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# Uncertainty of Seismic Amplification Characteristics based on Seismic Observations at Nuclear Sites

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## *Abstract*

In this study, uncertainty in the seismic amplification characteristics is examined using high-density seismic observation data collected from five nuclear sites. Using one of the points in the observation network as reference, the spectral amplitude ratios to the other points are obtained. It is well known that these ratios are not constant and change with each earthquake. This phenomenon implies that the ground structure is not completely parallelly stratified. And it is thought that the degree of variation reflects more-uncertainty in the seismic amplification characteristics of the upper ground than the seismic basement. During the examination of the standard deviation (SD) of the variation and the subsequent investigation of its characteristics, it was discovered that the SD increased with frequency and exhibited characteristics that were approximately proportional to the logarithm of that frequency. Furthermore, the average value of SD increased proportionally with distance from the reference point. Therefore, when considering the uncertainty of the input ground motion relative to the structure, it is imperative to consider the above-mentioned characteristics.

*Keywords: Seismic observation, Normalized spectrum, Standard deviation, Frequency and distance dependence*

## 1. Introduction

Previously, the author has conducted high-density seismic observations using high-sensitivity velocity seismographs at several nuclear sites to study ground irregularities that may trigger abnormal seismic amplification characteristics. The examination was undertaken in the following manner. First, a Fourier analysis was performed on the high-density seismic observation data to generate the analysis data set. Next, one of the observation points was as reference, the Fourier spectrum amplitude ratio (hereinafter referred to as the normalized spectrum) relative to the other observation points was computed for each earthquake and plotted against the azimuth angle of the epicenter. If the normalized spectrum deviates greatly from 1 at a certain azimuth, irregular ground may exist in the direction of that azimuth. As a result, it was confirmed that the ground irregularity contributed to trigger the unusual seismic amplification characteristics was not existed at any sites[1], [2].

However, this normalized spectrum varies for each observation point and from one earthquake to another, thereby indicating that the ground is not a perfectly stratified parallel structure and has a certain non-uniformity. Because the epicentral distance is very large compared with the distance between the high-density observation points, these variations may be attributed to uncertainty in the seismic amplification characteristics of the ground above the seismic basement. Therefore, the characteristics of standard deviation (SD), which is an index of variation, was investigated.

In this study, the following 5 nuclear sites were examined. That is, Higashidori and Onagawa of the Tohoku Electric Power Co., Inc., Ohma of the Electric Power Development Co., Ltd., Tsuruga of the Japan Atomic Power Co., Ltd. and Hamaoka of the Chubu Electric Power Co., Inc. ( see Fig.1).

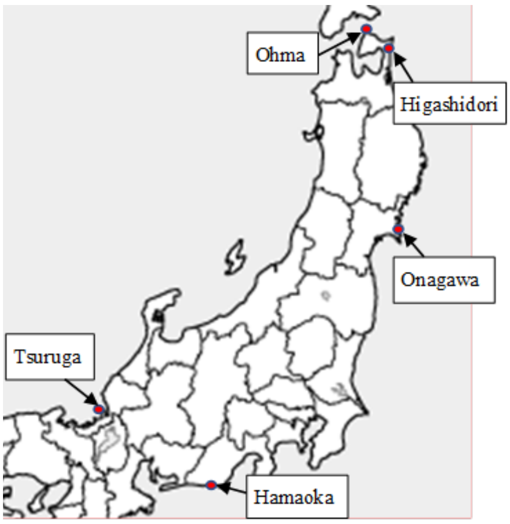


Fig.1 Location of nuclear sites.

In Japan, important facilities such as nuclear plants are installed on rocks, hence, their ground of these sites is characterized by a relatively thin unconsolidated layer and the hard ground.

## 2. High-density Seismic Stations, Observation Data and Analysis Method

High-density seismic observation is a continuous offline observation with the following equipment configured (except in Hamaoka) .

