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EFFECT OF RANDOM VELOCITY INHOMOGENEITY ON AMPLITUDE FLUCTUATION OF SHORT DISTANCE SEISMIC GROUND MOTION

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Abstract

To evaluate the effects of inhomogeneity in the propagation path on seismic ground motion, numerical simulations have been performed using medium models with random fluctuations in seismic velocity. In this study, from the viewpoint of engineering, inhomogeneity effects in a short distance (<50 km) region from the seismic source are investigated. 3D inhomogeneous models were generated assuming Gaussian type random fluctuation in the velocity. The inhomogeneity parameters—strength and correlation distance of fluctuation—were set as 5% and 4 km, respectively, based on our previous study. A double-couple type point source was located at a depth of 10 km assuming an inland earthquake and the slip was provided as a ramp function with a rise time of 0.25 s. Then, the finite difference method was applied to the models to obtain velocity records at observation points on the surface. The simulated records were revealed to have coda waves similar to the observed records, and they showed that the modulated wave forms differed from the ones calculated in a homogeneous medium. Fluctuations in amplitudes were also observed in the simulated waves of the inhomogeneous medium. The Fourier spectra amplitude at 1, 2, and 4 Hz are evaluated to confirm the fluctuation dependency on the frequency. They were calculated by FFT for 2 s from the onset of the S wave part of the transverse component. The calculated waves include the amplitude change because of the four-quadrant type source radiation. Therefore, to extract only the variation due to the inhomogeneous medium, the Fourier amplitude ratio of the calculated wave of the inhomogeneous medium to the homogeneous medium wave is calculated at each observation point. The ratios were decreasing with an increasing distance to show scattering attenuation. Further, it was confirmed that the fluctuation remains at a relatively short distance. The logarithmic standard deviation is distributed around 0.1 at 1 Hz and around 0.25 at 4 Hz, demonstrating an increase with frequency. Then, the standard deviation was compared with values obtained in some previous studies. These studies evaluated the intra-earthquake, inter-earthquake, and total errors of the empirical ground motion prediction formula of the acceleration response spectrum against the observed records. The intra-earthquake error, which is relevant to the scattering effect, has a slight change with frequency. It shows similar values to the standard deviation at 4 Hz of this study, while it shows a larger value at 1 Hz and 2 Hz. This can be attributed to the source radiation characteristics. As described above, considering the ratio (inhomogeneous / homogeneous wave) cancels the amplitude change due to the source radiation. Therefore, the logarithmic standard deviation for the inhomogeneous medium itself is evaluated for the ratio. The resulting standard deviation shows an increase for 1 Hz and 2 Hz, which reveals to be the same level as the intra-earthquake errors in the previous studies. As the increase at 1 Hz is large, it is possible that the amplitude variation due to the source radiation characteristics contributes greatly to the intra-earthquake error at low frequencies. Thus, even for a relatively short distance, such as several tens of kilometer, the effects of random inhomogeneity can cause amplitude fluctuations especially at the high frequency of several Hertz, while at a lower frequency, the source radiation pattern has a greater influence.

Keywords: Seismic ground motion; Propagation path; Inhomogeneity; Scattering; Fluctuation

1. Introduction

Empirical attenuation relations are often utilized for the practical prediction of ground motion; however, large fluctuations have been observed between the observed values and attenuation relation. Fluctuation measured as a common logarithmic standard deviation of attenuation relation is ~0.2–0.3 (Midorikawa and Ohtake [1]). As the value of the fluctuation of ground motions considerably affects probabilistic seismic hazard analysis that provides basic data for disaster prevention or seismic risk evaluation, more refined evaluation of the fluctuation is necessary. The observed seismic ground motion consists of three factors: source, path, and site effect. The contribution of each factor to the total fluctuation needs to be evaluated for modeling the fluctuation more physically. In this study, the path effect on the variability of seismic motion is focused on.

Although the seismic path is modeled as a homogeneous medium, the PS-logging data in deep boreholes suggested that random fluctuation of seismic velocity exists in one geological layer (Shiomi et al. [2]). In addition, coda wave arriving after the direct P or S wave can be interpreted as the scattered wave generated by inhomogeneity in the propagation path and the calculated envelope of the coda wave based on the scattering theory can provide a satisfactory explanation of the observed records (Sato and Yamashita [3]).

