17th World Conference on Earthquake Engineering, 17WCEE
Sendai, Japan - September 13th to 18th 2020

CHARACTERISTICS OF SPATIAL VARIATINON OF MICROTREMOR RECORDS AT ADJACENT POINTS

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Abstract

Spatial variation of strong ground motion at adjacent points could cause reduction effect on input motions to structures, so it is important to clarify the characteristics of spatial variation of ground motions. On the other hand, it is difficult to analyze the spatial variation of strong ground motions because larger earthquakes occur less frequently than smaller ones and ground motion data would not be obtained easily. But it would be useful for estimating the characteristics of spatial variation if microtremor records are correlated with strong ground motion data. So, the objective of this study is to analyze the characteristics of microtremor records at adjacent points and to clarify the relations between spatial variation of microtremor and ground motion.

To carry out the objective of this study, microtremor array data of the site where strong ground motion records have been obtained are needed. In this study, microtremor observation records are obtained on the ground surface of the Chiba array observation site, operated by the Institute of Industrial Science, University of Tokyo, as the soil site. Also, microtremor records are obtained on the ground surface of one of the K-NET and KiK-net observation site in Hayakawa Town, Yamanashi Prefecture, operated by the National Research Institute for Earth Science and Disaster Resilience, Japan, where the both observation seismographs are installed at the distance of only around 5 meters with each other, as the rock site. Spatial variation of microtremors is evaluated by coherence of the two adjacent observation points, and coherence of horizontal and vertical component of observation records are calculated individually. The relations between coherence and separation distance between observation points are examined in this study, as well as the relations between coherence and soil property, to compare the characteristics of spatial variation between microtremor records and ground motion records.

Coherence of microtremor data shows rapid decay with the increase in the frequency. It is also found that coherence of microtremor records data becomes lower as separation distance gets larger, and coherence of microtremor in soil site decay at lower frequency than in rock site. In addition, it is clarified that the coherence is affected by the thickness of soft soil layers and this effect becomes larger as the separation distance between observation points is larger. Also, when coherences are transformed into wavenumber of the depth that effects on spatial variation, all the coherences are in good agreement with each other in that decreasing at the wavenumber of approximately 0.5, regardless of soil property or separation distance between seismometers. Those characteristics of spatial variation of microtremor records are also seen in the strong ground motion records. And what is interesting, the frequency or wavenumber that the coherence of microtremor begins to decay is almost same as the coherence of ground motion records.

In conclusion, this study clarified that the spatial variation of microtremor records has almost the same characteristics as the spatial variation of ground motion records.

Keywords: spatial variation, coherence, microtremor, ground motion, heterogeneity

1. Introduction

Spatial variation of strong ground motions at adjacent points could cause significant effect on the dynamic response of large structures, for example a reduction in the amplitude of high frequency components of input motions and excitation of the rocking or torsional responses [1].

Characteristics of spatial variation of ground motion have been studied by observation record analyses at adjacent points or ground motion simulations using heterogeneous soil models. Many researchers have pointed out that spatial variation becomes larger as frequency gets higher, and the longer the distance between the observation points, the larger the spatial variation of ground motion becomes. On the basis of these analyses, some empirical equations of spatial variation have been proposed as a function of frequency and distance between observation points as parameter [2-5].

But it is difficult to analyze the spatial variation of strong ground motions because larger earthquakes occur less frequently than smaller ones and ground motion data could not be obtained easily. Also, there are some non-negligible differences of spatial variation between ground motion observation records and ground motion simulations using heterogeneous soil model, so we may not be able to obtain high-accuracy results of spatial variation from these simulations. On the other hand, it is very useful if the characteristics of spatial variation of strong ground motion could be evaluated from microtremor records, because microtremor survey can be performed easily in anytime and anywhere.

