave recordings to identify and estimate the degree of nonlinearity (DNL). Our results showed that strong-motion recordings having horizontal vector PGA greater than 50 to 150 cm/s^2, depending on site, display clear signatures of nonlinear site response. For PGAs > 100 cm/s/s, peak frequencies of strong-motions are found to be shifted between about 20 % and 55% of the peak frequencies of weak-motions in the analyzed data ranges (PGA ~ 450 cm/s/s). Similarly, the reduction of spectral ratios occurs by about 5 % to 70 % of the weak-motion peak spectral ratios. After identifying the thresholds for nonlinear response, we used the S-wave part of horizontal components having PGAs smaller than the thresholds to estimate amplifications at 0.2 Hz to 20 Hz by spectral inversion method. Our results showed amplification factors of about 10 to 50 at frequencies between 0.2 Hz and 10 Hz. In the case of strong shakings, the amplification factors may be substantially modified by nonlinear response and this effect should be investigated for real time application of the recorded motions. We describe in detail the data, methodology, and results of our study for identification of nonlinear site response at the OBS sites in (Dhakal et al., 2017).

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Keywords: Nonlinear site response, Ocean bottom seismograph, Site amplification

Automatic Shutdown System in Gas Regulators for Real-Time Seismic Risk Reduction of a Populated City: Bursa, TurkeyAutomatic Shutdown System in Gas Regulators for Real-Time Seismic Risk Reduction of a Populated City: Bursa, Turkey

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Bursa is a city located within a region of first grade earthquake risk, and it has occasionally suffered devastating and massive earthquakes for more than 2000 years. After a large disastrous earthquake in Izmit in 1999, many earth scientists are expecting the next large earthquake on the western extension of the Izmit earthquake rupture zone. Bursa is located south of the western end of the 1999 earthquake rupture and there are many active faults in and around Bursa. Bursa has now almost three million inhabitants, many heavy/industrial factories and historical monuments. Most of the people are using natural gas for heating, cooking and production in their buildings. Bursagaz is an inner-city gas distribution company and they are aware of the high seismic risk in Bursa city, so, they want to reduce causalities, fires and explosions in their natural gas district regulators and main pipelines. For these reasons, we have started to install accelerometers inside some of the main gas regulators and set up an algorithm for initiating an automatic gas shutdown system into their network for reducing the seismic risk in the city. We plan to install seismic instrumentation within a four-year-project and each year the seismic network will be growing by installing new accelerometers. We are also testing different algorithms to reduce false alarms aiming at a more secure and robust shutdown system. There are five different active fault lines in and around Bursa city having potential for creating M6.5 or larger earthquakes. Our first aim is to install accelerometers inside the inner city regulators located on and next to the main fault crossing highly populated regions of Bursa city center as a priority. By installing accelerometers very close to the active fault, we can detect PGAs more quickly and effectively. In the first phase of the project, we installed 15 accelerometers in the field and provided data collection and processing algorithm software in Bursagaz central building. All digital data are transferred by using GSM lines to this data center. In the second phase of the project, we installed another 10 accelerometers along the second active fault located in the Bursa city center. The project has not completed yet. During third and fourth project phases, the total number of accelerometers will be reach up to 50 within 2 years. At present, Bursagaz has 163 district regulators working in the city and all these regulators are connected to the company center with online SCADA communication system. Our main idea is to install one accelerometer at the central regulator and controlling at several district regulators in the surrounding to this instrument. Whenever the processing algorithm detects a certain level of acceleration due to a moderate or large earthquake, it will firstly observe PGA values for each single instrument and then calculate PGA values by using attenuation relationships for all regulators to finally compare these values with predefined threshold values. In case of exceedance of a threshold level, a shut-off signal will be send to those district regulators having higher PGA values than their threshold values. The installed algorithm will also calculate and estimate damage information in gas distribution infrastructure and create damage distribution maps very quickly and correctly. This information will be send to Bursagaz Technical and Emergency Response Teams that they could take all necessary actions to mitigate the disaster quickly and effectively. Our second aim is to use

