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Method for evaluating high-resolution spatial distribution of earthquake ground motions, using temporary seismic observation data

M. Korenaga (1), S. Tsuno(2)

(1) Senior Researcher, Railway Technical Research Institute, korenaga.masahiro.70@rtri.or.jp
(2) Assistant Senior Researcher, Railway Technical Research Institute, tsuno.seiji.75@rtri.or.jp

Abstract

In Japan, generally, permanent seismic stations have installed at intervals of several kilometers to tens of kilometers along railroads. Currently, the train operation immediately after earthquakes occurs is controlled based on seismic data recorded by the permanent seismic stations. Depending on the value of the observed earthquake ground motions by the seismometers, the staff will patrol and inspect the railway structures on foot or on the trains. However, due to the long interval of permanent seismic stations, it may take a long time to resume train operations. Therefore, in this research, we propose the method to estimate the spatial distribution of earthquake ground motions between permanent seismic stations with high density and high accuracy, using the temporary seismic observation data. By using the detailed distribution of earthquake ground motions calculated by the proposed method, it is possible to patrol more efficiently, so it is expected that the train operation can be resumed more quickly.

In this method, at first, high-density temporary earthquake observations is performed, and the relative site amplification factors between the two temporary seismic stations (Adjacent site characteristic ratios) is obtained using those earthquake data. This "Adjacent site characteristic ratios" effectively provides the high-precision site amplification characteristics that is less affected by the influence of source and propagation effects, with a few observation data. Secndary, the site amplification factor at the evaluation site (temporary earthquake seismic stations) with respect to the reference site (permanent earthquake seismic stations) is obtained by sequentially multiplying the "Adjacent site characteristic ratios" between the temporary earthquake seismic stations. When an earthquake occurs after the temporary seismometer is removed, the seismic ground motions at the evaluation points can be estimated by multiplying the site amplification characteristic ratios at each the evaluation sites prepared in advance by the earthquake records at the reference point.

As a result of verification by the seismic records, for examples along a railroad in Kumamoto Prefecture, Japan, it was shown that the evaluation of high-definition earthquake ground motion is possible by the proposed method.

Keywords: Temporary seismic observation, Adjacent site characteristic ratios, Earthquake ground motions

1. Introduction

In Japan, in order to ensure the safety of the train immediately after earthquakes, the train operation is controlled based on the value of seismic ground motions along railway. The train operation after earthquakes occurs is controlled based on seismic data recorded by the permanent seismic station installed along railway. The values observed by the seismographs are treated as representative values in the surrounding area. When the seismic intensity values observed by the seismographs exceeds a certain threshold, the railway operator inspects the safety of railway facilities in the predetermined range for each permanent seismic station. [1] Generally, these permanent seismic stations have been installed with an interval of about 10 to 20 km on the Shinkansen and up to about 40 km on conventional lines along railway. Due to the long interval of permanent seismic stations, it may take a long time to resume train operations. On the other hand, the seismic ground motion between the seismographs may not be uniform due to the influence of the source characteristic, path characteristic, and site amplification characteristic. If we can grasp the spatial variation of seismic ground motion with high density and high accuracy, it will be possible to carry out efficient inspection, which will contribute to quick operation restart. [2, 3, 4]

In order to evaluate spatial variation of seismic ground motion with high resolution and high accuracy, it is necessary to understand the spatial distribution of site amplification characteristics which is information unique to each site in detail. The methods for evaluating site amplification characteristics include a method using geophysical exploration data such as microtremor observations and a method using seismic observation data at the evaluation point. Among them, the method using seismic observation data provides a highly accurate result because the site amplification characteristics is directly evaluated. However, in order to perform reliable evaluation, it is necessary to record a lot of earthquake data to reduce the error due to deviations in the source characteristic and path characteristic. Consequently, since the long-term observation is performed, there is a problem that labor and cost may increase.

In this study, we proposed a method to determine the site amplification characteristics accurately even from a small number of seismic observation data. In this method, accurate site amplification characteristics were estimated taking by the ratio of Fourier spectra at two close seismic stations, excluding the effects of the source characteristic and propagation path characteristic. We performed high-density temporary seismic observations between permanent seismic stations and calculated the site amplification ratio between each seismic station using these observation data. The site amplification factor at each evaluation point site (temporary seismic stations) is obtained by sequentially multiplying these site amplification ratio of the adjacent seismic station pairs. Furthermore, we can evaluate seismic ground motions along the railway with high density and high accuracy, using the obtained site amplification characteristics and seismic data recorded at the limited number of permanent seismic stations.