In this study, we performed microtremor array survey in the former Nishi-Chiba Campus of Chiba Experimental Station, Institute of Industrial Science, the University of Tokyo where a dense seismometer array system had been installed (hereinafter referred to as "Chiba site"), and municipal tennis court in Hayakawa Town, Yamanashi Prefecture, Japan (hereinafter referred to as "Hayakawa site") where a pair of K-NET and KiK-net seismic network systems are installed adjacent to each other, in order to analyze characteristics of spatial variation of microtremor of both rock (Hayakawa site) and soil (Chiba site) sites. Also, we conducted microtremor simulations using heterogeneous soil model of Chiba and Hayakawa sites, comparing the characteristics of spatial variation of microtremor.

2. Microtremor Observations

Microtremor array measurements were performed at Chiba and the Hayakawa site. The location of both sites is shown in Fig. 1. Chiba site is the place in which Chiba seismometer array system had been installed [6]. Hayakawa site is the place where a pair of K-NET and KiK-net seismograph system by the National Research Institute for Earth Science and Disaster Resilience, Japan (NIED) [7], are installed adjacent to each other whose separation distance is about 5 m.

S-wave velocity structures of Chiba and Hayakawa sites are shown in Fig. 2 [6, 7]. It could be seen that subsurface of Chiba and Hayakawa site are soil and rock respectively. Fig. 3 shows the location of observation points of microtremor array in Chiba and Hayakawa sites. In Chiba site, C0-C4 and P1-P5 are the same points in which Chiba seismometer array system was installed. X1 was placed on the extension of a line of P1, C0 and P3, as well as X2 was placed at a distance of 5 m from P4, on the line of C0 and P4. In Hayakawa site, observation points were located on three kinds of lines whose separation distance between seismometers were 5–60 m, by the K-NET and KiK-net seismic network system.

In the microtremor survey, four pairs of over-damped accelerometer JEP6A3 from Mitutoyo Corp. and data logger LS880 from Hakusan Corp. were used. The sampling frequency was 200Hz and each data logger was calibrated every one second with GPS clock. To cover all the observation points with four seismometers, four kinds of seismometer location cases were set in Chiba Site and three kinds of location cases were set in Hayakawa Site, as shown in Table 1. The number of pairs of seismometers, whose separation distances are 5 m, 15 m, 30 m and 60 m, are also shown in Table 1. In this study, spatial variation of microtremor at these separation distances are analyzed.