Bursagaz seismic network as a core unit of Bursa City Earthquake Early Warning and Rapid Response System. The project team is going to cooperate with local authorities to integrate their system with the national network and increase the number of accelerometers for having a better station coverage for implementing an early warning and rapid response system for Bursa. To this aim, ArNET seismic network is integrated with Bursagaz network. Thus ArNET data of fifteen online seismic stations will be combined with Bursagaz data in the Bursagaz operation center. The SEISAN and SeisComp data acquisition and automatic location software are already installed and at present local earthquakes are monitored and located automatically. We are still working on the improvement of the system to reduce false alarms and time delays of information about location and magnitudes of earthquakes. Installation procedure of Bursagaz Real-Time Seismic Risk Reduction System, algorithms of automatic shutdown system, integration of seismic monitoring network, recorded events, system response, combination and integration with earthquake early warning and rapid response system will be discussed.

Keywords: seismic risk, early warning and rapid response, shutdown system

A new methodology for Earthquake Early Warning (EEW) by a high-dense seismic network

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Many of current EEW systems issue estimated intensity distribution maps according to empirical attenuation relationships which require information of source parameters and focal distance. These information are determined based on point source model which is not applicable for finite source model of large earthquakes. EEW is essential for the source area of inland earthquakes where heavy damages are expected. In most cases, EEW is issued lately in the source area which described as a "blind zone". Seismic networks, in case of Japan, are deployed for the determination of hypocenter at about 20-30 km interstation distance. That span delays the detection of P-wave arrivals by about 3-4 s. It should be suitable for the real time monitoring of seismic phenomenon that transfer on about 2.7 km/sec of the rupture, 3.5 km/sec of S waves and 6.0k m/sec of P-waves velocities. In this study, we present a new methodology for EEW which uses peak ground acceleration (PGA) estimated from P wave portion, taking advantage of the differential velocity (i,e., ~1.73) and the amplitude ratio (i,e., ~1/5) of P and S-waves. The efficiency of this method suggests the distribution of a high-dense seismic network of 5 km interstation distance, considering a span distance less than that of velocity of P-wave (i,e., 6 km/s). The slowness analysis of P waves tells information of the rupture starting point and its depth. Firstly, peak ground acceleration (PGA) on free surface is estimated from the maximum P-wave amplitude in one-second time step until the arrival of S-wave at the first detected station, and then adjusted to that on the engineering base (PGA_E) by eliminating the site effect. The S wave detection is performed by the amplitude comparison method of the synthesized amplitude of the two horizontal components and the vertical component. Secondly, we estimate PGA_E on far site from a relevant attenuation relationship and adjusted to PGA considering site amplification. Finally, we issue real-time intensity map in every second time step till the declining of PGA. The described method is useful to improve EEW system and also to perform disaster estimation immediately after the occurrence of large event, in order to avoid data extrapolation and the time consuming waveform inversion analysis.

Keywords: EEW, PGA, PGAE, P estimation, blind zone, real time intensity

The Attenuation Relation for Ratio of S- PGA to P-PGA

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The performance of the earthquake early warning (EEW) depends on rapidness and accuracy. Responding the needs of particular users, a hybrid system using the central EEW and the on-site seismometer has been pursued from 2006. The system estimates the PGA(S) using the P wave PGA(P) of earlier arrival. Here we tried to construct a new attenuation formula for the ratio α between PGA(S) and PGA(P) taking account of the individual radiation pattern.
The strong motion strength is composed a) the radiation effect,b) attenuation and scattering, c) ground site effect. Latter two terms have been extensively investigated using empirical parameters to be corrected under the condition minimum residual. Sample earthquakes are those under the capital. Seismic data of the K-net of NIED are analyzed to estimate PGA, dominant frequencies, and the P/S ratio.
The P/S ratio for the North Tokyo Bay earthquake and the Genroku- type EQ. are 3.7±1.8, an3.5±1.8 nearly the same as the default value 3.4. On the other hand, the Tachikawa City Eq. and Tokai earthquake have 6.0±1.7 and 5.1±1.1, respectively. The Tama City Eq. has 2.2±1.5, very small value. The factor analysis showed the radiation effect is the dominant among the four factors. Further, the transversal dissipation was found to be introduced to agree the estimated α with the observed one. The Q factor for the transversal direction Qt is found to be 1/5 of Qs, and Qso = 93, Qpo/Qso = 2/3, and the geometrical dissipation index are $n_s = n_p = 0.69$.
It is found that the constructed formula agrees with the observed value of P/S ratio within a limit of several tens percent of intensity scale of JMA I_{jma}. The α value of the first approximation α_1 is obtained at the arbitrary site using the seismic parameters, the second by using correction term for the i-th seismic zone ν i , and the third another correction ε ij due to the combined effects of the earthquake and site j.