2. Temporary seismic observations

First, we introduce the seismic observations required for applying this method. In this paper, we performed a temporary seismic observations along the north-south survey line in the Kumamoto and Yatsushiro plains in the Kyushu region of western Japan, and examined and verified the proposed method using the obtained seismic data. The Kumamoto Plain is composed of a diluvial upland on the western slope of the outer crater of Mt. Aso, and an alluvial lowland formed by rivers in the plain. In the Yatsushiro Plain, the alluvial fans and the tidal flats are formed by rivers flowing through the plains, and reclaimed land made after the early modern era occupy about two-thirds of the plain. In the both plains, the change in topography within the plain is small, and the change in site amplification characteristics is also considered to be small.

Fig. 1 shows the locations of the temporary and permanent seismic stations and the epicenter of the earthquake used for the verification. [5] The temporary seismic observations were conducted over several observation periods. The length of the survey line is 40 km from the northern end of the Kumamoto Plain to the southern end of the Yatsushiro Plain. In the section, two permanent seismic stations are installed at

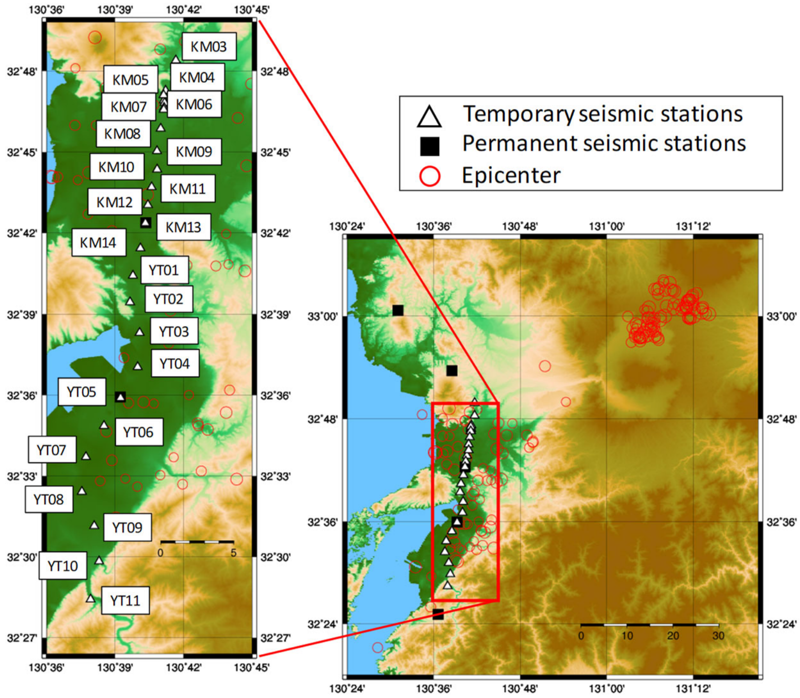

Fig. 1 Locations of the temporary and permanent seismic stations and the epicenter of the earthquake used for the verification

intervals of about 10 km (black squares in Fig. 1). Temporary seismic stations were installed at intervals of 300 m to 3 km, and several seismographs were installed during each observation period, for a total of 26 stations (open triangles in Fig. 1). We installed the portable seismograph consisting of an acceleration sensor (JEP-6A3 : Mitutoyo Corp.), a data recording device (LS-8800 : Hakusan Corp.), a battery, and a GPS antenna. The continuous data from the acceleration sensor was recorded on the SD card at 100Hz sampling.

We performed the temporary earthquake observations immediately after the 2016 Kumamoto earthquake. In order to record a large amount of data used for verification, the observation period is up to 10 months, and we obtained a large number of earthquakes data that occurred around the survey line. For the analysis in this report, 176 earthquakes with Mj 2.5 or more were used. The amplitude of the seismic ground motion data used in the analysis is a maximum of about 70gal in the horizontal two-component composite acceleration. The purpose of this study is to evaluate accurately the seismic ground motion up to the threshold for inspection in order to shorten the time until train operation resumes after the earthquake. Therefore, the effect of non-linearization surface layer is not considered.

