Preliminary Study on Variation of Ground Motion Indices within Very Small Distance

Y. Hata
R&D Center, Nippon Koei Co.,Ltd., Japan

K. Ichii
Hiroshima University, Japan

A. Nozu
Port and Airport Research Institute, Japan

SUMMARY:
At present, dense strong motion observation networks have been established in Japan. To evaluate characteristics of obtained seismic records, ground motion indices are used. Although various indices have been proposed, the robustness of the indices calculated from the records has not been fully studied so far. In this study, variation of ground motion characteristics between adjacent observation stations was examined. In particular, seismic observation records at neighbouring stations, where the distance are within about 100 meters, are systematically compared. Furthermore, validity of microtremor measurement as a method to detect the variation of ground motion was indicated. The results will contribute to a rational choice of ground motion indices for use in the future practice.

Keywords: ground motion, seismic observation, microtremor measurement, robust indices

1. INTRODUCTION

Strong motion observation in Japan started in 1953. After that, the number of the strong-motion observation sites has been increased. During the 1995 Hyogoken-nanbu (Kobe) earthquake, however, few records were observed in the disastrous belt zone where many buildings and infra-structures were totally collapsed. After the earthquake, importance of strong-motion observation has been strongly recognized. As a result, many nation-wide and local strong-motion observation networks were constructed. In total, more than 10,000 strong motion sites on ground are maintained by different institutions (e.g. Midorikawa, 2005). The nation-wide networks include K-NET (about 1,000 sites) and KiK-net (about 700 sites) by National Research Institute for Earth Science and Disaster Prevention (Aoi *et al*., 2004), the network by the Japan Meteorological Agency (about 600 sites) (Nishimae, 2004) and the network by the prefectural government (about 2,800 sites) (e.g. Takano *et al*., 2005; Goda and Atkinson, 2010). It has been found that, during large-scale earthquakes, observed ground motion characteristics at nearby stations have large variation due to the difference of site effects (e.g. Kataoka *et al*., 2007; Hata *et al*., 2012). In these previous reports, however, although the nearby stations are close to each other, distance between the nearby stations is 100 meters to several kilometers. The fact indicates the importance of the study on the variation of ground motion characteristics at very adjacent observation sites within 100 meters.

In recent years, in Japan, ground motion evaluation is frequently carried at a site of construction or at a site of seismic damage (e.g. Hata *et al*., 2010a; 2010b; 2012; Nozu and Wakai, 2011). In such cases, ground motion indices are used to quantify the evaluated ground motions. The various indices for ground motion characteristics, for instance PGA, PGV, JMA seismic intensity (Nishimae, 2004), acceleration power (e.g. Hata *et al*., 2010a), spectral intensity (SI) value (Housner, 1965), velocity power spectral intensity (PSI) value (e.g. Hata *et al.*, 2010a) and so on, have been proposed. These indices for ground motion characteristics are often used for the seismic design and practice. It is inconvenient in the seismic design and practice if these indices do not have robustness. Here, if a ground motion index is not easily affected by observation conditions such as installation conditions of seismometer, it is defined as "robust". The robustness of the indices has not been fully studied so far.

In this study, the variation of observed ground motion records at very adjacent stations is studied. First of all, the adjacent stations for strong motion observation, where the distance is within 100 meters in Japan were listed up based on the field reconnaissance results. The microtremor measurements were carried out at the selected observation station sites, and its microtremor H/V spectra were calculated. Next, the ground motion observation records in a same earthquake at the selected stations were compared. Then, based on the comparison of the microtremor H/V spectra and the site amplification factors, the variation of ground motion between the very adjacent observation stations were examined.

2. CONCEPT OF THIS STUDY

Figure 1 shows the concept of this study. As for the variation of ground motion characteristics between nearby stations, a lot of studies on spatial correlation were carried out (e.g. Goda and Atkinson, 2010). In this study, however, we are focused on the variation of ground motion characteristics between very adjacent stations. In particular, we are focused on spatial correlation for a very small aperture (see **Figure 1**). In other words, the examination of the spatial correlation as a function of distance is not the purpose of this study. In Figure 1, factors influencing variation of ground motion characteristics between very adjacent stations is classified into two factors; one is the difference of seismometer characteristics, and another is the difference of installation condition (e.g. Bycroft, 1978). The former includes the effects of seismometer type (including instrument characteristics), individual difference (within the same seismometer type) and so on. The latter includes the effects of ground condition (e.g. Hata *et al.*, 2012), station-case vibration (e.g. Kataoka *et al.*, 2007), foundation characteristics (e.g. Midorikawa *et al.*, 2012), adjacent permanent structures (e.g. Ohmachi *et al.*, 1988) and so on.