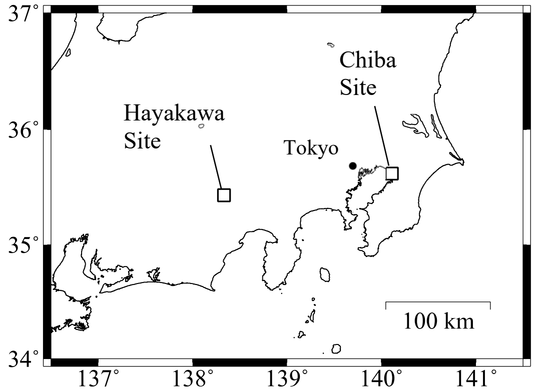


Fig. 1 – Location of microtremor array sites

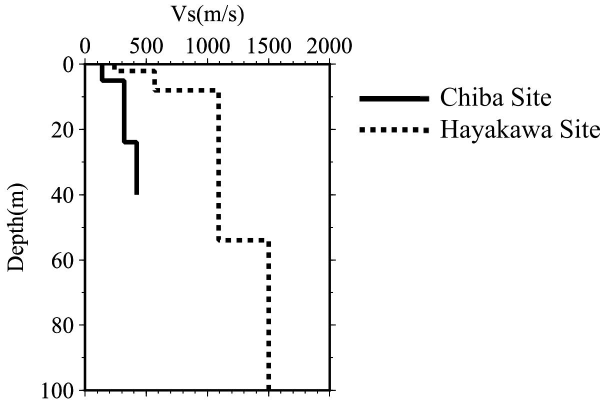
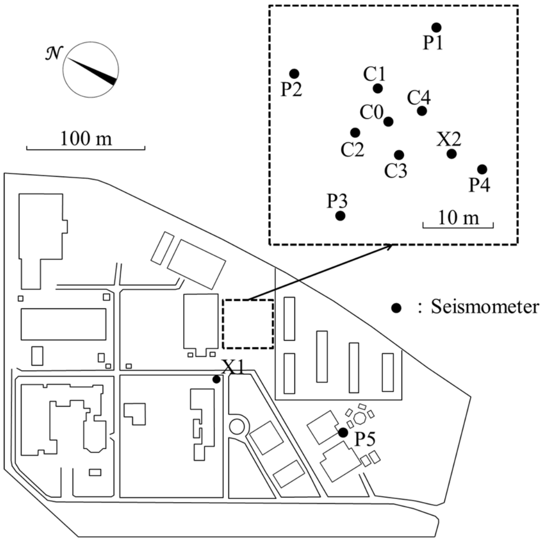
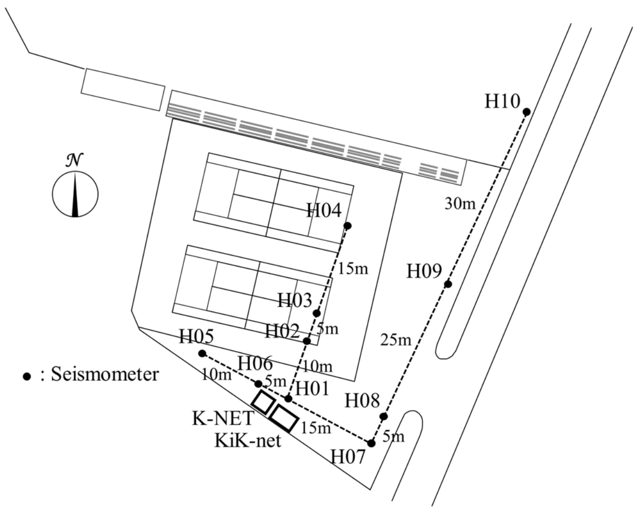


Fig. 2 – S-wave velocity structures



(1) Chiba site



(2) Hayakawa site

Fig. 3 – Location of observation points

Microtremor measurements were conducted during the daytime in Nov. 28th, 2018 in Chiba Site, and in Nov. 4th, 2019 in Hayakawa Site. Microtremors were measured about one hour at each location case. There was no rainfall during the all observation days.

3. Observation Records

3.1 Fourier Amplitude Spectra

Fig. 4 shows the Fourier amplitude spectra of microtremors at observation points of Case 1 of Chiba site, shown in Table 1(1), and Case 1 of Hayakawa site, shown in Table 1 (b). To evaluate the Fourier amplitude spectra in this study, microtremor records of each observation point were divided into 100 waveforms in 10.24 seconds, calculated the Fourier amplitude spectra of each waveform, and averaged them for each observation point.

Table 1– Number of pairs of seismometers by separation distance

(1) Chiba site

Location case	Obs. points	Distance between seismometers			
		5 m	15 m	30 m	60 m
Case 1	C0, C1, C2, C3	3	–	–	–
Case 2	C0, C3, C4, P5	2	–	–	–
Case 3	C0, P2, P4. X2	1	2	1	–
Case 4	C0, P1, P3, X1	–	2	1	1
Total		6	4	2	1

(2) Hayakawa site

Location case	Obs. points	Distance between seismometers			
		5 m	15 m	30 m	60 m
Case 1	H01, H02, H03, H04	1	2	1	–
Case 2	H01, H05, H06, H07	1	2	1	–
Case 3	H07, H08, H09, H10	1	–	2	1
Total		3	2	4	1

There are not so significant differences between the Fourier amplitudes of observation points, regardless of observation sites. Also, every spectrum has a peak at around 10–20 Hz, and the amplitude is greatly reduced in lower frequencies.