2. Proposal of seismic ground motion evaluation method

2.1 Adjacent site characteristic ratios

First, we describe a method evaluate the site amplification characteristics high density and high precision using seismic data obtained by dense temporary seismic observations. In general, the frequency characteristics of seismic ground motions observed on the surface are expressed by Eq. (1) as the product of the source characteristic, path characteristic, and site amplification characteristics.

$$O_{i,j}(f) = S_{i,j}(f) \cdot P_{i,j}(f) \cdot G_j(f) \tag{1}$$

Here, $O_{i,j}(f)$ is the acceleration Fourier amplitude spectrum of the seismic ground motion observed by the seismographs, $S_{i,j}(f)$ is the source characteristic, $P_{i,j}(f)$ is the path characteristic, and $G_j(f)$ is the site amplification characteristics. Represents F is a frequency, and i and j are subscripts representing the epicenter and observation site, respectively.

One of the conventional method evaluating site amplification characteristics using seismic observation data is to calculate the ratio of the Fourier spectrum of the seismic ground motion obtained at the reference point (permanent seismic stations) and the evaluation point (temporary seismic stations) : Eq. (2).

$$\frac{G_j(f)}{G_{j+1}(f)}=\frac{O_{i,j}(f)}{S_{i,j}(f)P_{i,j}(f)}\cdot\frac{S_{i,j+1}(f)P_{i,j+1}(f)}{O_{i,j+1}(f)}=\frac{O_{i,j}(f)}{O_{i,j+1}(f)}\cdot\frac{S_{i,j+1}(f)}{S_{i,j}(f)}\cdot\frac{P_{i,j+1}(f)}{P_{i,j}(f)} \qquad (2)$$

In this method, when the distance between the reference point and the evaluation point is large, there may be a large difference in the source characteristic and the path characteristic between the seismic data observed at the two points ($S_{i,\,j}+1(f)/S_{i,\,j}(f)\neq 1$, $P_{i,\,j}+1(f)/P_{i,\,j}(f)\neq 1$). Therefore, the ratio of the observed Fourier spectrum does not correspond to the ratio of the pure site amplification characteristics, resulting in variations and errors. In order to obtain a reliable site amplification characteristics by suppressing errors with the conventional method, it is necessary to calculate the average value using many seismic observation data, or to reduce the effects of source characteristic and path characteristic by using data of earthquakes that occurred sufficiently far away. However, in both cases, the need for temporary seismic observations on a long-term basis may increase the labor and cost. Therefore, we propose a new method that can evaluate effectively the spatial distribution of site amplification characteristics with high accuracy and high reliability even with a small amount of data.

Here, consider the case in which seismic ground motions $O_{i,1}(f)$ and $O_{i,2}(f)$ at two adjacent sites are obtained for the same earthquake i. If the distance between the two sites is sufficiently small compared to the size of the source fault and the source distance, it is assumed that the source characteristic and path characteristics for $O_{i,\,1}(f)$ and $O_{i,\,2}(f)$ are almost same ($S_{ij+1}(f)/\ S_{i,j}(f)\fallingdotseq 1$、$P_{i,j+1}(f)/\ P_{i,j}(f)\fallingdotseq 1$). The site amplification characteristics ratio $G_{2/1}(f)$ between the two sites is expressed by Eq. (3).

$$G_{2/1}(f) = G_2(f) / G_1(f) = O_{i,2}(f) / O_{i,1}(f) \qquad (3)$$

As shown in Eq. (3), by calculating the Fourier spectra ratio of two close sites, it is possible to obtain a highly accurate ratio of the site amplification characteristics, excluding the source characteristic and the path characteristic. At this time, in order to take into account the effect of geometrical attenuation when calculating the Fourier spectrum ratio, we correct based on the hypocentral distance (1/r: r is the hypocentral distance) .

In the proposed method, first, we calculated the Fourier spectral ratio of the seismic data that were observed simultaneously between two temporary observation sites installed at a short distance among the data obtained by high density temporary seismic observation along the railway. Furthermore, we averaged the spectral ratios for multiple earthquakes, and the result was defined as the site amplification characteristic ratio (Adjacent site characteristic ratios) at the sites : Fig. 2. By using the proposed method, we can obtain the site amplification characteristics more stably and more accurately than the conventional method, even if the data to use is an earthquake with a relatively small hypocentral distance, an earthquake with a biased location, or only a small amount of earthquake data. Since there are few constraints of data used for the analysis, the period of the temporary seismic observation can be shortened, and it is expected that the spatial distribution of the site amplification characteristics with high accuracy can be easily evaluated at low cost.