Keywords: Earthquake early Warning, strong motion forecast , Ratio of S- PGA to P-PGA, Attenuation Relation, Radiation Relation, 2D dissipation

Realtime estimation of eruption size using high-frequency seismic waves: empirical relations to predict eruption height from the seismic source amplitude of eruption tremor

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We studied the relationship between the eruption plume height and the high-frequency seismic amplitude of eruption tremor to explore the possibility to estimate eruption size in realtime. We estimated the source amplitudes (A_s) of eruption tremors using high-frequency (5-10 Hz) seismic amplitudes. We analyzed eruption tremors at Kirishima volcano in Japan and Tungurahua volcano in Ecuador. We found that the maximum eruption plume heights (H) during individual eruption tremors at these volcanoes were proportional to 0.21 power of A_s. We also compared time-series data of plume heights for the sub-plinian eruptions at Kirishima volcano in January 2011 with A_s values in corresponding time windows. The estimated relation between H and A_s was not represented by the power law relation when H is less than 6 km, and H becomes zero when A_s is less than a certain value. Based on these results, we proposed the empirical relations to predict the eruption plume height depending on the value of A_s. If we assume that the eruption volumetric flow rate is equal to the seismic source volume rate, the proposed relations can be reasonably explained with the physical process of plume rise. Our results suggest that the plume height can be predicted by the seismic source amplitude in realtime, which would contribute to improve eruption monitoring.

Numerical Shake Prediction incorporating heterogeneous structure: a case for the 2016 Kumamoto Earthquake

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Generally, ground motion prediction depends on three factors: source characteristics, path effects and site amplification. In the new concept of real time ground motion prediction scheme, called "Numerical Shake Prediction" proposed by Hoshiba and Aoki (2015), these three components are taken into consideration as follows: (a) Site amplification can be corrected using time domain filters (e.g. Ogiso et al., 2016). (b) Effects of source and path term are included in observed waveforms. Observed waveforms are used to estimate initial wavefield for prediction using data assimilation technique.
Incorporating heterogeneous structure in the real time ground motion prediction such as earthquake early warning should be one of the key issues to improve the precision of ground motion prediction. Homogeneous structure is used for the prediction of future wavefield in the current numerical shake prediction scheme. In this study, we took the heterogeneous structure into consideration in the prediction scheme so as to evaluate the effects of heterogeneous structure for the real time ground motion prediction.
First, we estimated heterogeneous intrinsic and scattering attenuation structure in the western part of Japan using Multiple Lapse Time Window Analysis (MLTWA: Hoshiba, 1993; Carcole and Sato, 2010). Derived structure shows strong intrinsic and scattering attenuation around active faults and volcanoes in the Kyushu area.
Then, we conducted ground motion prediction simulation based on the numerical shake prediction scheme with the heterogeneous structure estimated before. The target earthquake was the largest one of the 2016 Kumamoto earthquake sequence. In the case of 10 s ahead prediction, root-mean-square of seismic intensity prediction residuals became lower by 15 % in the case of heterogeneous structure than the case of homogeneous structure. The rate of improvement became higher in the case of longer lead time prediction.
Although there is still room for improvement in estimating structure, intrinsic and scattering attenuation structure derived by the MLTWA is useful for real time ground motion prediction as well as the discussion of tectonics of the region.

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We used waveforms observed by K-NET/KiK-net/Hi-net operated by NIED, the seismic network of Kyoto Univ., Kyushu Univ. and JMA. This study was supported by the Joint Usage/Research Center program of Earthquake Research Institute, the University of Tokyo.