Inhomogeneity in the path can also affect the variability of seismic ground motion. The theoretical methods for evaluating the effects of inhomogeneous media on seismic ground motion have been developed in the field of science; however, the evaluation target is mostly the average value of the amplitude, and there are a few evaluation examples related to the variation of the amplitude. The effect has been evaluated based on numerical simulations because analytical solutions such as envelopes have not been obtained yet. For example, Shapiro and Kneib [4] performed finite difference simulations assuming the path medium velocity has a random fluctuation. Further, Hoshiba [5] and Imperatori and Mai [6] performed numerical simulations and evaluated the fluctuation of ground motions based on the calculated waves. Although these studies have given insight into the nature of seismic motion fluctuation, the heterogeneous parameters used were assumed values.

Therefore, to perform realistic simulations, one of the most important problems is setting more realistic parameters of inhomogeneity. Generally random inhomogeneity is expressed by two parameters, the strength (ε) and correlation length (a) of the velocity fluctuation. In the past simulation analyses, these parameters were assumed based on values inferred from observation records. The inferred parameters in past studies seemed to have a wide range of values. For example, Wu and Aki [7] arranged the ε and a values estimated by past studies in various regions in the world. If these values were limited to the lithosphere, ε and a respectively change in the range from one to two orders. Sato and Midorikawa [8] showed that the fluctuation of the calculated waves varies with the change in the assumed ε and a based on the results of 3D finite difference simulations. As the change in ε or a may result from the difference of regions or scale of regions, it is important to use inhomogeneous parameters inferred in accordance with the objective of the simulations. In this study, we aim at simulating seismic waves in a relatively short distance by inland shallow earthquakes, and we used ε and a inferred based on seismic observation records in our past study (Sato and Midorikawa [9]). Then, numerical simulations are performed to study the effect of random inhomogeneity on the fluctuation of seismic ground motion.

2. Simulation Method

The finite difference method is applied assuming a 3D inhomogeneous medium as shown in Fig. 1. The size of model is 102 km × 102 km × 30 km, and it corresponds to the shallow part of the crust. The inhomogeneity in the medium is generated as follows. The seismic velocity in the medium is expressed as

$$V(\boldsymbol{x}) = V_0(1 + n(\boldsymbol{x})), \tag{1}$$

where $V(\boldsymbol{x})$ indicates the velocity of V_P or V_S at position $\boldsymbol{x}$ in the 3D medium. V_0 is the average velocity of V_P or V_S and $n(\boldsymbol{x})$ is the fluctuation in the velocity. In this study, V_P and V_S were set as 6.7 km/s and 3.7 km/s, respectively, and $n(\boldsymbol{x})$ was generated from auto-correlation function (ACF) $R(\boldsymbol{r})$ based on Sato and Midorikawa [8]. The ACF of the Gaussian function type was assumed here as

$$R(\boldsymbol{r}) = \langle n(\boldsymbol{x})n(\boldsymbol{x}+\boldsymbol{r})\rangle = \varepsilon^2 \exp(-|\boldsymbol{r}|^2/a^2) \quad (2)$$

where $\boldsymbol{r}$ is the distance vector between arbitrary two points in the medium and < > indicates the averaging operation. After $R(\boldsymbol{r})$ are evaluated assuming ε and a, $n(\boldsymbol{x})$ can be produced by Fourier transforming $R(\boldsymbol{r})$ assuming the phase is random. According to Eq. (1) the V_P and V_S values of each grid are assigned. The density was assumed to not exhibit fluctuations and have a constant value of 2.8 g/cm^3. Further, ε and a are set to 0.05 and 4 km, respectively, based on the result of Sato and Midorikawa [9].

A point source was assumed at a depth of 10 km with a focal mechanism of the vertical fault with a pure strike slip. The source time function is assumed to be a smoothed ramp function with a rise time τ = 0.25 s to generate waves with a central frequency of 4 Hz. The grid interval is 0.05 km to ensure calculations up to 6.4 Hz.