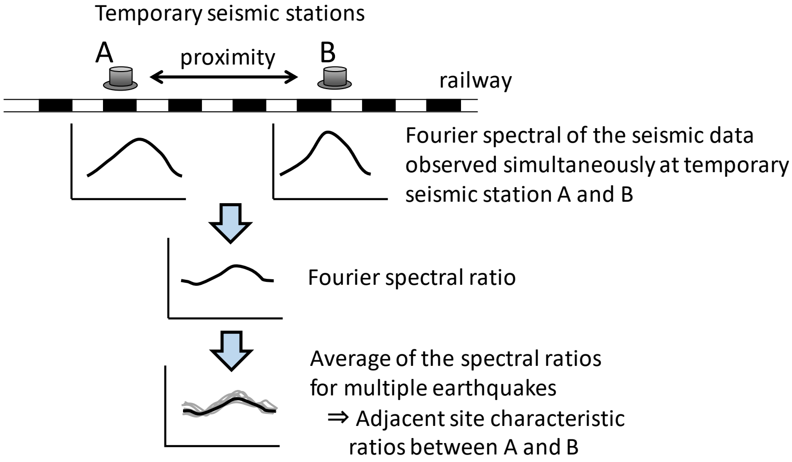

Fig. 2 Conceptual diagram of Adjacent site characteristic ratios

2.2 Evaluation method of seismic ground motion

Next, we propose a method to evaluate the spatial distribution of high definition seismic ground motions using the Adjacent site characteristic ratios described in Section 2.1. Fig. 2 shows the overall flow of the method.

First, high-density temporary seismic stations (intervals of several hundred meters to several kilometers) are performed between reference points (permanent seismic stations) installed at intervals of several tens of kilometers (Fig. 3(1)), and the Adjacent site characteristic ratios between each sites is calculated using the obtained seismic data : Fig. 3(2) (Section 2.1). Next, using the Adjacent site characteristic ratios, the site amplification characteristic ratio $G_{i/R}(f)$ of the evaluation points i (temporary seismic stations) with respect to the reference point R is calculated by Eq. (4) : Fig. 3 (3).

$$G_{i/R}(f)= G_{i/i+1}(f)* G_{i+1/i+2}(f) * G_{i+2/i+3}(f)* \cdot\cdot\cdot * G_{R-1/R}(f) \tag{4}$$

In the proposed method, the site amplification characteristics $G_{i/R}(f)$ of each evaluation point is obtained by sequentially multiplying the Adjacent site characteristic ratios between neighbor site pairs (a daisy chain method). It is assumed that the proposed method can obtain more efficiently the site amplification characteristic ratio with high accuracy compared to the conventional method of directly calculating the Fourier spectrum ratio of the seismic ground motion at the reference point to the evaluation point by eliminating the effects of the source characteristic and path characteristic.

Using the daisy chain method, a high-density site amplification characteristics ratio at each evaluation point is calculated in advance. When an earthquake occurred after the temporary seismograph was removed, it is possible to evaluate the seismic ground motion $A_E(f)$ at the evaluation point E (where the temporary seismic station was set up) as shown in Eq. (5), multiply the site amplification characteristic ratio $G_{E/R}(f)$ at the evaluation point E by the seismic observation data $A_R(f)$ at the reference point R : Fig. 3 (4).

$$A_E(f)= A_R(f) * G_{E/R}(f) \tag{5}$$

When calculating the seismic ground motion $A_E(f)$, the correction is performed based on the hypocentral distance of the reference point R and the evaluation point E.