*Seismometer* : 1Hz high-sensitive velocity seismograph (LE-3Dlite MKⅢ manufactured by Lennartz electronics GmbH). It was installed on the ground surface.

*Recorder* : 24bit A/D, 3ch data logger (the LS-8800 made by Hakusan Corporation)

*Power source* : Battery and solar panel.

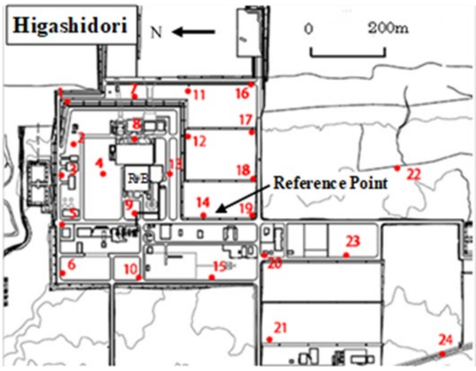


Fig.2 Distribution of observation points at Higashidori site.

Fig.2 shows an example of a high-density seismic observation distribution at the Higashidori site. Here, No.14 is the reference point, and the observation point interval is from 100-200m near the reactor facility. The reference point for each site is selected the point where the unconsolidated layer is thin and approximated to the rock ground.

Table1 Observation information.

| Site | Number of obs.point | Number of data | Period of obs. |
|---|---|---|---|
| Higashidori | 24 | 441 | 2013/07-2015/11 |
| Onagawa | 11 | 1055 | 2014/10-2015/11 |
| Ohma | 23 | 331 | 2013/11-2015/11 |
| Tsuruga | 13 | 32 | 2017/07-2018/02 |
| Hamaoka | 7 | 492 | 2009/09-2014/07 |

Table 1 summarizes the data collected for metrics like the number of observation points, observation data, and observation period for each site. Observations at the Hamaoka site were implemented by Chubu Electric Power Co., Inc. using 2Hz velocity seismograph, and 7 out of the 24 observation points were provided for this study. Looking at the number of observation data, Onagawa has the largest number, and 1055 earthquake records have been obtained in about one year. Then Hamaoka collected 492 records in about 5 years, Higashidori collected 441 records in 2 years and 5 months, and Oma collected 331 records in 2 years. In contrast, the number of earthquake at the Tsuruga site was 32, because the observation period was just about 6 months and its location is at the side of Japan Sea, where seismic activity is inactive. According to the relationship between the earthquake magnitude (M), epicenter distance (R), and number of earthquake (N), the observed earthquakes are distributed in M2 to M7, and the epicentral distance is distributed in the range of 10km to 600km. Most of the records were M2.5 to M4 class earthquakes.

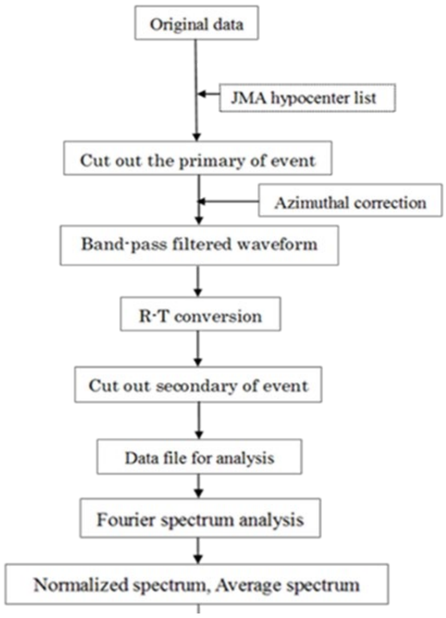


Fig.3 Data processing and analysis.

