A Support System for Early Resumption of Regular Train Operations Applying Public Earthquake Information

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At present, in case of earthquakes with tremors exceeding the operational control threshold, walking patrols must inspect seismographs for each relevant track section, to ensure safety. In order to resume train operations more rapidly after restrictions have been imposed on train operations due to an earthquake, a working model system was developed which can accurately estimate seismic motion just after the earthquake. This system makes facilitates decision making for earlier resumption of traffic following the earthquake. By obtaining seismic information not only from railway operator’s seismographs but also from public data sources in quasi-real-time, this system estimates the distribution of the shake over meshed planes and extracts the seismic motion at any given chainage point along the target railway section being evaluated.

Keywords: operation control after earthquake, resumption of regular train operation, public earthquake information, estimation of seismic motion

1. Introduction

When ground motion during an earthquake exceeds the operational control threshold traffic control stops trains as early as possible when there is the concern that the tremors could impact railway facilities and running safety [1, 2]. Patrols then check the affected railway sections within the vicinity of the relevant seismographs, as part of the procedure for maintaining safety. Generally the seismographs which trigger the command to stop trains in case of an earthquake are installed along the tracks. In the case of Shinkansen tracks however there are other seismographs installed remotely which can raise an earlier alarm for railway operators in the case of subduction-zone earthquakes. These seismographs are located along the coast. Trackside seismographs also collect information about the impact of the earthquake on railway installations, which are employed to assess when operations can be resumed. However, since this evaluation involves visual inspections to check the health of the tracks and surrounding structures, the process is time consuming. There is therefore a need to perform these checks more accurately and more speedily to allow earlier resumption of train operations. Consequently, it is necessary to find a way to obtain precise estimations of seismic motion. Following the South Hyogo prefecture earthquake in 1995, a large number of seismographs were installed across the country by public institutions such as the Japan Meteorological Agency (JMA) and the National Research Institute for Earth Science and Disaster Prevention (NIED) [3]. The data gathered by these meters is publicly available. Thanks to progress in information and communication technologies in particular, these earthquake data are available in quasi-real-time. Up until now, decisions about train operations were based solely on information from the train operators’ seismographic data. Now however there is access to this new information which can facilitate decision making about operations in case of earthquakes. Based on the extra data it is possible to determine whether on-site patrol checks are necessary, and it is possible to narrow down the sections needing further attention, shortening the overall inspection time for tracks and structures. To achieve this, a support system was developed for early resumption of regular train operation which estimates the ground motion by utilizing public earthquake data. In addition to a summary report on the prototype system, the paper also describes experiments which were performed to validate the performance of the system and information was gathered about the resulting estimates of seismic motion.

2. Outline of the prototype system

Figure 1 shows the block diagram of the prototype system which was produced, and which is divided into a server and a client system. The server side of the system, captures seismic parameters and waveform data automatically from the homepage of JMA and NIED [4], and calculates the seismic motion index to be applied to the train operation control. The client system, estimates the ground motion in consideration of site amplification properties by the attenuation relationship method, the inverse distance weighted interpolation (IDW) method or the KRIGING method. This client system produces ground motion estimations and plots target track section structural damage according to severity based on chainage on a map. The Miyazaki maglev test line owned by the Railway Technical Research Institute (RTRI) was chosen as the model railway.
for developing the prototype system. The system computed the seismic motion for an earthquake in the Kyushu area. The Miyazaki maglev test line was previously used for investigating linear motor cars, and the total length of the line is approximately 7km. The prototype system was built for this railway.

3. Estimation method of the seismic motion

3.1 Estimation of the seismic motion by the attenuation relationship method

An empirical attenuation equation is often used as a simple method to estimate seismic motion. This method can be used to produce an estimate from only a few parameters, such as distance, magnitude and focal depth, and so on. Various studies were completed which produced a number of possible attenuation equations [5]. The peak acceleration value used as a reference for train-operation regulations was found prior to producing the prototype system. The system computed the seismic motion for an earthquake in the Kyushu area. Therefore there are very few examples of studies which examine the attenuation relationship equation of this peak acceleration value [6]. Accordingly new equations were found prior to producing the prototype system. The type of seismic motion indices investigated were peak ground acceleration PGA (gal), peak ground acceleration of 5Hz after high cut filter processing PGAJR (gal), seismic intensity Is and spectral intensity SI (kine). The functional attenuation relationship equation used is shown in (1).