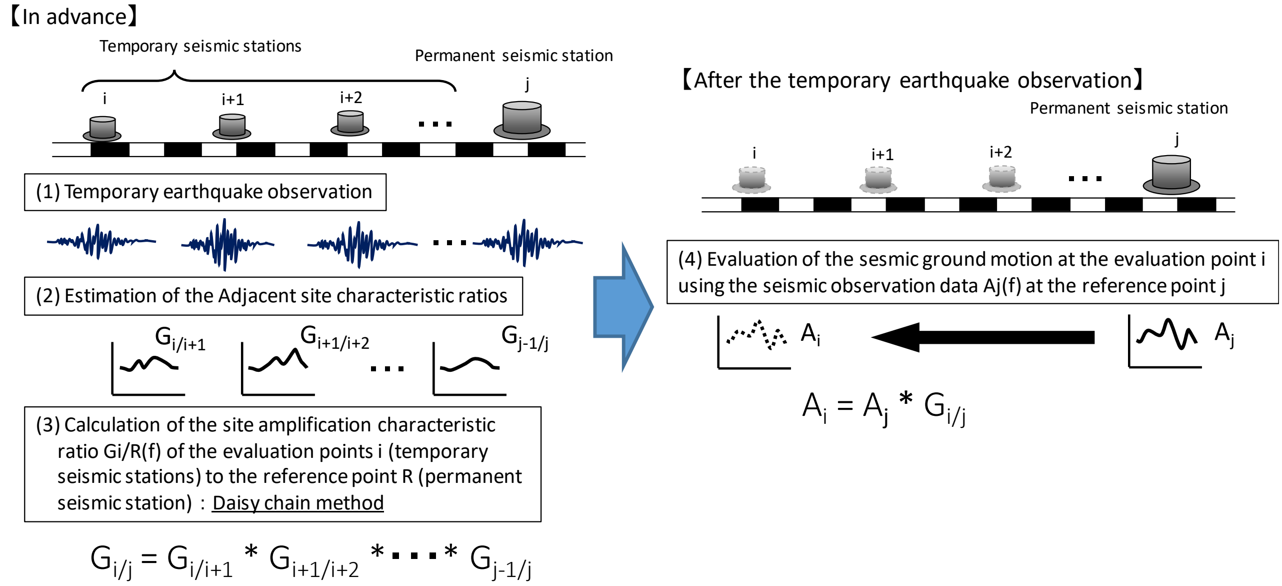

Fig. 3 Proposed seismic ground motion evaluation method

3. Accuracy verification of the proposed method

In order to verify the accuracy of the seismic ground motion evaluation result by the proposed method, the spectrum calculated from the proposed method and the actual observation record were compared using the temporary earthquake observation data shown in Chapter 2 and Eq. (5). For the seismic data observated simultaneously at the adjacent temporary and permanent seismic stations, we extracted 10.24 seconds data from the arrival of the S-waves, and calculated the Fourier amplitude spectra of ground acceleration. We obtained the Adjacent site characteristic ratios by smoothing the Fourier spectrum using a 0.2 Hz parzen window, correcting the amplitude based on the hypocentral distance and then calculating the ratio of the spectra. The Adjacent site characteristic ratios are obtained by averaging the north-south and east-west components of the spectral ratio of each earthquake. The site amplification characteristic ratio of each temporary seismic station (the evaluation point) to the permanent seismic station (the reference point) was calculated from this Adjacent site characteristic ratios by the daisy chain method.

An example of the verification result is shown below. Here, the permanent seismic station (KM13) is set as the reference point, and the temporary seismic stations (KM06 to KM12) installed around KM13 are set as the evaluation points ; Fig. 4. First, using the seismic data observed at each seismic station, the site amplification characteristics ratio of the evaluation point to the reference point was calculated using the proposed method. Observation sites KM06 to KM13 are located in the northern part of the Kumamoto Plain, and it is known that the thickness of the subsurface layer becomes shallower toward the north. Then, we evaluated the seismic ground motion at each evaluation point using the earthquake records (Mj3.2, 3:27 on April 12, 2017) observed at all stations, and compared with the actually observed seismic ground motion data. The result is shown in Fig. 5. The black line indicates the observation result, and the red line indicates the evaluation result calculated by the proposed method. The calculated results and the obtained values at each evaluation point show slight difference, but the features such as the peak of the frequency characteristics around 1 Hz to 5 Hz are in good agreement. It was shown that the proposed method can evaluate the seismic ground motion with high accuracy in the frequency domain.

At present, the Japanese railways have been conducting uniform inspections using only seismic ground motion records at the permanent seismic stations. By using this method, it is possible to grasp the spatial change of the high density seismic ground motion characteristics. Therefore, it is expected that the inspection range can be narrowed down efficiently, leading to early restart of the train operation.