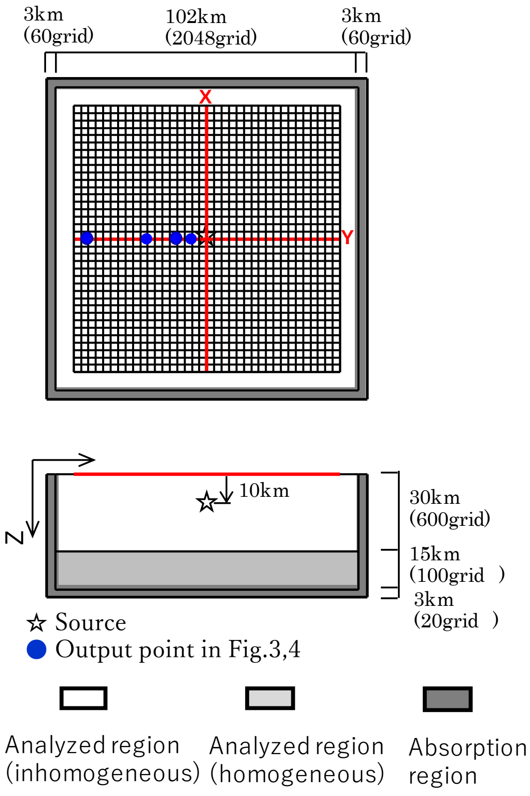

Fig. 1 — Numerical simulation model

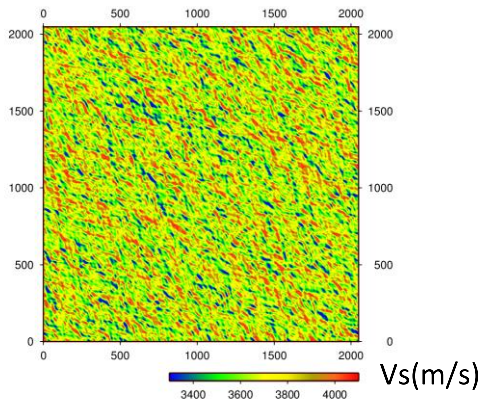

Fig. 2 — Example of inhomogeneous models

Table 1 — Average parameter of medium

Parameter		Value
Velocity (km/s)	V_P	6.7
	V_S	3.7
Density(g/cm^3)		2.8
Q		∞

3. Results and discussion

3.1 Effect of inhomogeneity on distance attenuation characteristics

Examples of calculated waves are shown in Fig. 3; simulated waves in homogeneous media are also shown for comparison in Fig. 4. In these figures, the simulated waves at grids on Y-axis are selected considering the radiation pattern of the source. In the case of the assumed source mechanism, the X and Y axis are in the direction of the node of the P wave radiation pattern. The amplitude of the S wave is maximized on the contrary, and only the transverse component is generated in these directions. The calculated waves in the homogeneous medium show such theoretical characteristics. Moreover, the shape of waves in the homogeneous medium does not change with an increasing distance. In the case of a inhomogeneous medium, not only the X-component but also the Y- and Z-components are generated. The later phases after the main pulses of direct S waves are also shown; these are coda waves by scattering.

Here, we first consider peak ground velocity(PGV). The data is the ratio of the PGV of the calculated waves of the inhomogeneous medium to the PGV of the calculated waves of the homogeneous medium. Since the radiation characteristics from the epicenter show a four-quadrant azimuth distribution, all observation points are classified by angle θ from the X and Y axes, as shown in Fig. 5, considering the amplitude difference depending on the azimuth. The range of θ is 0–45°, and in the case of this analysis, θ = 45° is the node of the S-wave radiation characteristics. The distance attenuation of PGV of the S-wave transverse component for the inhomogeneous model is shown in black in Fig. 5. For a comparison, the PGV of the calculation wave of the homogeneous medium is shown in red. The distance here is the hypocentral distance *r*. Since the depth of the point epicenter is 10 km, the hypocentral distance of 10 km corresponds