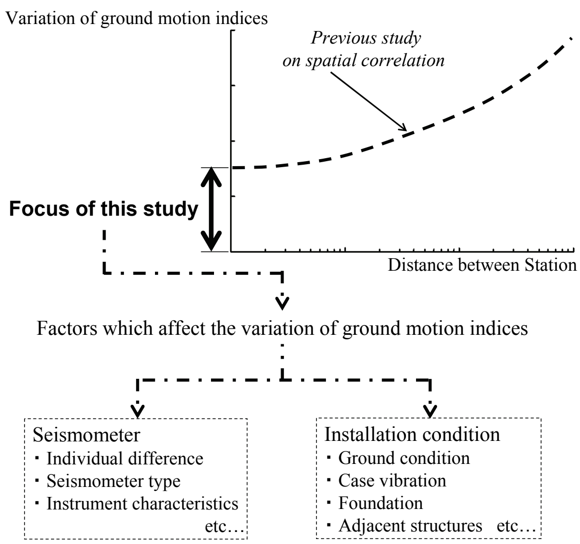

Figure 1. The concept of this study

Table 1. The list of very adjacent observation stations

Couple No.	Station_A	Station_B	The shortest distance between Station A and B
Couple-01	K-NET Takinoue	KiK-net Takinouekita	3 m
Couple-02	K-NET Honbetsu	KiK-net Honbetsu	5 m
Couple-03	K-NET Akan	KiK-net Akanminami	4 m
Couple-04	K-NET Yubari	KiK-net Yubari	27 m
Couple-05	K-NET Shiraoi	KiK-net Shiraoi	3 m
Couple-06	KiK-net Rokkasho	JMA Rokkasho	5 m
Couple-07	K-NET Nakamura	KiK-net Nishikawanishi	1 m
Couple-08	K-NET Hasunuma	SK-net Hasunuma	90 m
Couple-09	K-NET Misaki	SK-net Misaki	4 m
Couple-10	K-NET Hiratsuka	SK-net Hiratsuka	2 m
Couple-11	K-NET Shirakawa	KiK-net Shirakawa	6 m
Couple-12	K-NET Tochio	KiK-net Kamitakara	11 m
Couple-13	K-NET Hamamatsu	JMA Hamamatsu	23 m
Couple-14	K-NET Owase	KiK-net Owase	11 m
Couple-15	K-NET Kitagawa	KiK-net Kitagawa	73 m

In this study, robustness of indices of ground motion characteristics was examined based on the observation result which is affected by various factors. In particular, seismic observation records at neighbouring stations, where the distance are within about 100 meters, are systematically compared. Here, we did not specially discuss each of the above-mentioned factors which influences the variation of ground motion indices. This is because, in the seismic design and practice, it is very difficult to distinguish between contributions from different factors and it is necessary to handle a gross variation due to a combination of many factors anyways. Therefore, we carried out fundamental studies on the evaluation method for the gross variation of ground motion characteristics due to a combination of many factors.

3. TARGET SITES

3.1. Selection of Observation Stations

Table 1 shows the list of very adjacent observation stations in Japan. The adjacent stations for strong motion observation, where the distance is within 100 meters were selected from the stations in K-NET (Aoi *et al*., 2004), KiK-net (Aoi *et al*., 2004), the network of JMA (Nishimae, 2004) and SK-net (Takano *et al*., 2005). The shortest distance between Station A and Station B (see Table 1) was determined based on in-situ measurement (the error is less than 1 m). **Photograph 1** shows the installation condition of the observation instruments at the sites.

3.2. Microtremor Measurements

In this study, microtremor measurements were carried out. The specifications of the instrument for microtremor measurement can be found in Senna *et al*. (2006). The measurement was done in 12 days from 14 May until 25 May 2010. The measurement direction was 3 directions of NS, EW and UD components. The mean of the horizontal 2 components were adopted in the calculation of the H/V spectral ratio. The measurement was done for 11 minutes (≒163.84 s×4 sections), and the sampling frequency was 100Hz. The process to calculate a microtremor H/V spectral ratio is based on Hata *et al.* (2010b). **Figure 2** shows the calculated microtremor H/V spectra at the adjacent observation stations. In Couples-01, 02, 03, 05, 07, 09, 10 and 14, the H/V spectra at Station A are almost similar to the H/V spectra at Station B (see also Figure 4). However, in Couples-04, 06, 11, 12, 13 and 15, the similarity was not confirmed, and the spectral characteristics (ex. spectral shape and peak frequency) at the Station A are different from Station B.

