Earthquake Early Warning Using Ocean Bottom Seismic Data for Railways

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This article explains processes for improving the railway earthquake early warning system. These processes were introduced to use data transmitted in real time from recently developed ocean bottom seismic networks. Three mechanisms were designed to be able to exploit this data: 1) an algorithm for servers in OBS system base stations; 2) a procedure to allow transmissions between the servers and railway company receivers; and 3) a system built into the receiver to determine whether running trains need to be stopped or not. Confirmation was obtained that the proposed processes were able to reduce the risks to railways from earthquakes, because they are capable of extending the lead time before the arrival of strong seismic motion.

Keywords: earthquake early warning, ocean bottom seismic network, S-net, DONET, S-wave warning, ground motion prediction equation

1. Introduction

Railway companies in Japan utilize an earthquake early warning (EEW) system to reduce the risks to running trains in case of large-scale earthquakes [e.g., 1]. The EEW systems issue alerts to halt trains or to reduce the speeds of trains by measuring and analyzing seismic ground motions, when it is deemed that the earthquake event may cause damage to railway structures. Conventionally, railway company EEW systems used data collected from their own seismic stations installed along tracks (track-side seismometer) or away from tracks to be able detect earthquakes earlier (front-detection seismometer) [1]. Even though they also make use of public EEW data published by the Japan Meteorological Agency (JMA) to improve system redundancy, this data is derived only from land-based seismographs.

Recently, the Japan Agency for Marine-Earth Science and Technology (JAMSTEC) and the National Research Institute for Earth Science and Disaster Resilience (NIED) have been building ocean bottom seismic (OBS) networks in and around the Nankai trough and the Japan trench in order to provide further disaster management information [2, 3]. The OBS systems have densely distributed seismic stations, which can transmit the data in real time via cable connections. Using OBS network data in addition to the conventional measurements is expected to help improve railway running safety. This article introduces three developed procedures that show how OBS data can be applied to railway operations.

2. Ocean bottom seismic networks applied to railway operations

The NIED operates the Seafloor Observation Network for Earthquakes and Tsunamis (DONET) [e.g., 2, 3] (Fig. 1). The S-net consists of 150 stations contained inside of six cables deployed off the coast from Hokkaido to the Boso peninsula, while DONET consists of approximately 50 observation sites located off the Kii peninsula all the way to Shikoku island which is the area assumed to be the source of the Tonankai and Nankai earthquakes. Each station in both networks is equipped with seismometers (as well as pressure gauges for measuring tsunamis) and is connected via optical fiber cables with a base stations built on the coastline so that data can be delivered in real time. These sources of information are a valuable input for improving the EEW system for railways, because it should help extend warning lead times.

Figure 2 illustrates the process showing how S-net data is applied to railway operations. Data measured at stations is collected in the server at the base station. The server checks for any missing data and distinguishes noises from seismic signals; the server then converts the data into seismic index values, such as JR-PGA [e.g., 4] (referred to as the ‘on-site algorithm’). Processed results are then transmitted to the railway company receiver using a transmission procedure. Considering the transmitted data, the receiver decides whether it is necessary to halt train operations (decision procedure).

The mechanisms developed in this study were: 1) the on-site algorithm; 2) the transmission procedure; and 3) the decision-making procedure for managing railway operations. They are described in the sections below.
2.1 On-site algorithm

The conventional EEW system for railways employs P- and S-wave warning methods [1]. The P-wave warning estimates epicenter location [e.g., 5, 6] and magnitude [e.g., 7, 8] from the initial P-wave waveform and determines the area of potential damage using the M-Δ diagram [1, 4]. Although the P-wave warning has the advantage of speed, its accuracy relies on having a clear picture of seismic and noise data characteristics. Given that the OBS system has only just been launched, it was decided that the P-wave warning system should be tested at a later stage when sufficient recorded data was available to do this. The S-wave warning system, on the other hand, looks at whether or not the observed signal exceeds a pre-defined threshold, suggesting that the S-wave system may be more robust than the P-wave system if confronted with noise mixed into seismic data. Even though the S-wave warning system may be relatively slower, seismometers are installed in and around offshore hypocentral areas demonstrating that the S-wave warning is still capable of producing a long lead time. As a consequence, the EEW using the OBS data was first developed only for the S-wave warning method.

