REAL-TIME ESTIMATION OF EARTHQUAKE DAMEGE ON RAILWAY

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Abstract

Rapid resumption of operation after a medium-scale earthquake of frequent occurrence, has been greatly required in order to quickly recover a function of railway service. It is obvious that decision of resumption and inspection is able to be made effectively by using information on distribution of strong motion and structural damage along rails. So as to provide the above mentioned information to railway companies as quickly as possible after an earthquake occurrence, we developed a system for real-time estimation of earthquake damage on railway, named DISER (Damage Information System for Earthquake on Railway), and started its operation in August, 2019.

This system is firstly triggered by an earthquake early warning information disseminated from Japan Meteorological Agency. Then data on strong motion indices observed at K-NET, a nation-wide seismic observation network in Japan operated by the National Research Institute for Earth Science and Disaster Resilience, are automatically transmitted to the system. By using the K-NET data, the system estimates two kinds of information: strong motion indices at about 500m spatial interval along rails and a damage level for each railway structure. In the system, strong motion indices are calculated based on interpolation of the K-NET data, taking non-linear amplification characteristics of the ground into account. A damage level for a viaduct or a bridge is estimated from a nomograph by using *PGA*, *PGV*, a natural period of structure and a yield seismic intensity, and further a damage level for an embankment is estimated by using *PGA*, *PGV*, hypocentral distance, magnitude, a characteristic value determined by its shape, material property and a yield seismic intensity.

By analyzing information for 51 earthquakes processed in this system, it is confirmed that an average time to output information is 407 seconds (about 7 minutes) after earthquake occurrences, which includes a time to wait for data from the K-NET system. We also carried out an off-line blind test for 3 major earthquakes to evaluate an average estimation error by comparing with data observed by KiK-net, and found that the average estimation error of seismic intensity is 0.56. Finally we concluded the performance of the system is almost acceptable at the current stage for a practical use in the railway field.

Keywords: damage estimation, strong motion estimation, rapid resumption of railway, DISER

1. Introduction

Improvement of earthquake resilience is one of essential issues for railways in Japan. It was proposed that earthquake resilience of railway consists of two components, one is "strength" which prevents the functional decline of railway during earthquakes and the other is "recovering ability" which quickly recovers railway functions after earthquakes [1]. Though various countermeasures against earthquakes to improve "strength", such as an earthquake resistant design, have already been implemented in the field of railway, countermeasures to improve "recovering ability" are still limited.

Related to "recovering ability", rapid resumption of operation after a medium-scale earthquake has been greatly required by the public in these days. In particular, in a large city which has dense and wide railway networks, it may take a long time to inspect the safety of all the lines after a shaking of earthquake. If information on distribution of strong motion and structural damage along rails are provided immediately after the earthquake, it is obvious that decision of resumption and inspection is able to be made more effectively by using the information. However, it had not been feasible to utilize such information in a short time after an earthquake, because we need both real-time data from a dense seismic network and an effective method to rapidly estimate damage levels for a large number of railway structures in order to provide the information.

Since 1996, the National Research Institute for Earth Science and Disaster Resilience (NIED) has developed and began to operate K-NET, a nation-wide seismic observation network in Japan [2]. K-NET consists of about 1000 stations distributed over Japan and each station of K-NET automatically transmits seismic data to a central sever just after an earthquake. Furthermore, simplified methods to estimate damage of a railway viaduct, a bridge and an embankment with less computing time have been developed in these years [3, 4].

By using those seismic-network data and estimation methods, we developed a system for real-time estimation of earthquake damage on railway, named "Damage Information System for Earthquake on Railway" (DISER), so as to provide the information on distribution of strong motion and structural damage to railway companies as quickly as possible after an earthquake occurrence, and started its operation in August, 2019. In this paper, we describe a data processing flow of the system, damage estimation methods used in the process, and evaluation results on a practical performance of DISER.

2. Data processing flow

DISER has been specially designed to rapidly inform railway companies of information on strong motion distribution and damage levels of structures along rails just after an earthquake. Since rapidness is one of key issues of the system, the system effectively uses real-time data as well as databases prepared in advance. The prepared databases, real-time input data and output information of DISER are summarized as follows.