4. COMPARISON OF SEISMIC OBSERVATION RECORD

4.1. Earthquake Event and Evaluation Indices

The earthquake events for which the JMA seismic intensity at both Station A and Station B exceeded 3.0 were extracted. As a result, 57 earthquake events were extracted. **Figure 3** shows difference degree D_i for various indices obtained in the extracted 57 earthquake events. The difference degree D_i for an earthquake event i is defined by the following equation.

$$D_i = \frac{\left| I_{B,i} - I_{A,i} \right|}{I_{A,i}} \tag{4.1}$$

(a) Couple_01 **(b)** Couple_02 **(c)** Couple_03

(d) Couple_04 **(e)** Couple_05 **(f)** Couple_06

(g) Couple_07 **(h)** Couple_08 **(i)** Couple_09

(j) Couple_10 **(k)** Couple_11 **(l)** Couple_12

(m) Couple_13 **(n)** Couple_14 **(o)** Couple_15

Photograph 1. The installation conditions of adjacent observation stations

Here, $I_{A,i}$ and $I_{B,i}$ are seismic indices which calculated from the observed ground motion at Station A and Station B in an earthquake event *i*. A total of 6 seismic indices (PGA, PGV, JMA seismic intensity (Nishimae, 2004), acceleration power (e.g. Hata *et al*., 2010a), spectral intensity (SI) value (Housner, 1965), velocity power spectral intensity (PSI) value (e.g. Hata *et al*., 2010a)) were chosen to evaluate the difference of observed ground motion between Station A and Station B.