Fig. 5 shows the comparison of the Fourier amplitude spectra of C0 at Chiba site and H0 at Hayakawa site. The Fourier amplitude of C0 is about ten times larger than that of H01, though there are not so significant differences in shape of the spectrum in that having a peak around 10–20 Hz and declining rapidly in lower frequency. The difference of the Fourier amplitudes between two sites indicates that the lower S-wave velocity of subsurface is, the larger the amplitude of microtremor becomes.

3.2 Spatial Variation

In this study, spatial variation of ground motion is quantified by coherence. Coherence of microtremor records between the observation point i and j $\mathrm{Coh}_{ij}(f)$ is described by equation (1).

$$\mathrm{Coh}_{ij}(f) = \frac{1}{N}\sum_{m=1}^{N}\frac{\left|G_{ij}^{m}(f)\right|}{\sqrt{G_i^m(f)G_j^m(f)}} \tag{1}$$

Where f is frequency, $G_{ij}^{m}(f)$ is the cross spectrum of the microtremor record m between observation points i and j, $G_i^m(f)$ and $G_j^m(f)$ are power spectra of the microtremor record m at observation points i and j. N is the total number of microtremor records. In this study, 100 of consecutive microtremor records of 10.24 seconds were used for evaluating $\mathrm{Coh}_{ij}(f)$. Note that real and imaginary part of cross spectra and power spectra were smoothed with Parzen window at 1.0 Hz, and $\mathrm{Coh}_{ij}(f)$ of horizontal component was derived from the average of $\mathrm{Coh}_{ij}(f)$ of NS and EW components.