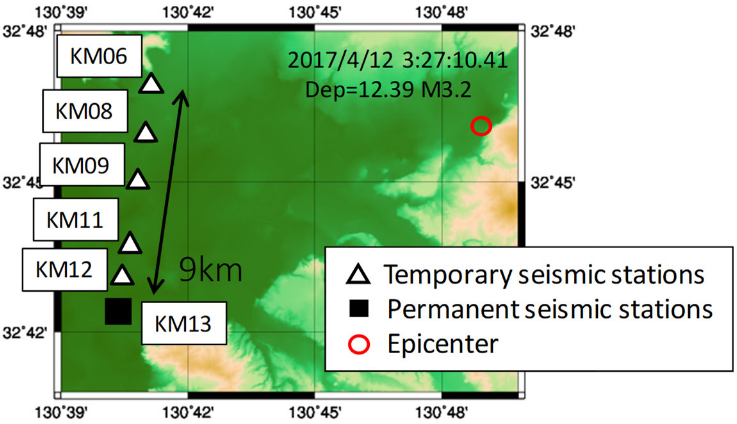

Fig. 4 Locations of the seismic stations and epicenter used for verification

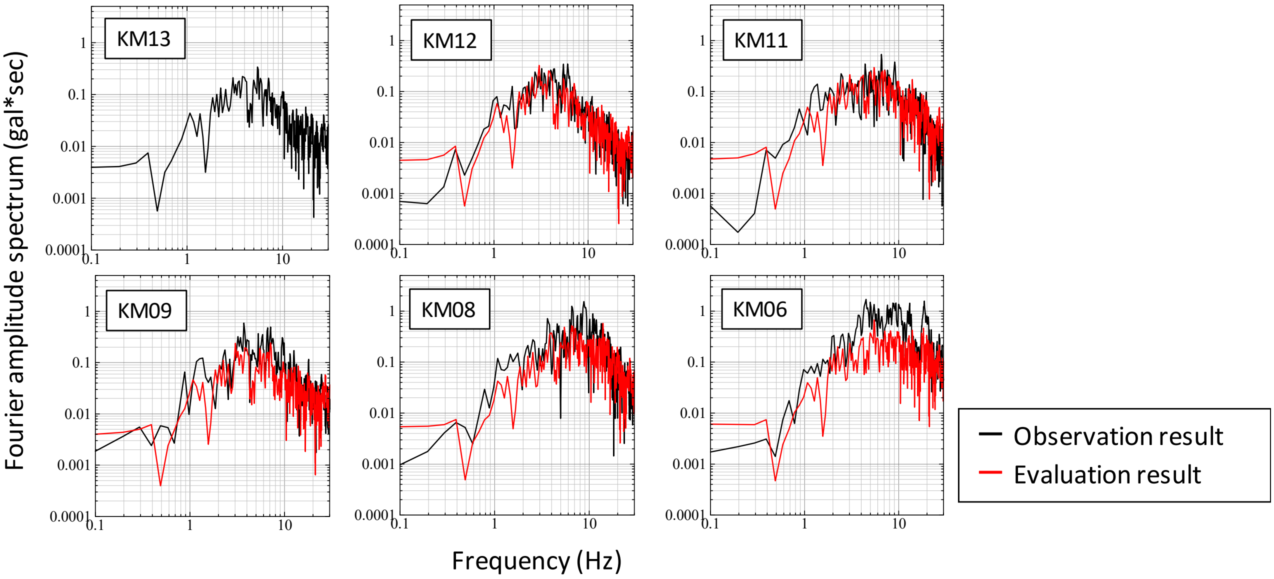

Fig. 5 Comparison between the seismic ground motion evaluated by the proposed method and observed data (Mj3.2, 3:27 on April 12, 2017)

4. Application to seismic intensity value evaluation

In the seismic ground motion evaluation method proposed in Section 2.2, the spectrum was output. The earthquake motion spectrum is very useful information for extracting damage areas and estimating damage to railway structures. On the other hand, in order to make the determination easily and early, a scalar value (seismic intensity values) is currently used for the train operation restart determination after an earthquake, for example the maximum acceleration, the instrumental seismic intensity, and the SI value. Therefore, we try to apply the seismic ground motion evaluation method using the Adjacent site characteristic ratios so far to to the method to evaluate the seismic intensity values.