\[
Y = a_1 M + a_2 D - b X + c_0 - \log_{10}(X + d_1 10^{-d_2}) + c_f
\]  

(1)

Where, \(Y\) expresses the seismic motion index to be calculated, which is \(\log(\text{PGA})\), \(\log(\text{PGAJR})\), \(\text{Is} \) or \(\text{log(SI)}\). And \(X\) is distance [km], \(M\) is JMA magnitude, \(D \) is focal depth [km], and \(a_1, a_2, b, c_0, d_1 \) and \(d_2 \) are calculated coefficients by regression analysis. The calculated coefficients are indicated in Table 1. The coefficient of \(c_f \) is a site modification factor that is computed in every observation point. It is fixed so as to make the average of the values zero at the seismograph point to use for a regression analysis.

| Table 1 Coefficients list of the attenuation relationships |
|------------------|------------------|------------------|------------------|------------------|------------------|
| \(a_1\) | \(a_2\) | \(b\) | \(c_0\) | \(d_1\) | \(d_2\) |
| \(\text{PGA}\) | 0.51404 | 0.00607 | 0.00404 | 0.48503 | 0.00581 | 0.5 |
| \(\text{PGAJR}\) | 0.54634 | 0.00588 | 0.00332 | 0.01746 | 0.00492 | 0.5 |
| \(\text{Is}\) | 1.09849 | 0.01065 | 0.00865 | -1.38401 | 0.00279 | 0.5 |
| \(\text{SI}\) | 0.65626 | 0.00531 | 0.00295 | -1.63288 | 0.01284 | 0.5 |

3.2 Estimation of the seismic motion by the IDW method

The IDW method is an estimation technique, which utilizes the distance between the calculation point and the observation site [7]. The definition expressions incorporated in the prototype system are shown in (2).

\[
Y = \sum_{j=1}^{n} w_j Y_j
\]

\[
w_j = \frac{1/r_i}{\sum_{i=1}^{n} 1/r_i}
\]

In this, \(Y\) expresses a calculated seismic motion value, \(Y_j\) is an observed seismic motion value, \(w_j\) is a weighting function, \(r_i\) is distance between an evaluation point and an observation site.

The IDW method in the prototype system only used observation data inside the search radius around the evaluation point, and this radius could be set at will. The procedure of the space interpolation is demonstrated in Fig. 2. The ground amplification information used by the prototype system is based on the public information from...
the public institute, NIED [8].

3.3 Estimation of the seismic motion by the KRIGING method

After the seismic waveform data was acquired, the KRIGING method can be used to estimate quake distribution [9], in the same manner as the IDW method. The technique introduced for the prototype system is called the Simple KRIGING method. It employs both the mean and the covariance. In this method, the trend component is the value of the attenuation relationship for the ground plane. And the random component is the difference between the observation value and the value of the attenuation relationship in terms of the ground plane. Here, the attenuation equation defined in this report is introduced to the KRIGING method. The definition expressions of this method are shown in (3).

\[ Y = \sum_{i=1}^{10} w_i \cdot Y_i \]  
\[ C(d) = a \cdot \exp \left( -\frac{d}{D} \right) \]  
\[ \sum_{i=1}^{10} w_i \cdot C(x_i - x_j) = C(x_i - x_j) \]

where, \( Y \) expresses differences between calculated value and the value of the attenuation relationship, \( Y_i \) expresses differences between actual value and the value of the attenuation relationship in the observation point \( i \), and \( w_i \) is a weighting function. And \( C(d) \) is a covariance function, \( d \) is a distance between two points, \( D \) is a parameter of a correlation distance, and \( a \) is a coefficient to express the covariant maximum. The spatial distribution of the quake motion to be provided by the KRIGING method equals an actual value on the ground surface of the observation site. When an evaluation of the ground surface amplification in the observation site is appropriate, though the space interpolation is performed on the ground plane, the estimated seismic motion of the KRIGING method is better than that of the attenuation relationship method generally.

4. Function for improving reliability of the estimated seismic motion

In order to improve the reliability of strong motion estimation, the prototype system has a function for distinguishing noise wave data from seismic wave data. When the recorded time of wave data which the prototype system downloaded is different from the time of occurrence of an earthquake announced by JMA, and there are a small number of the observation sites that recorded the seismic wave, users can avoid using this wave data, given that the precision of the interpolation calculation is deemed to be low. When the discrepancy observed wave data is more than the constant threshold obtained from the attenuation relationship for the seismic motion estimation, this wave data can be rejected.