Elementary data processing and analysis is undertaken for this study, with the flow illustrated in Fig.3. The object of study is the horizontal component of the seismic wave after the arrival time of the S wave. The primary cutout of the seismic wave part was performed on the collected continuous records based on the hypocenter list of JMA. The cutout time width is 1-3min, depending on Magnitude. An original waveform file was made, and the azimuth correction was as necessary. In order to remove equipment noise and traffic noise components, band-pass filter processing with a bandwidth of 1-10Hz was conducted, and R-T (radial and transverse components) conversion was carried out.



 

A secondary cutout was performed on the waveform later arrival of the S wave. The cutout time width was visually between 5.12-20.48s, and only data with good S/N ratios were adopted to create the final data file for analysis. The Fourier spectrum amplitude (smoothened by a Parzen Window with a bandwidth of 0.5Hz) was calculated for each earthquake record in the analysis data file. The spectral ratios of observation points to the reference point and those average (hereinafter, called average spectrum) were obtained.

## 3. Normalized and Average Spectrums

Fig.4 draws the normalized spectrum and average spectrum obtained at an observation point (No.13) around the reactor building in the Higashidori site. And Fig.5 shows the average spectra at two points (No.19, No.22) with different distance (r) from the reference. In Fig.4, graph (a) denotes the radial component (R), and (b) is the Transverse component (T). The gray solid line is the normalized spectrum for 441 earthquake records. The black solid line represents the average spectrum of each component, and the black dots are the standard deviation (SD) for each frequency. Graph (c) indicates the average spectrum of R (in red) and T (in blue), and the average spectrum of those (in black). The dotted lines are SD for each frequency.

The normalized spectrum of each observation point shows various shapes owing to the influence of the surface layer where the seismometer was installed. In Fig.4, a remarkable peak exists at approximate 6Hz. When the ground property of the observation point is similar to that of the reference point, the normalized spectrum does not exhibit any frequency characteristics and is distributed around 1, as shown in the left side graph in Fig.5. Moreover, the dominant frequency is seen 10Hz or higher in the right side graph of Fig.5. In addition, the S-wave velocities of the rock at each site are 800m/s (in Hamaoka) to 1500m/s (in Onagawa).

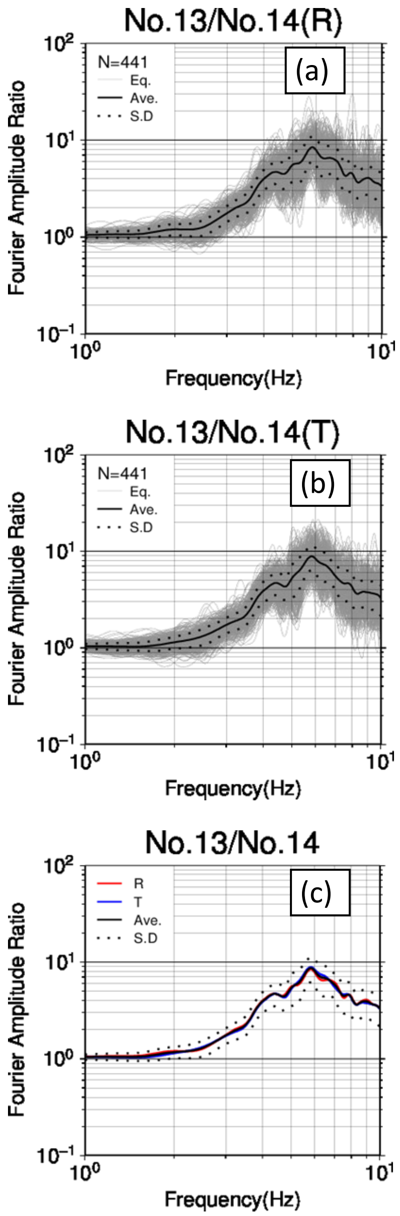


Fig.4 Example of normalized spectrum (Higashidori).

## 4. Study of SD Characteristics

Fig. 5 helps to draw inference concerning the characteristics of the SD of the normalized spectrum as below.