Keywords: Real time ground motion prediction, Heterogeneous attenuation structure, The 2016 Kumamoto Earthquake

Real-time P-phase discriminator for earthquake early warning based on wavefield-estimation methods

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To improve prediction accuracy of earthquake early warning for large earthquakes (M>˜8), wavefield-estimation methods have been recently proposed that predict ground motion directly from observed ground-motion wavefield without hypocenter estimation (e.g., numerical shake prediction (Hoshiba and Aoki, 2015); PLUM method (Kodera et al., 2014)). These methods, however, have room for improvement in rapid warning issuance since their prediction processes rely only on strong motion by S phase and do not utilize P-phase information available before the S-phase arrival. In this study, we introduce a simple real-time P-wave discriminator using on-site V/H to extract P-phase information and discuss the effectiveness of P- phase discrimination by simulating the PLUM method combined with the P-phase discriminator.

1. P-phase discrimination

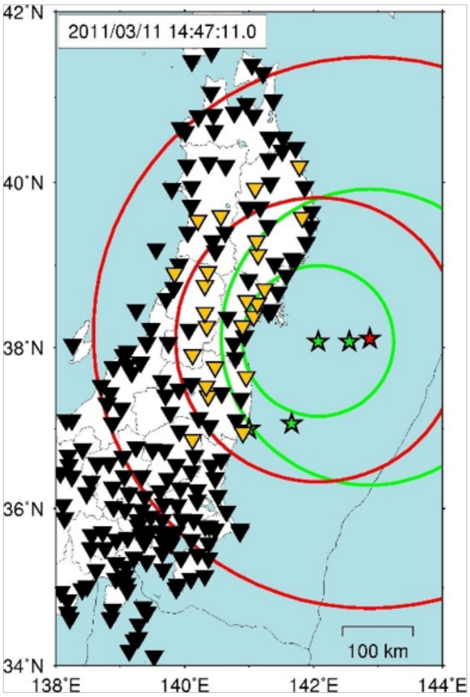
Many previous studies on P-phase discrimination use the polarity of particle motion (e.g., Ross and Ben-Zion, 2014). In this study, we focused on V/H (ratio of vertical to horizontal components of acceleration), which is easy to implement in a real-time system. The discriminator continuously calculates V/H independently of earthquake occurrences and declares P-phase arrivals when V/H reaches 1.0 or more. We tested this simple P-phase discriminator, applying to (1) the Tohoku-oki earthquake (Mw 9.0), (2) the Kumamoto earthquake (Mj 6.5), and (3) the Kumamoto earthquake (Mj 7.3). Results showed that the discriminator can clearly detect P phase of the initial part of the ground shaking in the all three events. Additionally, in (1), the discriminator recognized the P phase of strong motion generation areas (SMGAs) near the initial rupture point at some observation stations (Fig. a). In (3), the discriminator detected the P phase of the induced earthquake (Mj ˜5.7) in Oita prefecture (Fig. b). On the other hand, there were some cases where the discriminator declared P-phase arrivals just after theoretical S wave arrivals, and the discriminator could not clearly recognize the P-phase of southern SMGAs near Fukushima prefecture, which may indicate the discriminator needs to be improved.

2. PLUM method with P-phase discriminator

We modified the PLUM method by combining with the P-phase discriminator. We used a statistical relationship reported by Yamamoto et al. (2008), which states that seismic intensities of P phase are roughly 1.0 less than those of S phase. The calculation processes of the modified PLUM method are as follows: (i) (on-site S-phase prediction using P phase) add 1.0 to real-time seismic intensities at observation stations where V/H is 1.0 or more. (ii) (prediction based on the original PLUM method) take the maximum of real-time seismic intensities among observation stations within 30 km from a target point. We applied the modified PLUM method to earthquakes (1)–(3), mentioned in section **1**. The modified method provided longer warning times by 5 s in (1) and 1 s in (2) and (3) at the first warning issuances, compared with the original method. The final predicted seismic intensities of the modified method were comparable to those of the original method, which implies the on-site S-phase prediction did not cause serious adverse effects on prediction accuracy.