1) Prepared databases: A ground amplification database [5] developed by Railway Technical Research Institute (RTRI) and a structural database provided by a railway company.

2) Real-time input data: Earthquake Early Warning (EEW) information [6] issued by Japan Meteorological Agency (JMA) and strong motion indices of the K-NET stations transmitted from NIED.

3) Output information: Estimated strong motion indices (0.5Hz low-pass acceleration, Spectrum Intensity and seismic intensity) along rails and estimated damage levels of structures along rails.

Fig. 1 shows a data processing flow of DISER. The system is triggered by the final result of EEW information which is usually issued within a few minute after an earthquake occurrence. When the seismic intensity scale estimated in the EEW is larger than 3, the system receives strong motion indices observed at K-NET stations directly from NIED using a dedicated line. After receiving the K-NET data, the system determines an analysis area and calculates a spatial distribution of strong motion indices for the area by using methods described in 3.1. Then the system estimates strong motion distribution at about 500m spatial interval along a rail and finally evaluates damage levels of structures on the rail by methods explained in 3.2. Railway companies that use DISER are able to confirm the above mentioned results on a web page of the system. Fig. 2 shows an example of the web page.

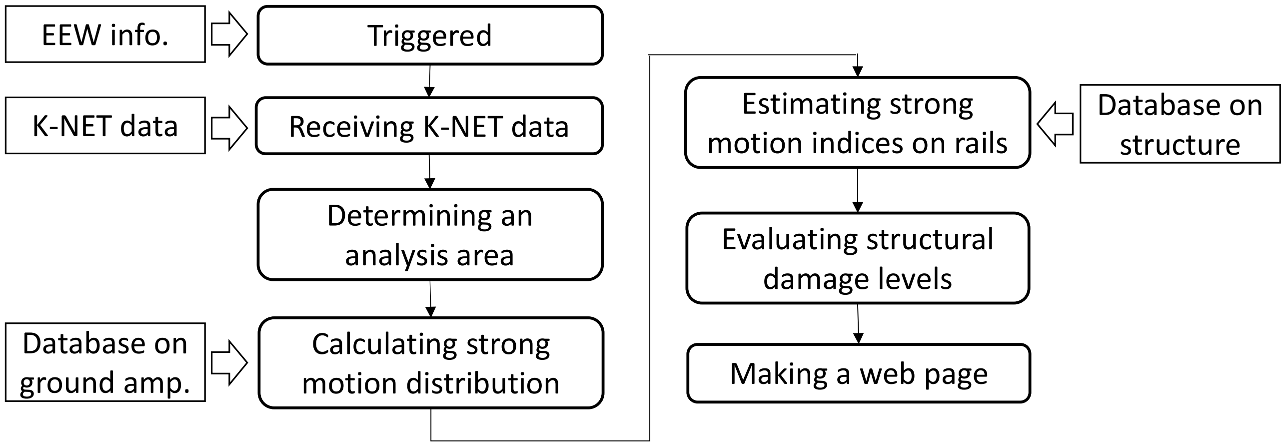

Fig. 1 – Processing flow of DISER

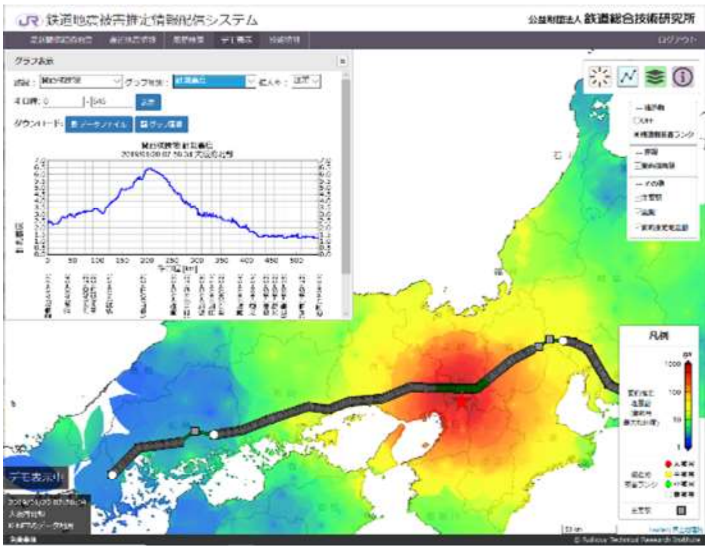

Fig. 2 – Example of the web page of DISER

3. Estimation method of strong motion and damage level

3.1 Estimation of strong motion

In this section, a process for estimation of spatial distribution of strong motion is explained. Fig. 3 demonstrates an image of its processing