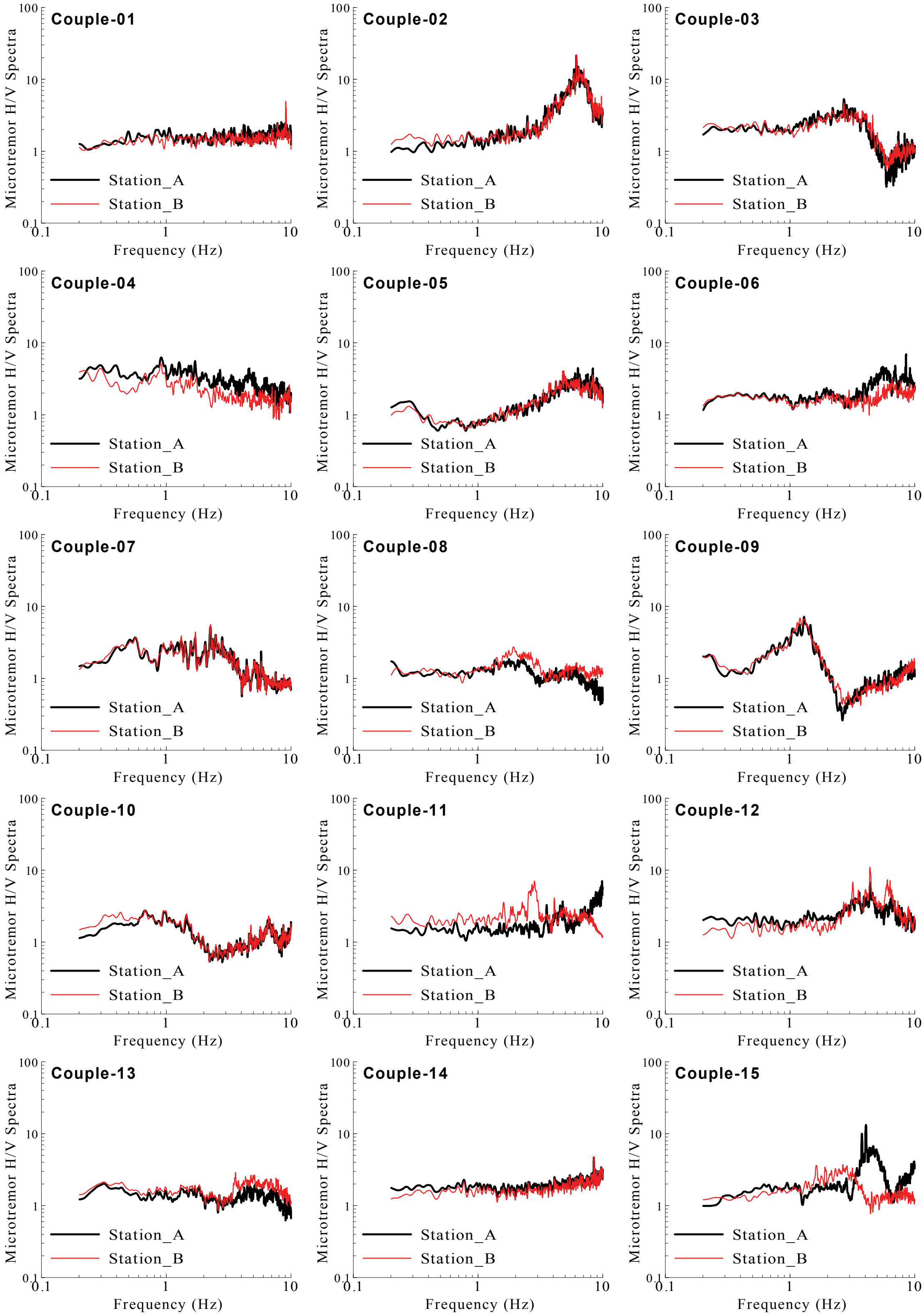

Figure 2. The microtremor H/V spectra at very adjacent observation stations

4.2. Evaluation of Variation

As shown in **Figure 3**, for the JMA seismic intensity and indices based on seismic velocity (PGV, SI value and PSI value), when the value of the indices increased, the difference degree was decreased. This is because the large values were brought about by earthquake events with large seismic magnitude. In other words, generally, a large magnitude earthquake contains low-frequency ground motions, therefore, the JMA seismic intensity, PGV, SI value and PSI value were dependent on the low-frequency ground motions. Usually, spatial variation is small for low-frequency ground motions.