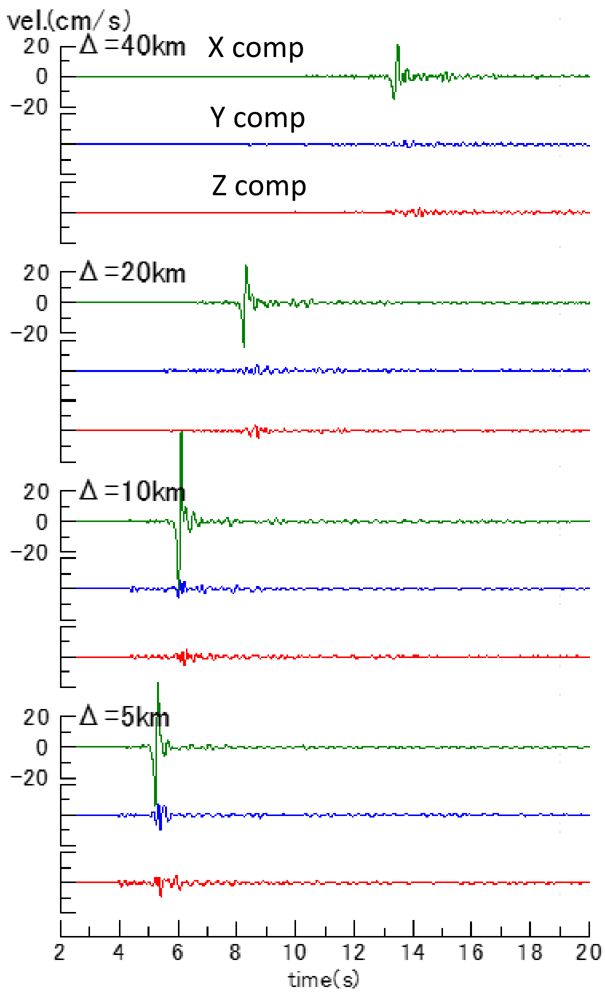

Fig. 3 — Examples of calculated velocity wave in inhomogeneous media (Δ: epicentral distance)

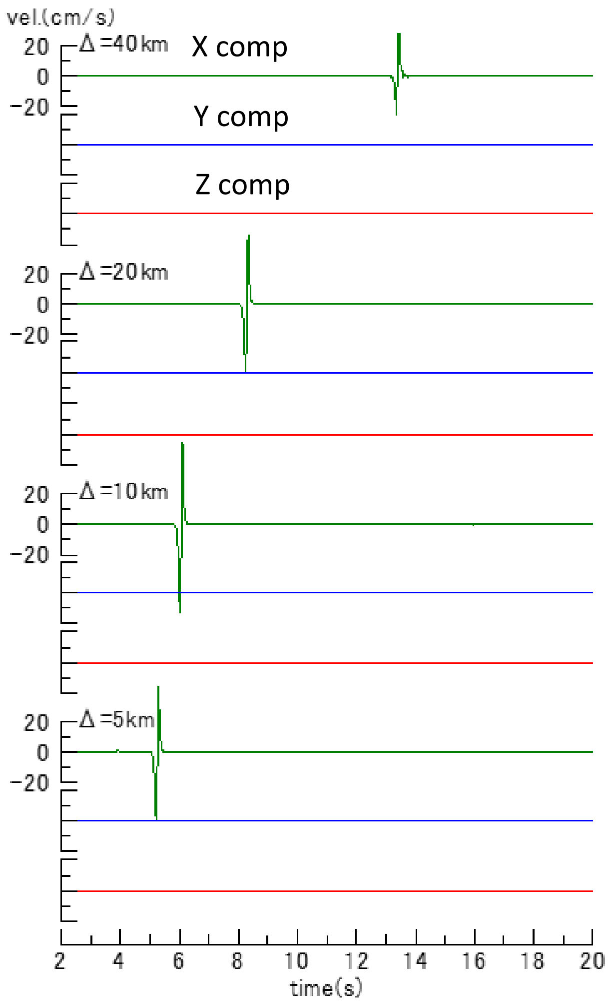

Fig. 4 — Examples of calculated velocity wave in homogeneous media (Δ: epicentral distance)