The server at the base station computes the seismic intensity indexes and generates a telegraphic message for transmission to the railway company receiver. The on-site algorithm checks the quality of data for errors or noise due to a fault in seismometers or in the system, to avoid any impact on railway operations. Figure 3 shows the flowchart: first, the server monitors if the data packets from the seismometers are successfully received without omissions or corrupted data; second, physical values (acceleration) are calculated from the digit samples and the coordinate system may be rotated because the on-site algorithm checks the quality of data for errors or noise due to a fault in seismometers or in the system; third, the server determines how long data has been missing; fourth, the server examines whether the information is noise or seismic data; then finally, accelerograms are converted to JR-PGA [4] and real-time JMA seismic intensities [9] for the S-wave warning system using OBS measured data. Note that these indices are the same as those applied when using ground data.

The noise-discrimination method in step four uses multiple techniques. For example, a pulse input due to an electronic fault in the system can result in a false alert. To avoid this, the difference in acceleration between a sample and the previous sample is computed, which can reveal...
pulse-like noise when the difference is significant. Another method to detect anomalies in data is to look at the ratio between components (NS, EW and UD). Large ratios are again sought out because some data elements may be unmeasurable due to a fault.

2.2 Transmission procedure

It is crucial in the EEW system for information computed in the server at the base station to be transmitted without omissions and delays to the receiver. However, if all seismograms are forwarded from the server to the receiver simultaneously, data transmission is likely to become congested due to the large amounts of data, because the OBS seismographs record data every 0.01 s (the sampling frequency = 100 Hz). To solve this, the server was programmed to send telegraphic messages at a longer interval (1 s or so) than the recording frequency (Fig. 4) and the message format defined to reduce packet volume. The format was composed of a couple of sections, e.g., the header section which contains general information such as sending time, and a data section containing seismic strength and the data-quality check. The total volume of data was about 1,000 bytes which is small enough to be sent stably even over a 64 kbps connection at 1 s intervals. User datagram protocol (UDP) was employed, allowing delivery without any unnecessary burden, because the protocol does not check errors in sending. To keep the transmission load constant, the sending interval is constant (1 s or so) regardless of whether an earthquake occurs or not.

2.3 Decision procedure

Section 2.1 describes how the S-wave warning employs OBS data. Because this method requires a threshold for the seismic index to be determined, the attenuation relationship of ground motion strength and the site-amplification effect were investigated in OBS data. Figure 5 compares the JR-PGA measured at S-net stations during the earthquake off the coast of Fukushima (Mj 7.4; 5:59AM, November 22, 2016 [JST]; the blue triangles) and a ground motion prediction equation derived from surface records (the black line), which demonstrates that OBS intensities decay at a similar rate as ground data. It is likely, however, that OBS values were significantly higher than surface observation data suggesting that the OBS data was amplified compared to data recorded on land because, for example, of soil conditions on the seafloor. Thresholds were therefore determined for each seismometer considering these facts.

The noise-detection methods shown in section 2.1 were
applied to data in each station. To further improve the reliability of the system, an approach was proposed that depends on multiple station data (Fig. 6) which was then applied to the receiver system. S-net stations are deployed at intervals of about 20 km, which means that strong ground motion observed at several stations without significant delay would indicate a large earthquake. Considering this, the developed approach is programmed to release a signal to stop operations if the ground motion strength exceeds the threshold (determined above) at one station (“parent” station), and simultaneously exceeds a lower strength threshold at another station (“child” station). That is to say, it is necessary to detect significantly large seismic index values in at least at two stations (value which can be modified by users) close each other. The reason why the threshold of the ‘child’ station value can be lower than the ‘parent’ station value is that if the observation at the child station is significantly greater than the noise level, it can be regarded as an earthquake which is also affecting the parent station. This means a warning can be emitted without any unnecessary delay. Given that there is no guarantee that a station will not develop a fault, groups of stations are formed to control the parent-child relationships. For example, if two OBS stations are separated by less than a certain distance (e.g., several tens of km), they can be set as parent and child.