First, peak accelerations and peak velocities on a bedrock (*PBA*s, *PBV*s) are calculated from peak ground accelerations (*PGA*s) and peak ground velocities (*PGV*s) observed at K-NET stations by using amplification factors of acceleration (Z_A) and amplification factors of velocity (Z_V). In the system, Z_A and Z_V is defines by

$$Z_A, Z_V = \sqrt{\frac{1+4h^2\left\{\alpha\left(T_g/T_b\right)^\beta\right\}^2}{\left(1-\left\{\alpha\left(T_g/T_b\right)^\beta\right\}^2\right)^2+4h^2\left\{\alpha\left(T_g/T_b\right)^\beta\right\}^2}}\ , \qquad (1)$$

where T_g and T_b are a natural period of subsurface layers and a predominant period of input motion at a bedrock (=$2\pi PBA/PBV$). Moreover h, α and β represent coefficients depending on amplitude levels. By using Eq. (1), nonlinearity of ground deformation and resonance phenomenon of subsurface layers are taken into account for calculation [7].

Second, a spatial interpolation of *PBA*s and *PBV*s is carried out at 500m mesh points on a bedrock. Inverse Distance Weighted (IDW) method with 40km search radius is adopted for the interpolation. IDW is selected because it was found that IDW performs better than other method such as Kriging interpolation for this purpose. Then *PGA*s and *PGV*s at all mesh points on a surface are estimated by using Eq. (1) again.

Finally, 0.5Hz low-pass acceleration, Spectrum Intensity and seismic intensity at all mesh points are converted from *PGA*s and *PGV*s by using Eqs. (2), (3) and (4).

$$\log_{10}PGA_{0.5lp}=0.4974*\log_{10}(PGA*PGV)+0.4684, \qquad (2)$$

$$\log_{10}SI=0.9751*\log_{10}PGV+0.0563, \qquad (3)$$

$$Is=1.0019*\log_{10}(PGA*PGV)+1.2463, \qquad (4)$$

where $PGA_{0.5lp}$, *SI* and *Is* represent 0.5 Hz low-pass acceleration, Spectrum Intensity and seismic intensity respectively.

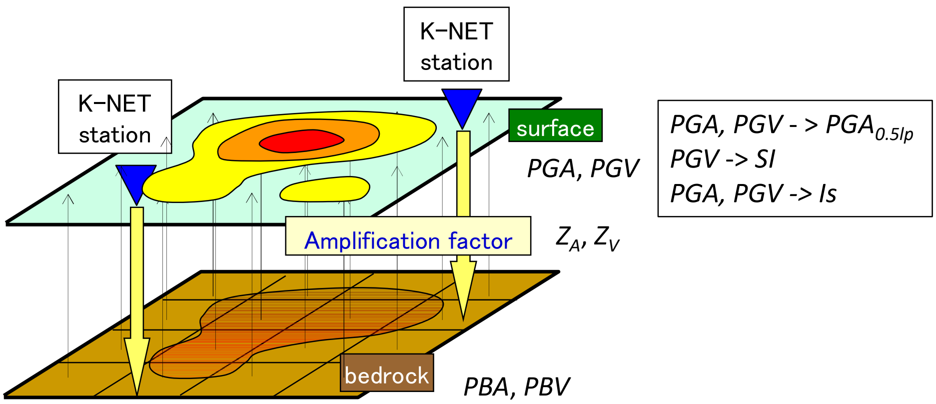

Fig. 3 – Processing image for estimation of spatial distribution of strong motion

3.2 Estimation of structural damage

Rapid estimation of structural damage just after an earthquake is greatly demanded by railway companies. Since a large number of structures are located along a rail, simplified method for estimating structure damage is necessary to compute damage levels of all structures in a short time. Recently simplified methods for damage estimation have been developed for some structure types. DISER uses the following methods for rapid estimation of structural damage along rails.