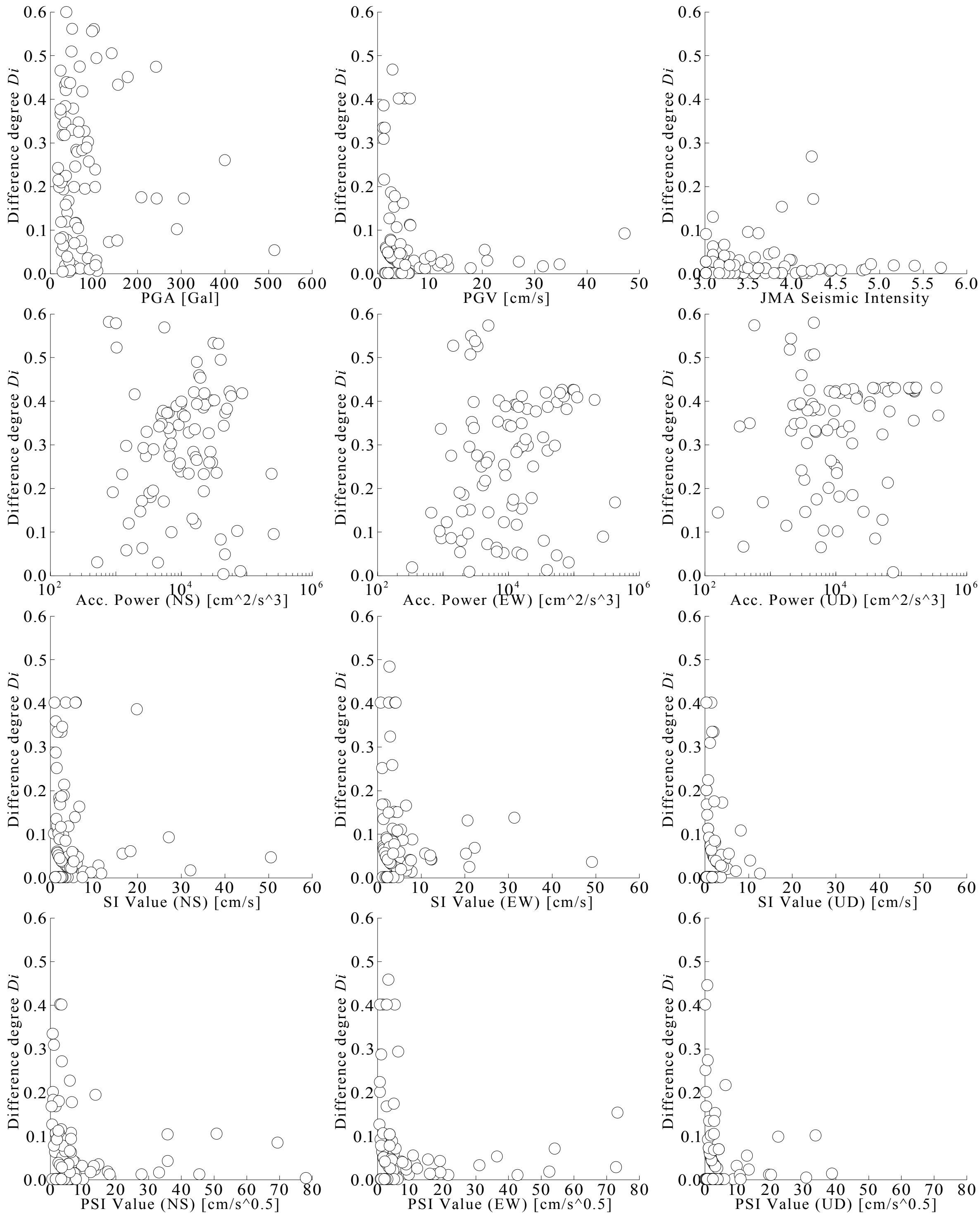

Figure 3. The relationships between the ground motion indices and the difference degree

On the other hand, as shown in **Figure 3**, for the indices based on seismic acceleration (PGA and acceleration power), even when the value of the indices increased, the difference degree did not decrease. It suggests that PGA and acceleration power can vary significantly within a small distance even for a large-scale earthquake.