Keywords: earthquake early warning, P-phase discrimination, PLUM method, numerical shake prediction, SMGA, induced earthquake

(a) Tohoku-oki earthquake (Mw 9.0)



★ : initial rupture point (JMA hypocenter)

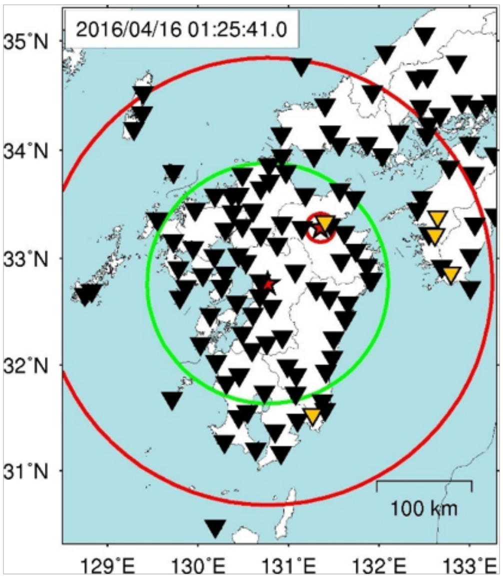
★ : SMGA (Asano and Iwata, 2012)

— : theoretical P wave

— : theoretical S wave

▽ : station where $V/H \geq 1.0$

(b) Kumamoto earthquake (Mj 7.3)



★ : JMA hypocenter

— : theoretical P wave

— : theoretical S wave

▽ : station where $V/H \geq 1.0$

Accuracy of real-time GPS/Acoustic measurement using a slackly moored buoy

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Coseismic geodetic data near the source region of an offshore large earthquake is crucial for the real-time estimation of its magnitude and source mechanism. GNSS network enables us to obtain onshore geodetic data in real-time. In offshore area, seafloor pressure gauge network (e.g. DONET) provides offshore geodetic data in vertical component. However, offshore geodetic data in horizontal component cannot be obtained in real-time because a seafloor positioning by means of GPS/Acoustic (GPS/A) method is carried out only by a campaign style using a research vessel. For the real-time detection of seafloor crustal movement associated with a large earthquake in subduction zone, we have developed a real-time GPS/A seafloor positioning system using a moored buoy. The buoy is moored by a slack cable which is 1.5 times longer than the water depth against strong current. The seafloor positioning is performed at unpredictable position due to drifting of the buoy, which is generally apart from the array center. This is a unique drawback of buoy observation compared to ship observation because this results in significant systematic positioning error. Therefore, we assess the accuracy of the GPS/A positioning for this ill-conditioned survey.

We have tested the system over a year in Kumano-nada, Nankai Trough and obtained the data for seafloor positioning in real-time as follows. A single acoustic ranging, which consists of continuous 11 pings with 65 sec interval, was carried out once a week and optionally on-demand. This sequence totally amounts to 102 times of ranging during the trial. The buoy position during acoustic ranging was estimated using kinematic PPP technique. The data for seafloor positioning were transmitted to the land station via iridium Short Burst Data service. Due to the low bite rate of the satellite communication, the data were automatically pre-processed and compressed within the buoy. It takes about ten minutes to transmit the compressed data for seafloor positioning after acoustic ranging, while GPS raw data and acoustic waveform data were stored in the buoy logger for technical purpose.

Using the data transmitted in real-time, we can estimate the seafloor array position for each ping. We regard the two standard deviations of the estimated array positons as the accuracy of the GPS/A positioning, because actual movement during the trial is negligible compared to the error. The final accuracy is 0.9/0.7 m in EW/NS component, which is significantly larger than that using a vessel (~0.1 m). During the trial, the buoy is randomly located within a ~4 km radius around the array while a vessel can stay on the above the array center. Apart from the array center, the error propagation of the observation data (e.g. the buoy position, travel time) arises due to uncertainty of the array geometry. Then, we classified the accuracy into two types; the buoy is within or out of the array. The former is 0.3/0.3 m while the one of the latter is 1.0/0.8 m. The seafloor crustal deformation associated with offshore large earthquakes (~M8) on the above of source area is considered to amount to a few meters. For the detection of it, we should improve the accuracy when the buoy is out of the array. There is room for the improvement also by re-determining the array geometry more precisely.

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Keywords: GPS/Acoustic measurement, Moored buoy

GEONET real-time analysis system for rapid finite fault modeling

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Geospatial Information Authority of Japan (GSI) has been operating a continuous GNSS observation network system since 1994. This system is known as GEONET (GNSS Earth Observation Network) and consists of approximately 1300 nationwide GNSS stations (GEONET stations) and the analysis center. Most stations collect GNSS data with 1-Hz sampling and transfer them to the analysis center in real time. Those data are available for surveying or research using real-time kinematic positioning technique. This technique is expected for describing cataclysmic earthquake from crustal displacement in short time especially after the 2011 off the Pacific Coast of Tohoku Earthquake in March 2011.