A damage level for a viaduct and a bridge is estimated by using the method proposed by Sakai and Murono [3]. In this method, damage level is evaluated from a nomograph by using seismic data (*PGA* and *PGV*) and structural data (a natural period of structure and a yield seismic intensity). The nomograph is shown in Fig. 4 and the definition of each damage level is denoted in Table 1. This method is simple enough to compute damage levels of a large number of structures in a very short time.

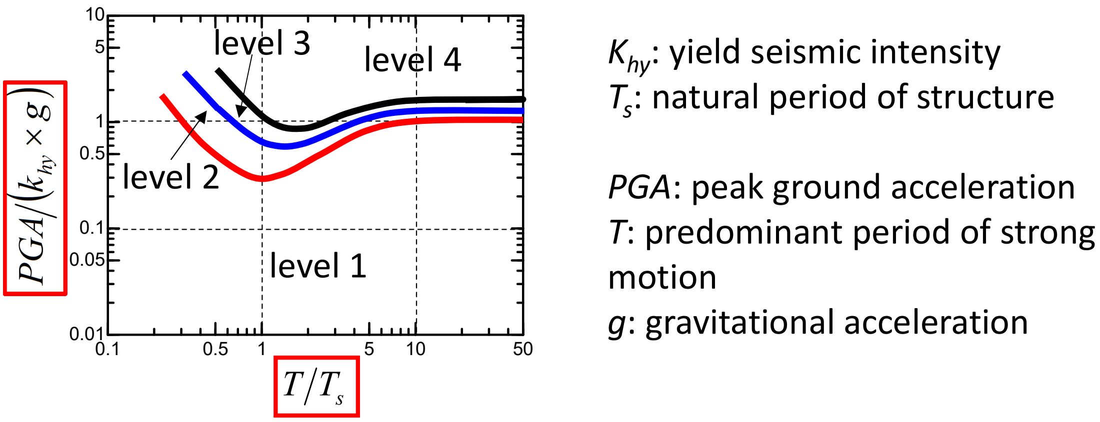

Fig. 4 – Nomograph for estimation of damage level for a viaduct and a bridge

Table 1 – Damage levels defined in DISER

Damage level	description
1	No damage or non structural damage
2	Minor restoration is required
3	Restoration is required
4	Major restoration is required

For estimating a damage level of an embankment, Sakai et al. [4] proposed the simplified method. The method is able to estimate a damage level by using seismic data (*PGA*, *PGV*, hypocentral distance and magnitude) and structural data (a characteristic value determined by its shape and a material property, and a yield seismic intensity). The computing time of this method is also minimum.

By using those methods, estimation of damage levels for numbers of railway structures is able to be done effectively in a limited time in DISER.

4. Performance and discussion

The system started its operation in August, 2019 and updated its software in September, 2019. The update was carried out to improve the rapidness of the process. After update, the system processed 51 earthquake data from September to December, 2019. In this chapter, rapidness and estimation accuracy of DISER are shown and discussed by using the data which were processed online.

Fig. 5 shows variation of measured processing times (from an origin time of earthquakes to an output time of information) with the change of magnitude for the 51 earthquakes. We can see a slight trend that indicates a time gets longer with an increase in magnitude. It is supposed that this trend can be seen because data collection time of K-NET and processing time of DISER get longer due to an increase of number of seismic stations for the process. An average time for the 51 earthquakes is 407 seconds (about 7 minutes). Considering the purpose of this system (ex. focusing inspection areas after an earthquake), we think 7 minutes is almost acceptable for railway companies.