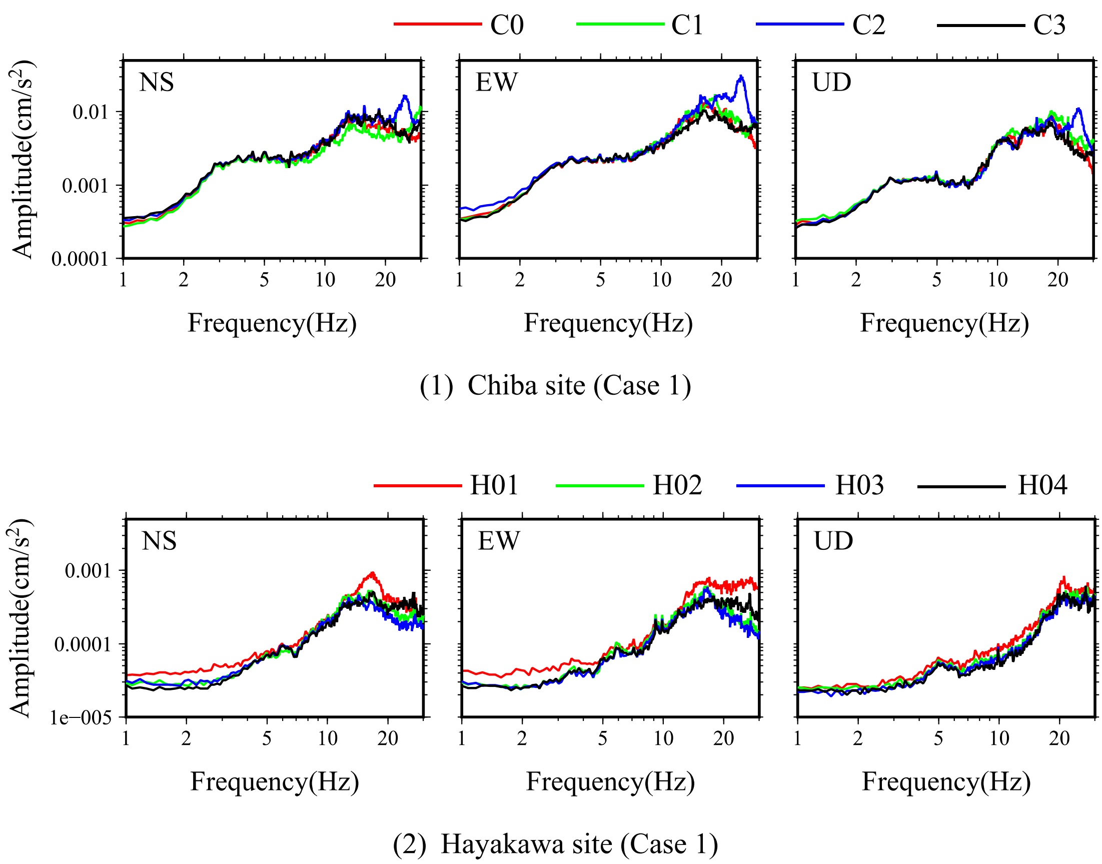


Fig. 4 – Fourier amplitude spectra at each observation site

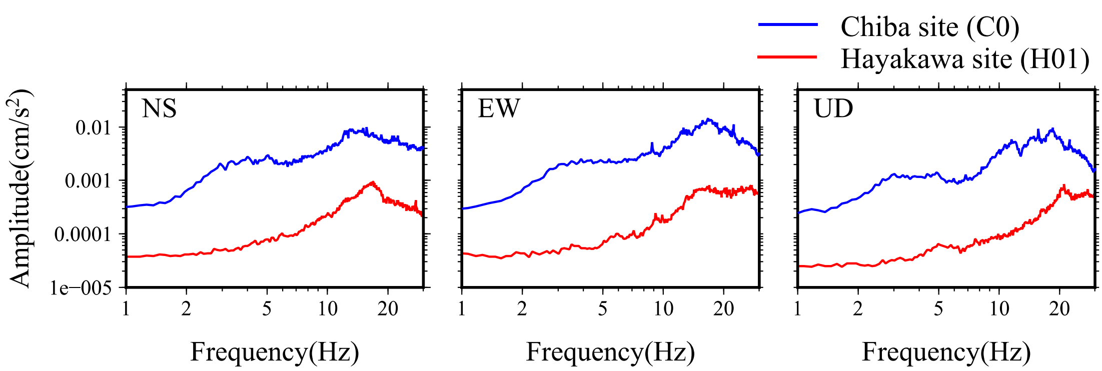


Fig. 5 – Comparison of fourier amplitude spectra between observation sites

The comparison of the average of $Coh_{ij}(f)$ of microtremor records at the separation distance of 5 m between Chiba and Hayakawa site is shown in Fig. 6. There are not so significant differences between $Coh_{ij}(f)$ in horizontal and vertical components. $Coh_{ij}(f)$ should be high in lower frequency, but $Coh_{ij}(f)$ in Hayakawa site is very low. It is thought to be due to very low amplitude of microtremor records in lower frequency in Hayakawa site, shown in Fig. 4 or Fig. 5. $Coh_{ij}(f)$ in Chiba site declines sharply at the frequency of around 5 Hz, while $Coh_{ij}(f)$ in Hayakawa site has a peak at 10–20 Hz and gets lower as the frequency increases. It could be thought that the difference of frequency that $\mathrm{Coh_{ij}(f)}$ begins to decline refrects the characteristics of spatial variation of different S-wave structures on subsurface soil.

The average of $\mathrm{Coh_{ij}(f)}$ of microtremor records at the separation distances of 5 m, 15 m, 30 m, 60 m in Chiba and Hayakawa sites are shown in Fig. 7 and Fig. 8. $\mathrm{Coh_{ij}(f)}$ begins to decrease in lower frequency as the separation distance becomes longer. Fig. 7 and Fig. 8 also show the average of $\mathrm{Coh_{ij}(f)}$ of ground motion observed in the former Chiba seismometer array system in Chiba site and K-NET and KiK-net system in Hayakawa site. In this study, $\mathrm{Coh_{ij}(f)}$ of ground motion were calculated from waveforms for 10.24 seconds from S-wave arrival time of seismic events whose magnitudes (M_J) are 5.5–6.5 and hypocenter distances are 100–200 km. $\mathrm{Coh_{ij}(f)}$ of microtremor records are about the same or lower than $\mathrm{Coh_{ij}(f)}$ of ground motion records, but the frequency that $\mathrm{Coh_{ij}(f)}$ begin to decline are almost the same between microtremor and ground motion records at every separation distance.