(1) The SD increases with frequency.
(2) The average SD (Ave.SD) between 1-10Hz also increases with distance from the reference point (r).

With (1), it is conceivable that the smaller the wavelength of the seismic wave, the more likely it is to be affected by the non-uniformity of the ground above the seismic basement. And for (2), it can be thought that it is attributed to a slight difference in the propagation path from the hypocenter to the seismic basement.

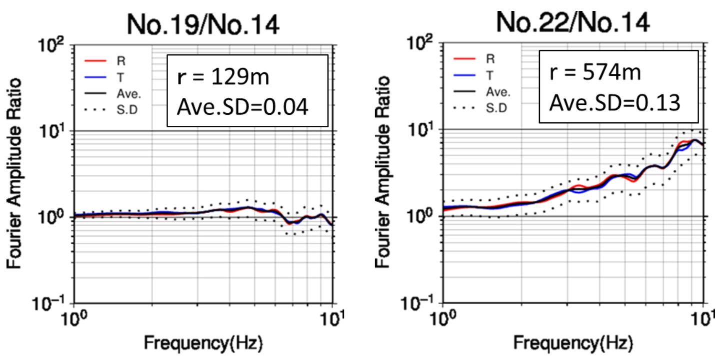


Fig.5 Example of normalized spectrum at two difference distances (Higashidori).



 

### 4.1 Frequency Characteristics of SD

Considering that the important structures of nuclear site are constructed on rock ground, in, it is desirable to examine the SD at the rock observation point. However, because most of the observation points at each site are set on unconsolidated layer, it is necessary to utilize them to investigate the distance dependence of the SD. To this reason, the author investigated the relationship between the SD and frequency, for the rock observation point ("Rock") and all observation points ("All") at each site. Here, except for the reference point, the number of rock observation points is 3 out of 24 in Higashidori, 2 out of 11 in Onagawa, 2 out of 23 in Ohma, 1 out of 13 in Tsuruga and 2 out of 7 in Hamaoka.

The result is shown in Fig.6. It is evident that the SD is proportional to the logarithm of the frequency. The Higashidori and Tsuruga sites evinced a small difference of about 0.03 between "Rock" and "All", while no significant difference was observed in the other 3 sites. Note that the large variation in Tsuruga can be attributed to a small sample size of observation data. The correlation coefficient of the approximate expression of the data at each site is substantially high. Although the slope and absolute value slightly different depending on the site, there is no significant difference. Therefore, by averaging the SD for each frequency at each site, a general empirical formula was obtained as shown in Fig.7. Since the difference between "Rock" and "All" empirical formulas is slight, it can be said that either can be used in practice.

On the other hand, if the relational expression in Fig.7 is applied to the input seismic motion to the actual structure, it will be a little too safe evaluation. The reason is that, as shown in section 4.2 below, the Ave.SD for frequencies between 1Hz and 10Hz indicates a distance dependency.

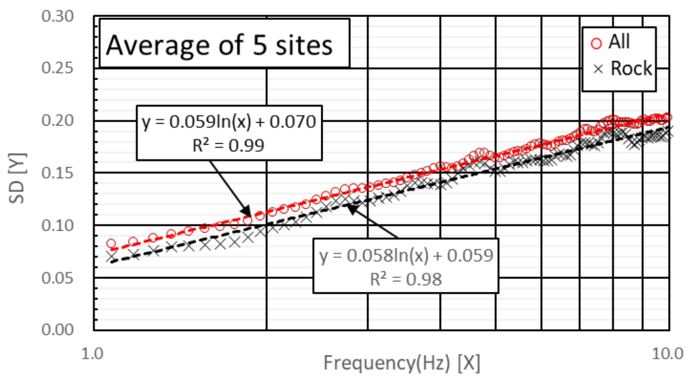


Fig.7 General empirical formula of "All" and "Rock" for 5 sites.