We also confirmed estimation accuracy of DISER. In this analysis, we used the data of 3 major earthquakes (magnitude range: Mj5.5-Mj6.7). Seismic parameters of those earthquakes are shown in Table 2. These earthquakes include one which occurred during the test operation of the system. In order to evaluate the estimation accuracy we compared estimation data at KiK-net [2] locations with observed data by KiK-net. The number of the KiK-net data for 3 earthquakes is 456. Fig. 6 shows the comparison of the observation data and estimates in a scale of seismic intensity. Error RMS of the estimates is 0.56 in this analysis and it should be noticed that most of the estimates have errors less than 1.0 in a scale of seismic intensity. Comparing with the previous studies [8], it is reasonable to support that the estimation accuracy of the system is very stable.

The accuracy of estimation may be further improved by including seismic data and underground data of trackside areas measured by railways companies. Alhough it is necessary to consider the delay and estimation error of the information, it appeared that the information issued by DISER have great potential to improve rapidity of resumption of a railway operation after an earthquake.

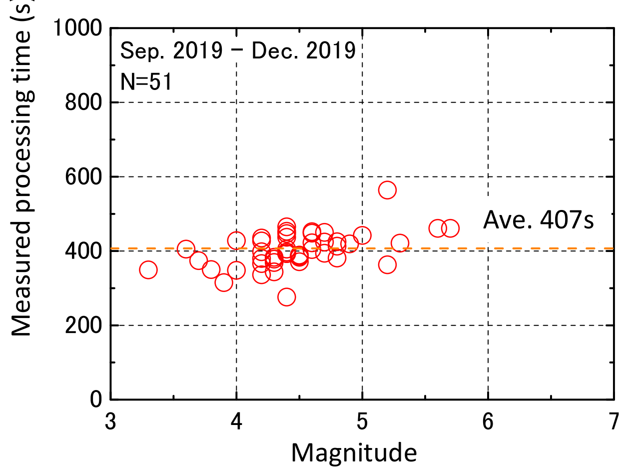

Fig. 5 – Measured processing times for 51 earthquakes

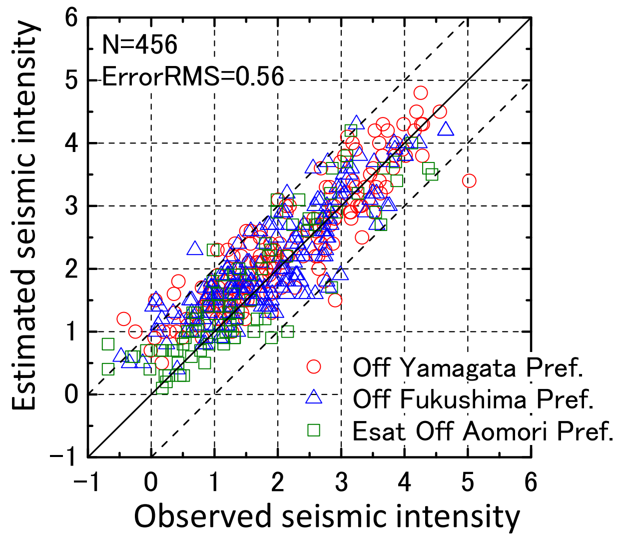

Fig. 6 – Comparison of observed and estimated seismic intensity for 3 major earthquakes

Table 2 – Seismic parameters of 3 earthquakes analyzed in this study

date	M_{JMA}	Depth (km)	Location	Max Intensity
18 Jun. 2019	6.7	14	Off Yamagata Pref.	6 upper
4 Aug. 2019	6.4	45	Off Fukushima Pref.	5 lower
19 Dec. 2019	5.5	50	East off Aomori Pref.	5 lower

5. Conclusions

We developed the system for real-time estimation of earthquake damage on railway, named DISER (Damage Information System for Earthquake on Railway), which estimates and issues a spatial variation of strong motion indices and damage levels of structures on rails just after the occurrence of an earthquake by using K-NET data. It is confirmed that the system can issue the information about 7 minutes after an earthquake and an average estimation error is found to be 0.56 in a scale of seismic intensity. Those performances are almost acceptable for the purpose of inspection after an earthquake and it is considered that the information by DISER will effectively support "recovering ability" of railway. We will continue to improve the system in order to provide more useful information to railway companies.

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