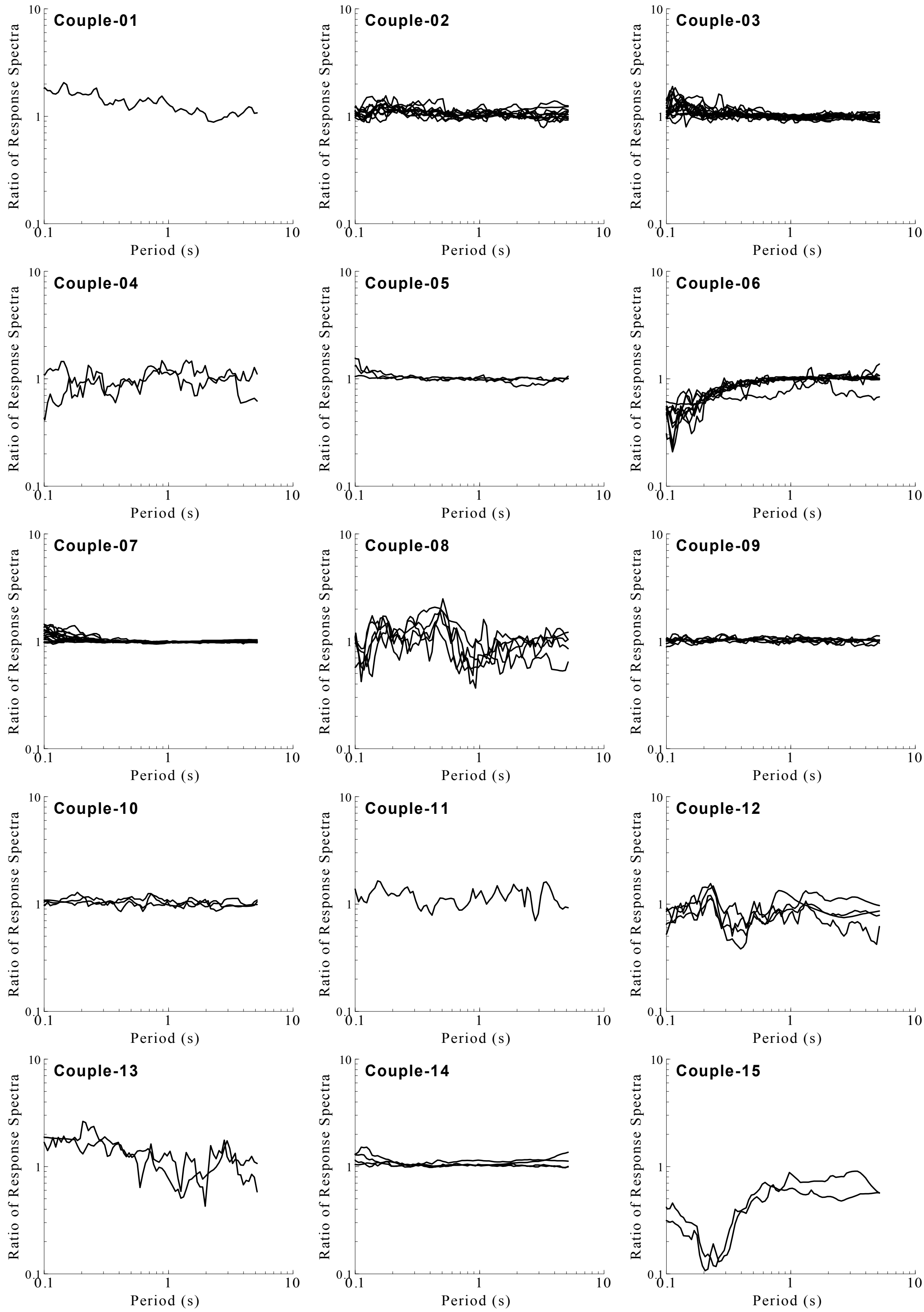

Figure 4. The ratio of acceleration response spectra (Station A / Station B) for NS direction

Figure 4 shows the ratio of acceleration response spectra (Station A / Station B) of damping ratio 5% for NS direction between 0.1 seconds and 5.0 seconds for each couples (see Table 1) for the extracted 57 earthquake events. As shown in **Figure 4**, the ratio of the response spectra is almost 1.0 at Couples-02, 03, 05, 07, 09, 10, 14. On the other hand, the ratios of the response spectra in Couples-04, 08, 12, 13, 15 were fluctuated. From the comparison of **Figure 2** versus **Figure 4**, it is indicated that when the variation of the microtremor H/V spectra was larger, variation of the ratio of the acceleration response spectra was also larger. In Couples-02, 03, 05, 07, 09, 10, 14, where the variation of the microtremor H/V spectra was small, the ratios of the acceleration response spectra were almost 1.0. It suggests that variation of the ground motion characteristics have a positive correlation with the difference of ground shaking characteristics.

5. DISCUSSION

As a detail examination, quantitative evaluation on the difference of the microtremor H/V spectra and the site amplification factors (Hata *et al.*, 2012) in the adjacent observation stations was carried out. In this study, as an index of differences, the DGS (Difference of Ground Shaking characteristics) value is proposed referring to concept of DNL (Degree of Non-Linearity) value by Noguchi and Sasatani (2011). The proposed DGS value is defined as the integration of logarithmic ratio in the frequency range from 0.2Hz to 10Hz as shown in the following equation.

$$DGS = \sum \left| \log\left(\frac{G_{Station\_B}(f)}{G_{Station\_A}(f)} \right) \right| \cdot \Delta f \tag{5.1}$$

Here, $G_{Station\_A}(f)$ and $G_{Station\_B}(f)$ were the microtremor H/V spectra or the site amplification factors at Station A and Station B, respectively. This DGS value can be calculated for both the microtremor H/V spectrum and the site amplification factor in the same way (Hata *et al.*, 2012). In this study, as an index of difference of ground motion characteristics between Station A and Station B, the DRS (Difference of Response Spectra) value is also proposed referring to the above mentioned DGS value.