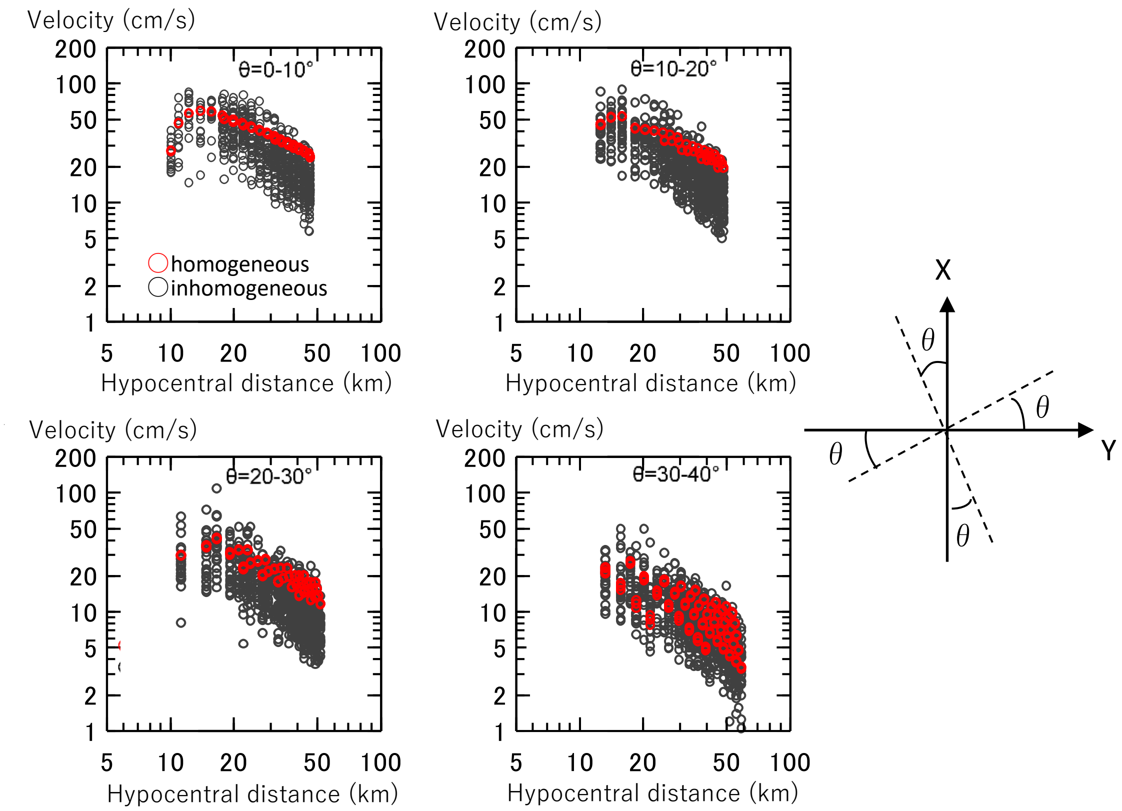

Fig. 5 – Relation between PGV of calculated waves and hypocentral distance

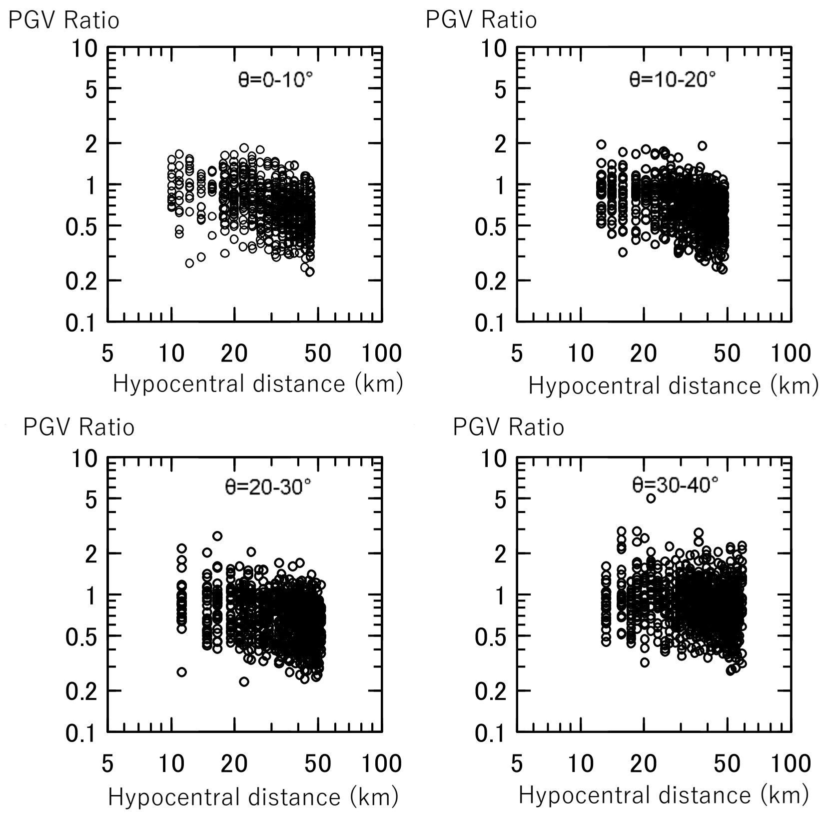

Fig. 6 – Relation between ratios of PGV (inhomogeneous/ homogeneous) and hypocentral distance

directly above the epicenter. The observation points are divided into the above-mentioned regions of 10° for θ, and θ = 40° to 45° are excluded from the target to avoid nodes in the source radiation pattern. The PGV of the homogeneous medium is attenuated in all directions in proportion to the distance dependence r^{-1} of the geometric attenuation theoretically. The amplitude of the PGV of the inhomogeneous medium fluctuates with respect to that of the PGV of the homogeneous medium, and the tendency of the overall distance attenuation is larger than that of the homogeneous medium.