GSI and Tohoku University have developed the Real-time GEONET Analysis System for Rapid Deformation Monitoring (REGARD) since September 2011 to estimate moment magnitudes (Mw) soon after large earthquakes struck. This system consists of three subsystems. First subsystem does real-time kinematic positioning using RTKLIB (Takasu, 2013) and GSILIB (GSI, 2015). Second one detects seismogenic behavior using the RAPiD algorithm (Ohta et al., 2012) or the Earthquake Early Warning (Kamigaichi et al., 2009) and immediately run the third subsystem. This subsystem estimates Mw within three minutes using displacement vectors of GEONET stations (Kawamoto et al., 2014). Finally, results are mailed to persons involved.

The REGARD system successfully estimated the single rectangular fault models for the 2016 Kumamoto Earthquake (M7.3) occurred at 01:25 JST on April 16, 2016. The coseismic displacements as large as 1 meter were detected. The REGARD system calculated that Mw of the mainshock is 6.85 in 58 seconds from event origin time. The final fault model of REGARD was estimated along the Futagawa fault zone within 6 minutes. This result is consistent with the evaluation by the Headquarters for Earthquake Research Promotion, which reports that the Kumamoto earthquake is considered to be mainly due to the activity of the Futagawa fault zone.

Keywords: GEONET, RTK-GPS, real-time

Near-field tsunami forecasting from offshore pressure data in association with the earthquake early warning

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Effective mitigation of tsunami disasters requires tsunami forecasts that are made in real time and the provision of timely evacuation warnings to affected communities. Tsushima et al. (2014) developed tFISH/RAPiD, which is the initial sea surface height distribution estimated from rapidly acquired GNSS data provides robust finite source size information that is incorporated into an offshore tsunami data inversion for reliable tsunami predictions along the near-field coast. In contrast, it is slightly difficult to obtain the reliable initial sea surface height distribution for M7 class earthquakes in the offshore region by RAPiD because of the difficulty of the accurate estimation of small coseismic displacement field compared with more large events.
Based on these backgrounds, we have developed an alternative algorithm that improves near-filed tsunami forecasting based on offshore tsunami data after an earthquake by incorporating earthquake early warning (EEW) data. Basic scheme is the same with the tFISH/RAPiD, we estimate the initial sea surface height distribution using the EEW data. We assumed that the single rectangular fault deduced from the scaling law between the earthquake magnitude and the fault dimension.
We retrospectively applied tFISH/EEW to the 2011 Sanriku-Oki earthquake (March 9, 2011, Mw 7.2) based on the actual ocean bottom pressure (OBP) record and EEW information. The predicted results immediately after the earthquake (~2 to 3 min) the arrival times and wave heights of the first tsunami wave along the near-field coast could be predicted more accurately than the estimation based only on offshore tsunami data. After more time, the estimated initial sea surface distribution by the tFISH/EEW had continuously changed, and it was similar to that based on offshore tsunami data alone.
We will discuss more detail characteristic and its ability of the tFISH/EEW algorithm based on the various case studies.

Keywords: Earthquake Early Warning, Ocean bottom Pressure, Tsunami early warning

Rapid estimation of tsunami source information based on forward analysis of real-time data from dense offshore observation network

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Tsunami source information is generally obtained by inversion analysis of observation data. For the real-time tsunami forecast, predicted coastal tsunami height is derived by forward calculation using tsunami source model derived by the inversion of seismic waveforms or tsunami waveforms. However, the inverted source information has possibly large uncertainties in the real-time tsunami forecast because forecast information should be issued before arriving to the coast. In this study, we propose the method for estimating tsunami source information based on the forwarding analysis of offshore tsunami observation data from Dense Oceanfloor Network system for Earthquakes and Tsunamis (DONET) and the Seafloor Observation Network for Earthquakes and Tsunamis (S-net).

Keywords: Rapid estimation, Tsunami, S-net, DONET