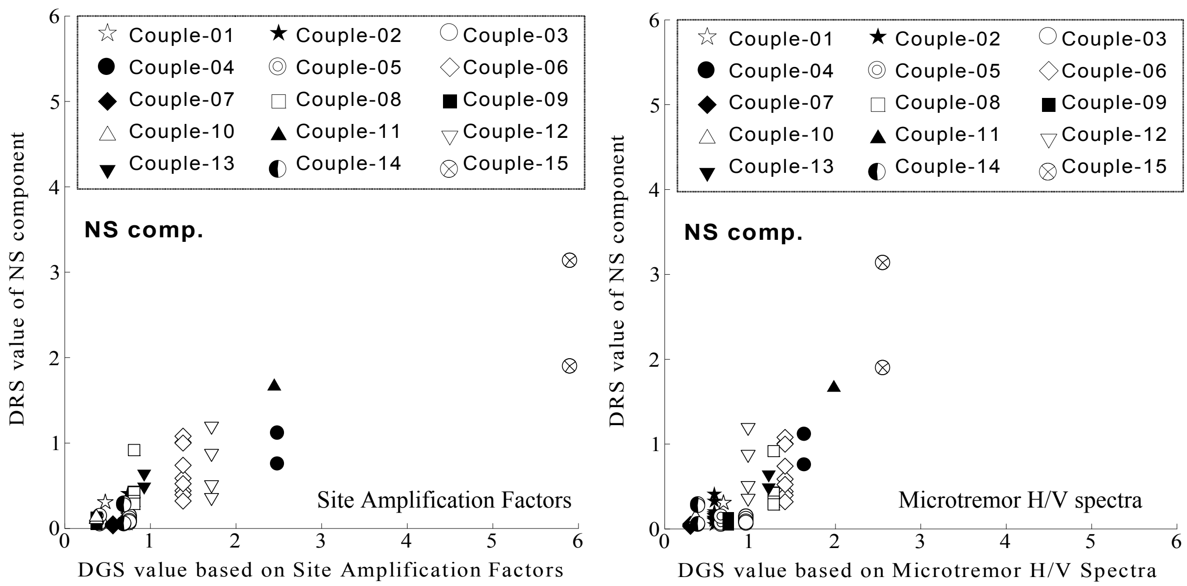

Figure 5. The relationships between the DGS value and the DRS value for NS components

The proposed DRS value is defined as the integration of logarithmic ratio in the natural period range from 0.1 seconds to 5.0 seconds as shown in the following equation.

$$DRS = \sum \left| \log \left(\frac{R_{Station\_B}(T)}{R_{Station\_A}(T)} \right) \right| \cdot \Delta T \tag{5.2}$$

Here, $R_{Station\_A}(T)$ and $R_{Station\_B}(T)$ were the acceleration response spectra at Station A and Station B (see **Figure 4**), respectively. **Figure 5** (left side) shows the relationship between the DGS value based on the site amplification factors and the DRS value. Furthermore, **Figure 5** (right side) shows the relationship between the DGS value based on the microtremor H/V spectra and the DRS value. In **Figure 5** (left side), the DGS values based on the site amplification factors are positively correlated with the DRS value. The positive correlation was a reasonable consequence, because the site amplification factors were based on the observed ground motions at Station A and Station B (Hata *et al.*, 2012). In **Figure 5** (right side), the DGS values based on the microtremor H/V spectra are positively correlated with the DRS value as well as **Figure 5** (left side). It suggests that the microtremor measurements were the effective method to evaluate the difference of the ground shaking characteristics due to the difference of the site amplification factor between adjacent sites. This can be a good technique in detecting variation of ground motions at adjacent sites.

6. SUMMARY AND CONCLUSIONS

In this study, first, very adjacent stations for strong motion observation, where the distance is within 100 meters in Japan were listed up based on the field reconnaissance results. Next, the observed ground motion in very adjacent stations was examined. Finally, the difference of ground shaking characteristics between very adjacent observation stations was evaluated considering the microtremor H/V spectra and the site amplification factors. The following conclusions are obtained.

(1) Even for very adjacent observation stations within the distance of about 100 meters, observed ground motion characteristics can be greatly different. Particularly, the ground motion indices based on seismic acceleration, for instance PGA and acceleration power, could be significantly different. **(2)** The degree of difference of the microtremor H/V spectrum between very adjacent observation stations was consistent with the degree of difference of the site amplification factor between the stations. **(3)** The microtremor measurements can be an effective method to detect variation of ground motions at adjacent sites. In the future study, a lot of temporary seismic observation sites should be created near the permanent observation stations to examine the difference of the ground motion characteristics in a very narrow area.

DATA AND RESOURCES
K-NET and KiK-net data were obtained from the National Institute for Earth science and Disaster prevention (NIED) at http://www.kyoshin.bosai.go.jp/kyoshin/ (last accessed April 2012). SK-net data were obtained from Seismic Kanto Research Project, Earthquake Research Institute, the University of Tokyo at http://www.sknet.eri.u-tokyo.ac.jp/ (last accessed April 2012). Seismic observation data of JMA were collected from the Japan Meteorological Business Support Center by CD-ROM.

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