3. Performance assessment

An assessment was made of how the railway EEW system using OBS data performs during an earthquake in terms of warning and lead times. The $M_j$ 5.8 earthquake off the coast of Fukushima (5:42PM, July 31, 2018 [JST]) was chosen as an example. This earthquake caused shaking in OBS sites on S-net and K-NET stations installed on land (also operated by NIED). Figure 7 shows the results of the assessment. In this test, for OBS stations, the JR-PGA threshold for the ‘parent’ station was set at 200 gal (cm/s/s) and at 5 gal for the ‘child’ station. For S-net stations, S2N14 (large red circle), was the closest to the hypocenter which can issue warnings about 10 s after the origin time. When 200 gal was exceeded at the seismometer, the measurement at the next station, S2N13 (small red circle), was already more than 5 gal. On the other hand, the K-NET station, FKS007 (large green triangle), gave a P-wave warning about 13 s after the earthquake began using the

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**Fig. 4** Schematic illustration of the transmission procedure

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**Fig. 5** Comparison of JR-PGA measured at the S-net stations during the earthquake off the coast of Fukushima ($M_j$ 7.4; 5:59AM, November 22, 2016 [JST]; blue triangles) and a ground motion prediction equation determined from surface records (black line)
C-Δ algorithm [6], and the FKS001 station (large yellow triangle) recorded the strongest motion on the ground after about 23 s. This demonstrates that the lead times using the OBS procedure based on the S-wave warning and using observations measured in surface stations using the P-wave method were approximately 13 s and 10 s, respectively. This therefore shows that the OBS network can be useful even for earthquakes rupturing close to land, because the OBS data using the S-wave warning alone can produce a longer lead time than the P-wave warning issued from a station located on land.

4. Conclusions

With a view to improving train running safety this paper introduces three methods that allow data from the OBS networks, S-net developed by NIED and DONET by JAMSTEC, to be applied to railway EEW systems. The benefits to use the OBS data are that they can be measured directly above the source area and that they are sent in real time.

The first developed method is an on-site algorithm for deployment on OBS base stations. The algorithm selects S-wave warnings for the system at the beginning of the operation and is equipped with some noise-resistant techniques.

The second method is a procedure for transmissions between servers and railway company receivers, which define the format of telegraphic messages communicated periodically using UDP.

The third method developed is a decision-making procedure method, developed to allow computations to be made in the receiver, in order to determine whether trains need to be stopped or not. The S-wave system warning threshold value was determined by examining comparisons between OBS and surface records in terms of an attenuation relationship (i.e., ground motion prediction equation), and, to further upgrade the robustness against noise, proc-

![Fig. 6 Approach to prevent a false alarm considering “parent” and “child” stations](image)

![Fig. 7 Performance assessment during the Mj 5.8 off Fukushima earthquake (5:42PM, July 31, 2018 [JST]) for the EEW system examining S-net and K-NET records: a) Distribution of stations and epicenter. The circle with the black solid line encompassing the epicenter estimated from FKS007 (the black cross) shows the potential-damage area using the M-Δ diagram; b) Time series of JR-PGA recorded at the S-net station S2N14, the K-NET FKS007 and FKS001 stations. The flipped triangles indicate the warning times derived from data analysis](image)
posed an approach which looks at ground-motion strength observed at multiple stations.

The conclusion to this study is that the developed procedures are useful for railway EEWs because they can extend the lead time even in cases where an earthquake occurs close to land.

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