First, the coefficient for correcting the seismic intensity values (the site correction coefficient) is obtained from the site amplification characteristics ratio between the reference and evaluation points. Here, we show an empirical method for calculating the site correction coefficients using earthquake data obtained from the temporary earthquake observations. We caluclated the average of the Fourier amplitude spectrum ratio between seismic stations, and the ratio of the seismic intensity values, using the earthquakes data obtained simultaneously between the two adjacent permanent and temporary seismic stations. The average value of the spectral ratio between the seismic stations was calculated by extracting the data in the frequency band of 1 to 5 Hz, which has the best correlation with the ratio of the seismic intensity values. From a large number of earthquake data, we obtained the relational expression between the average of the Fourier amplitude spectrum ratio and the ratio of the seismic intensity values. Furthermore, using this relational expression, the site correction coefficient of each seismic intensity value of the evaluation point to the reference point was converted from the site amplification characteristic ratio obtained by by the daisy chain method. We propose a method to evaluate the seismic intensity values at each evaluation point by multiplying this site correction coefficient and the seismic intensity values recorded at the reference point (permanent seismic station).

Next, we applied the above-mentioned evaluation method of seismic intensity values to the earthquake data and confirmed its accuracy. Fig. 6 shows an example of a comparison between the obtained evaluation result and the value observed at the evaluation point. The estimation error of the seismic intensity is approximately 0.5 or less at all evaluation points, and it is indicated that the seismic ground motion in the entire section is correctly obtained. Furthermore, as a result of evaluating the seismic intensity values for multiple earthquakes data, the error RMS was about 0.5 to 0.6 for the instrumental seismic intensity. It is clear that this proposed method can evaluate the seismic intensity values with sufficient accuracy.

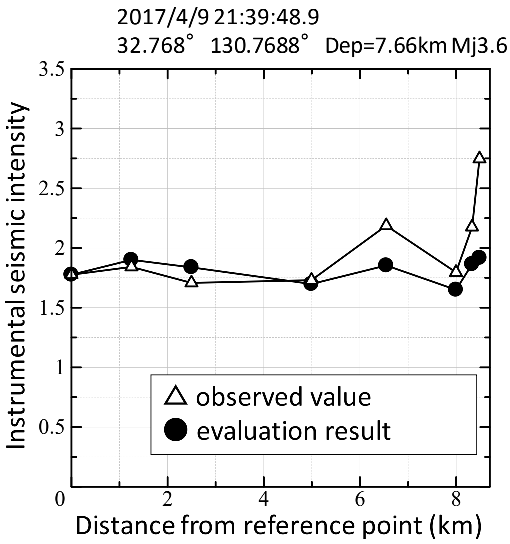

Fig. 6 Comparison between the obtained evaluation result of seismic intensity values and the observated value at the evaluation point (Mj3.6, 21:39 on April 9, 2017)

5. Conditions for applying the proposed method

We confirmed the application conditions of the proposed method in order to use the method appropriately. We verified the relationship between the accuracy of the Adjacent site characteristic ratios and the interval of the temporary seismic staions, or the number of data used to calculate the Adjacent site characteristic ratios.

5.1 Interval of the temporary seismic stations

Fig. 7 shows the relationship between the interval of the seismic stations and the standard deviation of the Adjacent site characteristic ratios. It can be seen that the standard deviation value tends to increase as the interval between the temporary seismic stations increases. It is presumed to indicate that the calculation of the Adjacent site characteristic ratios of the seismic station pair at a long distance may not be a pure site characteristic ratio, because larger intervals are more susceptible to differences in the source characteristic and the path characteristics. When the distance between the observation points is 5 km or less, the standard deviation value is about 0.2 to 0.3 or less, which indicates that the Adjacent site characteristic ratios can be obtained stably. Considering the use of the proposed method, it is more effective to reduce the space between the temporary seismic stations as much as possible, since the spatial distribution of the seismic ground motions can be grasped in more detail and the time to resume the train operation after an earthquake is reduced. On the other hand, considering the labor and cost involved in the temporary seismic observations, it is advantageous to increase the interval between the temporary seismic stations and reduce the number of stations. For places where the change in the surface structures is considered to be small, such as the central part of the plain, temporary seismic observation data with the 5km station intervals as the upper limit can be used to more efficiently grasp the spatial distribution of the site amplification characteristics. In addition, at the edge of the plain where the change of the surface structure is considered to be large, it is thought that accurate site amplification characteristics can be grasped by shortening the distance between the temporary seimic stations according to the change of the structure.