To discard the influence of the source radiation characteristics and clarify the changes in the amplitude with respect to the homogeneous wave, Fig. 6 shows the ratio of the maximum velocity value between the inhomogeneous medium and the homogeneous medium at each observation point (heterogeneous /homogeneous medium PGV; hereinafter, PGV ratio). Although the PGV ratio has a variation, the center of the distribution decreases with distance as a whole, and the center of the ratio distribution is approximately 0.5 near the hypocentral distance of 50 km, which is approximately half the value above the epicenter (hypocentral distance 10 km). This indicates that the ground motion in the inhomogeneous medium is affected not only by geometrical attenuation but also by scattering attenuation. In the range of θ = 30 to 40°, the decrease in the value of the ratio is smaller than that in the other regions; however, the tendency of the attenuation is similar.

Fig. 7 shows the result of evaluating the average value of the PGV ratio in Fig. 6 to confirm the average amplitude attenuation tendency. Near the epicenter, the number of observation points is small, and as shown in Fig. 5, the S-wave radiation characteristics immediately above the epicenter also have a small amplitude. Therefore, an evaluation was performed for the hypocentral distance of 15 km or more, which deviated from the node to some extent and whose amplitude was determined to be stable. Fig. 7 indicates that there is almost no difference in the average value of the PGV ratio up to a θ of 30°, the amplitude ratio at the epicenter distance of 15 km is about 0.8, and the amplitude ratio at the epicenter distance of 45 km is about 0.6.

In the range of θ = 30–40°, the values are larger than other direction, and the slope with respect to the distance is smaller, which indicates that the effect of the scattering attenuation is weaker. This is because the region of θ = 30–40 ° is closer to the node direction of the S-wave radiation characteristic; the seismic wave amplitude in the homogeneous medium in the node direction is smaller, and in the inhomogeneous medium, the waves wraps around from the nearby direction. The mixing of the generated scattered waves may cause the effect of amplification by scattering in this region, indicating that the effect of scattering attenuation is

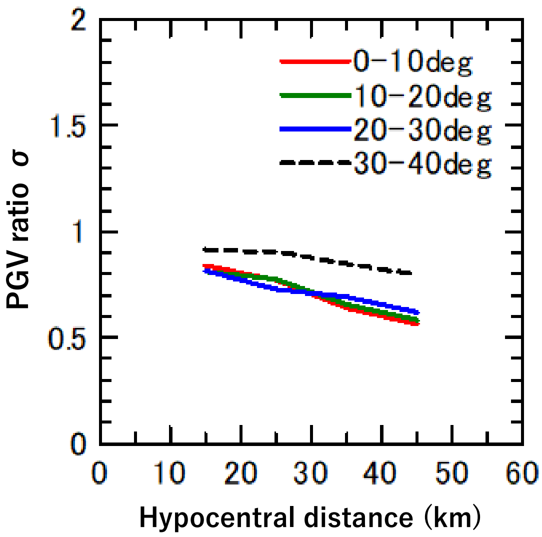

Fig. 7 — Average of PGV ratio

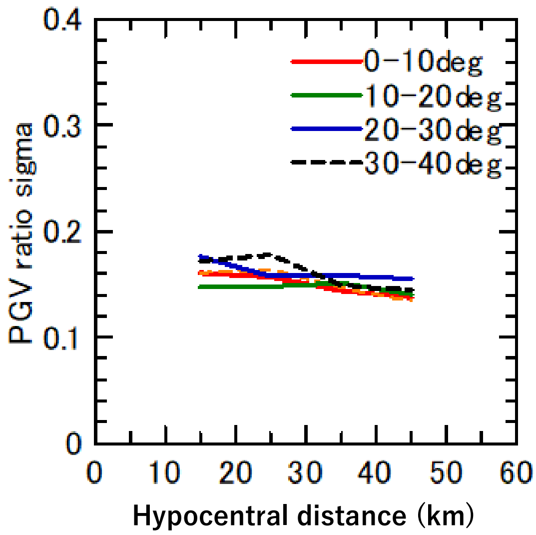

Fig. 8 — Standard deviation of PGV ratio

unclear.

3.2 Effects of inhomogeneity on ground motion fluctuation

The fluctuation of the PGV ratio shown in Fig. 6 can be regarded as the fluctuation of the ground motion caused by the influence of the inhomogeneous medium. Therefore, the logarithmic standard deviation of the variation in the PGV ratio was evaluated, and the results are shown in Fig. 8. In the calculation, the hypocenteral distance was divided into 10–20 km, 20–30 km, 30–40 km, and 40–50 km; the values included in each section were plotted against the center distance of each section. In terms of the logarithmic standard deviation, the difference based on the azimuth and epicenter distance is not clear and is distributed between 0.14 and 0.18.