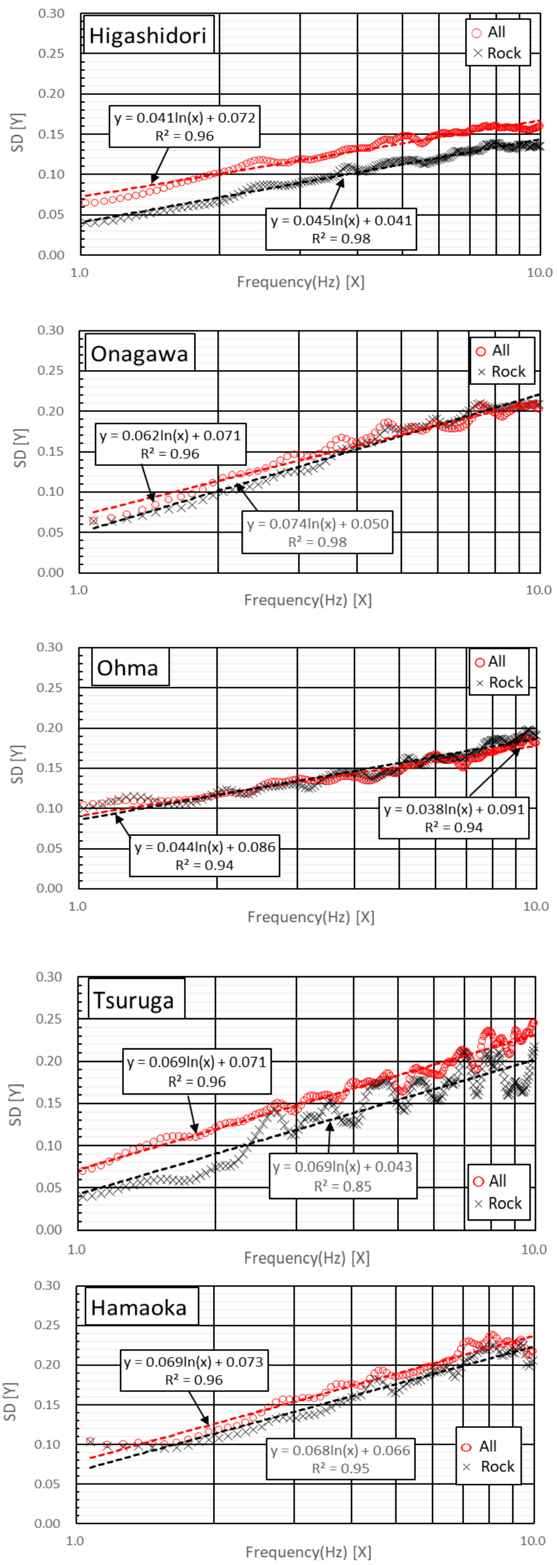


Fig.6 Relationship between the SD and frequency of "All" and "Rock" at each site.



 

### 4.2 Distance Dependency of SD

In principle, the SD converges to 0 as the observation point nears the reference point. Fig. 8 shows the relationship between the Ave.SD for frequencies between 1-10Hz at each observation point of each site and associated distance from the reference point (for "All"). The curves in the figure are plotted for instances where the distance is logarithmic. At each site except Ohma, the Ave.SD is also proportional to the logarithm of the distance. As for Higashidori, a second observation has been conducted from December, 2018 to June, 2019 by shortening the distance of the observation point. The data from this observation has been added.