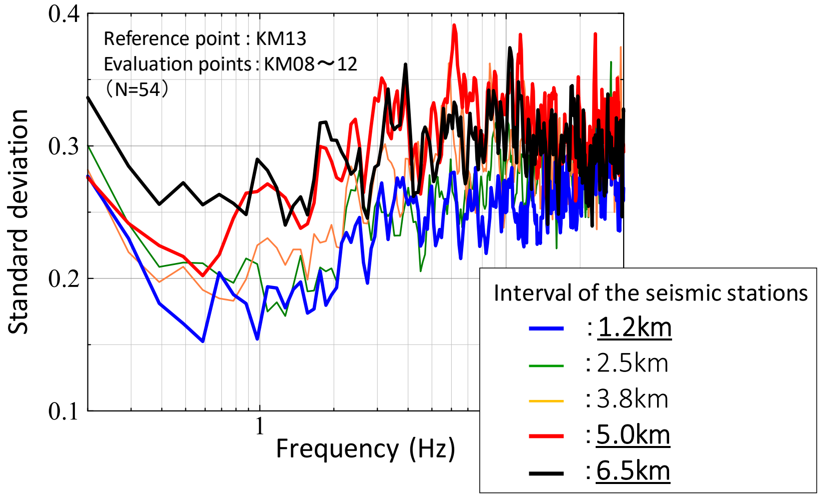

Fig. 7 Relationship between the interval of seismic stations and the standard deviation of the Adjacent site characteristic ratios

5.2 Number of data used for evaluation

Next, we confirmed the relationship between the number of data used for calculating the Adjacent site characteristic ratios and the accuracy of the calculation result. We extracted randomly 5, 10, 15, and 20 records from the seismic data observed at each temporary seismic station, and calculated the Adjacent site characteristic ratios for each. This was performed five times, and the RMS of the error from the correct answer was obtained for each number of data. Here, the correct answer was defined as the Adjacent site characteristic ratios calculated from all the seismic data (about 50) simultaneously observed the temporary seismic stations pair. The results are shown in Fig.11. The larger the number of data used for the calculation, the smaller the RMS of the error and the Adjacent site characteristic ratios is obtained more stably and accurately, so it is desirable to calculate using as many seismic data as possible. However, if the number of data is about 10 or more, the RMS of the error is small, and it is considered that the calculation of the Adjacent site characteristic ratios can be stably performed. For example, the period of the temporary seismic observation required to record about 10 data was about four months in the observation conducted one year after the 2016 Kumamoto earthquake in this study. Although it depends on the seismicity around the seismic stations, it is considered that the seismic observation for a relatively short period of time enables highly accurate evaluation of site amplification characteristics.

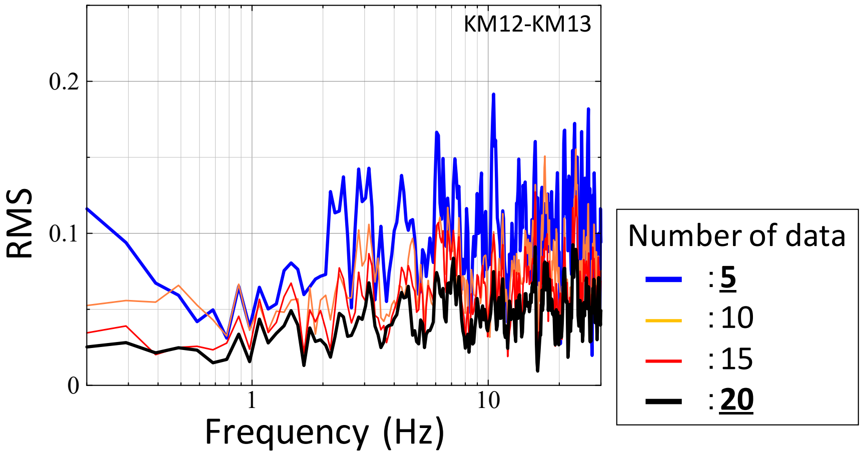

Fig. 7 Relationship between RMS of the Adjacent site characteristic ratios estimation error and number of data

5. Conclusion

Using the high density temporary seismic observation data, we proposed a method for calculating site amplification characteristics (the Adjacent site characteristic ratios). We also proposed a new high definition seismic ground motion evaluation method using the obtained site amplification characteristics and the seismic data of the permanent seimic stations. As a result of applying the proposed method to observated earthquake recordes, it was confirmed that high precision and density seismic ground motion evaluation can be performed with a small amount of data. By using this method to the railway, it is expected that the efficiency of the inspection after an earthquake and the early train operation restart can be achieved.

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