To evaluate the variation in the frequency component, the logarithmic standard deviation was

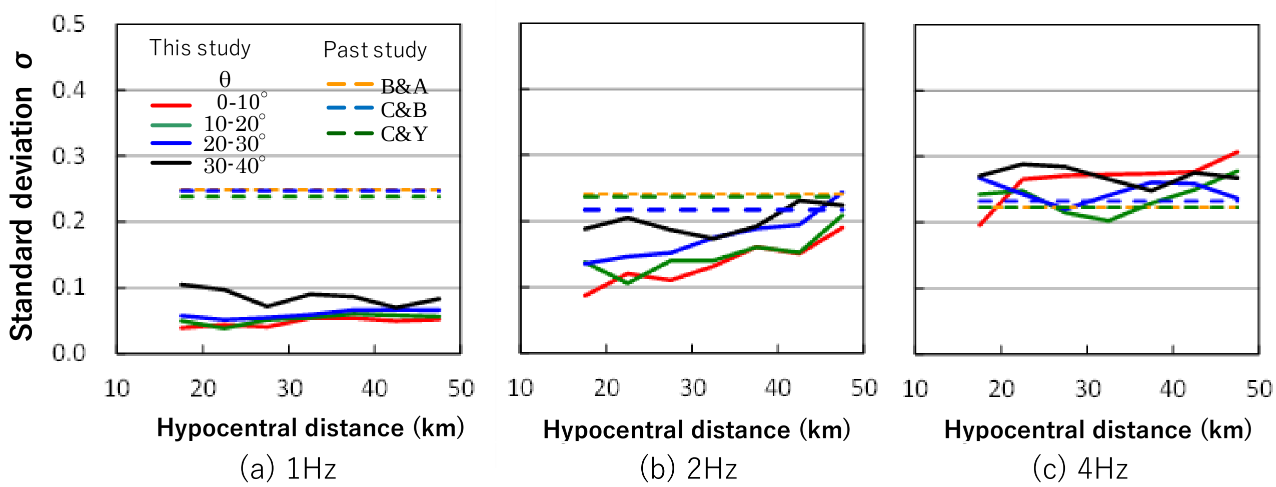

Fig. 9 — Logarithmic standard deviation of Fourier amplitude ratio (inhomogeneous/ homogeneous) of 1Hz, 2Hz and 4Hz

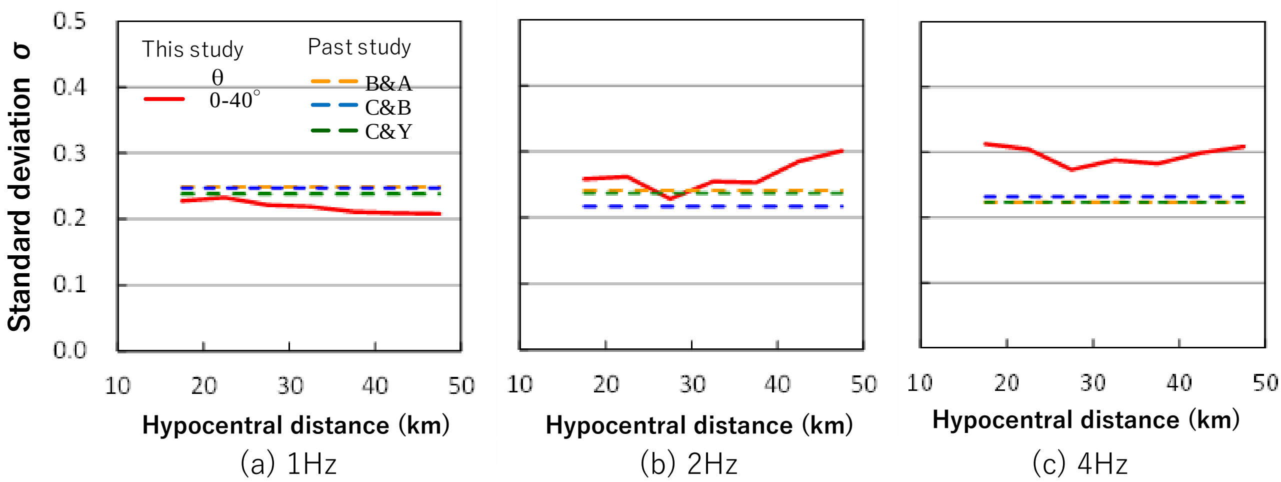

Fig. 10 — Logarithmic standard deviation of Fourier amplitude of 1Hz, 2Hz and 4Hz

calculated for the Fourier amplitude ratio, and the result is shown in Fig. 9. The Fourier spectrum was calculated for 2 s from the onset of the S wave part, targeting the transverse component. Fig. 9 shows a logarithmic standard deviation when angle θ from the X or Y axis shown in Fig. 5 is 0 to 40°, and θ is divided into regions every 10°. The logarithmic standard deviation over the entire range of 0–40° indicates that the distribution is about 0.04–0.11 at 1 Hz, 0.83–0.23 at 2 Hz, and 0.20–0.31 at 4 Hz, and it increases with frequency.