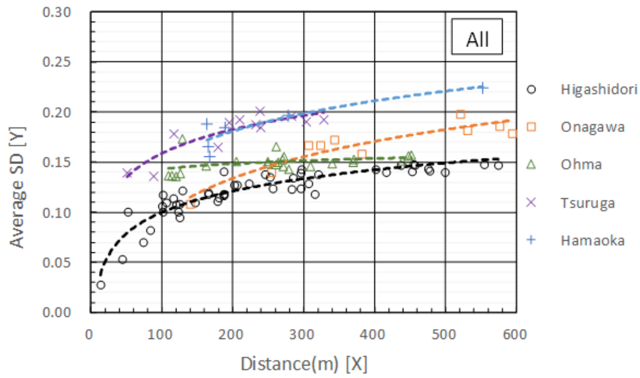


Fig.8 Relationship between Ave.SD at each observation point of each site and distance from reference point

### 4.3 Empirical Formula at a Distance of 100m

The Ave.SD, as a function of distance, essentially indicates that the degree of uncertainty of the input ground motion fluctuates with the size of the foundation of the structure. Since the scale of nuclear structures, such as reactor and turbine buildings, are less than 100m, the empirical formula for "All" in Fig.7 at a distance of 100m was estimated in the following manner.

First, the Ave.SD at each site was computed for "All" using the approximate expressions given in Fig.6. Next, the Ave.SD at a distance of 100m was estimated at each site with the approximate expressions derived in Fig.8, and the empirical expression was corrected by taking the difference between the two values. Figure 9 highlights the results. The empirical formula at a distance of 100 m, compared to that estimated from Fig7 for "All", was approximately 0.035 smaller for the corresponding SD, and empirical formula became about 0.04 at 1Hz and 0.17 at 10Hz.

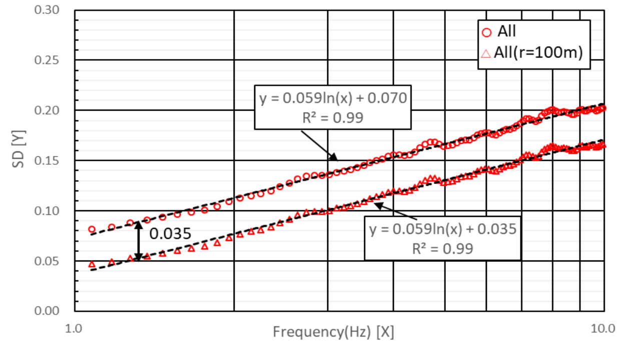


Fig.9 General empirical formula of "All" at distance from reference point (r) = 100m.

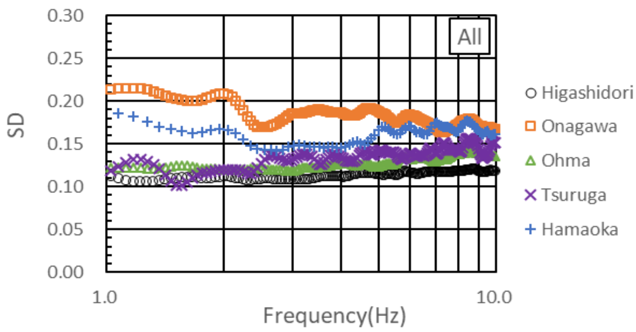


Fig.10 Relationship between SD of H/V spectral ratio and frequency.

### 4.4 SD of H/V Spectral Ratio

The above results are for the horizontal component of the S-wave, and the vertical component is not specifically considered. For this reason, the H/V spectral ratios at each observation point were calculated, and the relationship between the SD of H/V spectral ratio and frequency was investigated for "All". The results are shown in Fig.10. Evidently, the SD of the H/V spectral ratio at each site does not show significant frequency dependence and the plotlines are generally flat, implying that the above empirical formula can also be applied to the vertical component of the S-wave.



 

## 5. Conclusion

The normalized spectrum obtained from high-density seismic observation data at 5 nuclear sites has some variations from one earthquake to another. The degree of this variation is suggestive of uncertainty of the seismic amplification characteristics in upper ground than the seismic basement. Therefore, by examining the standard deviation (SD), considered as the index of variation, it was apparent that the SD was proportional to the logarithm of the frequency and the average SD demonstrated a distance dependency. Considering these characteristics, the general empirical formula for the relationship between the SD and frequency was proposed.

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