H/V spectral ratio can be calculated using the earthquake data recorded at the observation sites in advance and be stored in a database. Data can then be accepted or rejected by comparing it with the H/V spectral ratio obtained from the earthquake in question. As an example of the H/V spectral ratio of the seismic motions, the results of analysis of MYZ006 (Tsuno) are shown in Fig. 3, which is the nearest K-NET observation site from the model railway of the Miyazaki maglev test line. This figure shows that the H/V spectral ratio is stable without depending on earthquakes in the equivalent site. It can be used to confirm whether a vibration is a quake motion or not. The evaluation index was defined as (4) to quantify the difference between the database H/V spectral ratio of the past earthquake and that of the newly acquired data.

\[ Misfit = \frac{1}{N} \sum_{i=1}^{10} \left[ \log_{10}(O_{in}) - \log_{10}(O_{oi}) \right]^2 \] (4)

where, \( Misfit \) expresses the evaluation index, \( N \) is the number of data in the frequency domain, \( O_{in} \) is the H/V spectral ratio of the database, and \( O_{oi} \) is that of the current recorded data. The calculation band of \( Misfit \) is from 0.5Hz to 20Hz, and the threshold can be adjusted. Judgments are made in X/Z and Y/Z. If neither exceeds the threshold, the data is deemed to be acceptable.

Fig. 3   H/V spectral ratio of seismic motions at MYZ006

5. Examination of performance and estimation results

5.1 Outline of the seismic observation on the Miyazaki maglev test line

As mentioned above, the Miyazaki maglev test line was chosen for testing the prototype system. In order to study
the estimated shake using this system, seismographs were located in the middle and end points of the test track and observations were made. The observation systems recorded three component acceleration waves by 100Hz sampling. Figure 4 illustrates how the sensors were installed along the tracks.

5.2 Examination of estimated results obtained from the prototype system

Three earthquakes were used to examine estimations obtained with the prototype system, namely an earthquake (Magnitude 4.9) on 3:18 January 30, 2012, an earthquake (Magnitude 4.6) on 12:55 February 9, 2012 and an earthquake (Magnitude 4.7) on 12:36 May 14, 2012. The hypocenters of these earthquakes were all located in Hyuga-nada, which is to the east off of Kyushu, Japan. The most suitable parameters for the IDW method and the KRIGING method were examined. The parameters were determined with a view to minimizing the root mean square (RMS) between the observed and estimated seismic indices.

Following are examples of the RMS errors found in the results from each method: in the attenuation relationship method it was 0.87, the IDW method, 0.77, and the KRIGING method, 0.88. It was considered that the accuracy of estimations and most suitable parameters would vary with different evaluation targets and with public data collected from different seismographs. Consequently, special attention needs to be paid to the input parameters if the system is to be used in practice. In Fig. 5 shows the estimated results (earthquake of January 30, 2012) of the tremor distribution over meshed planes using the IDW method when inputting the most suitable parameters.

Figure 6 compares actual measured results from seismographs with estimations calculated using the prototype system. The figure reveals that calculated results are often higher than observed results. However, the estimations converge with observed results as the measured seismic intensity increases. It is thought that because the coefficient used in the attenuation equation is determined on the basis of middle to large earthquake data, this may become the tendency for estimations of small earthquakes to be relatively high. Given that values for points away from observation points are also based on the attenuation equation, estimations using the KRIGING method will also be affected and be systematically higher than actual values.

Figure 7 compares observed results and chainage based estimations for the earthquake at 3:18 on January 30, 2012. It is possible to see that estimations from all methods for point B are higher than the observed value. The reason for this is that the ground amplification information according to which the public seismograph is located at point B is different from the actual ground characteristics. Thus the ground amplification information held by the public institution may not show the value of the very point at which to evaluate the seismic motion exactly. Actual survey data such as microtremors should be used to determine amplification properties of the surface ground layers, in order to improve estimation accuracy.

6. Conclusions

In order to guarantee safety, a support system was developed to help resuming regular train operations more rapidly following earthquakes. Public earthquake information and ground amplification information were used for a
prototype system which can be applied to estimate seismic motion distribution against chainage of a target railway. The users of this system are able to obtain precise ground motion estimates. This signifies that the system may be used to determine effectively which sections can be confirmed as safe, and which sections require most urgent attention.

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References