Next, we will compare the variability due to past researches based on observation records. Here, we refer to Boore and Atkinson [10], Chiou and Youngs [11], and Campbell and Bozorgnia [12] as examples of evaluation of the inter- and intra-earthquake variabilities that can be compared with simulation results. We compare the intra-earthquake variability evaluated by these studies with our results. The inter-earthquake variation is a difference in systematic ground motion characteristics among multiple earthquakes, and the causes thereof include a difference in source excitation characteristics and a difference in a macroscopic propagation path structure. Intra-earthquake variation is a variation observed within one earthquake, and the causes thereof include a difference in propagation path characteristics and a difference in ground characteristics. Boore and Atkinson [10] and others evaluated the variability of the distance attenuation formula based on records of crustal earthquakes. They evaluated the intra-earthquake variability (σ), inter-earthquake variability (τ), and the total variance σ_T ($(\sigma^2 + \tau^2)^{1/2}$) for the maximum ground motion velocity, maximum ground motion acceleration, and response acceleration with a damping constant of 0.05.

The variability of the ground motion for one earthquake evaluated by the simulation in our study corresponds to the intra-earthquake variability. First, focusing on PGV, the intra-earthquake variability due to Boore and Atkinson [10], Chiou and Youngs [11], and Campbell and Bozorgnia [12] is 0.22, 0.21, and 0.20, respectively, in the common logarithmic standard deviation. The variation of the PGV of this study shown in Fig. 8 is ~0.14–0.18, and thus, the value obtained in this study is slightly smaller than that in the past studies.

Fig. 9 shows the intra-earthquake variability for each frequency according to Boore and Atkinson [10] and others in comparison with the variability in this study. The intra-earthquake errors according to Boore and Atkinson [10] and others are almost the same as the variation of the calculated wave observed in this study, and there is almost no change in the frequency. At 4 Hz, the variability of this study is almost the same as that in the past studies; however, at 1 Hz and 2 Hz, the variability of this study is smaller. One of the reasons is that in this study the azimuth fluctuation of the amplitude caused by the source radiation characteristics was canceled out by taking the ratio of the inhomogeneous waves to the homogeneous waves.

In Boore and Atkinson [10] and others, the effects of source radiation characteristics are included in the evaluation of variability in observed values, and therefore, we evaluated the logarithmic standard deviation of the Fourier spectrum of the calculated waves in inhomogeneous media and the results are shown in Fig. 10. On comparing the logarithmic standard deviations by Boore and Atkinson [10] and ohters, the values in this study are almost similar. In particular, the logarithmic standard deviation at 1 Hz in this study is greatly increased compared to the variation in the spectral ratio shown in Fig. 9. From this result, it may be that the intra-earthquake variation at low frequencies is largely contributed by the amplitude change caused because of the source radiation characteristics.

4. Conclusion

Assuming 3D propagation path models with random velocity inhomogeneity, the effect of inhomogeneity on the fluctuation of ground motion amplitude was studied by numerical simulation using the three-dimensional finite difference method. The variation of the amplitude in the inhomogeneous medium model is seen from a short distance, and it is about 0.15 in the logarithmic standard deviation with respect to the velocity wave, and almost constant in the range of the epicenter distance of 15–50 km. For each frequency component, if the influence of the source radiation pattern is removed, it becomes about 0.25 for a frequency of 4 Hz and slightly less than 0.1 for a frequency of 1 Hz. Variations in the distance attenuation formula may include the influence of the source radiation. Therefore, if this is included in the evaluation, it will be about 0.3 for a frequency of 4 Hz and slightly more than 0.2 for a frequency of 1 Hz. The intra-earthquake error in the past attenuation equation includes the dispersion of propagation characteristics and ground characteristics. Compared to these errors, the standard deviation of this study is slightly larger at 4 Hz and slightly smaller at 1 Hz. From this result, it is evident that random inhomogeneity can cause amplitude fluctuation especially at a high frequency of several Hertz. Considering the result at 1 Hz, the source radiation pattern may have a greater influence on the fluctuation at a lower frequency.

5. Acknowledgements

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