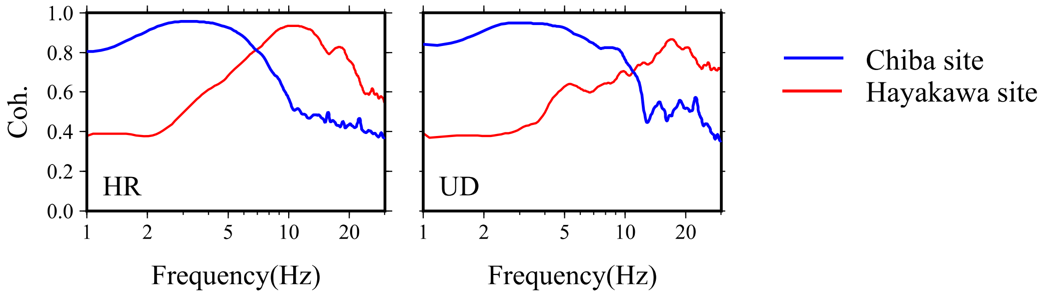
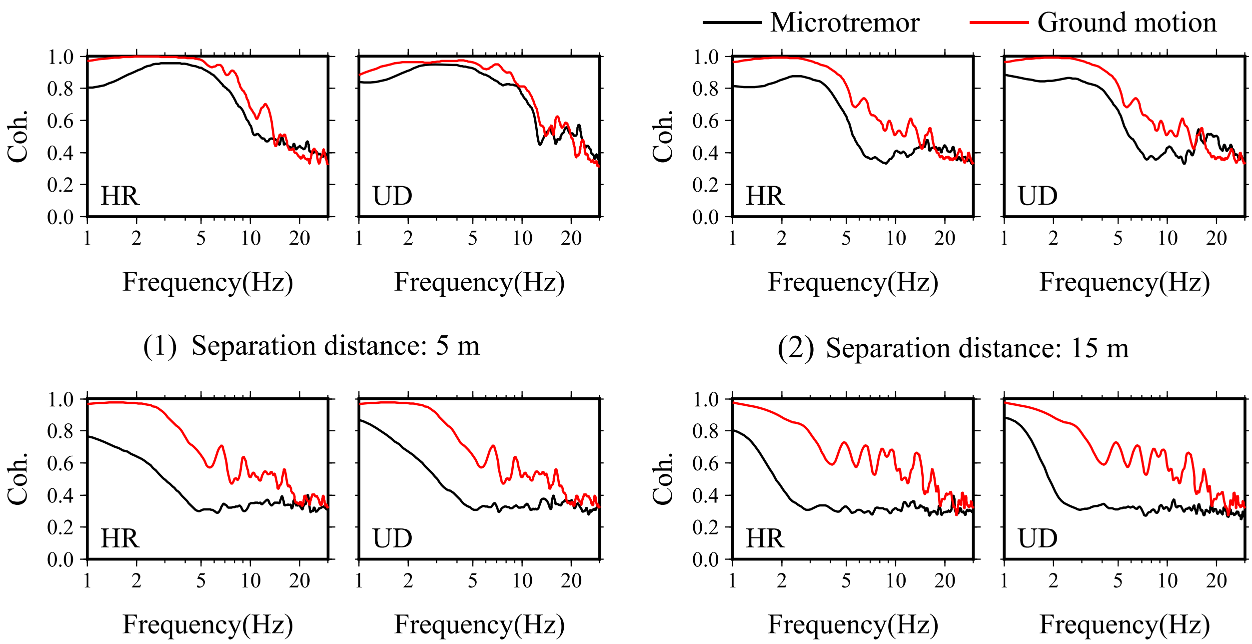


Fig. 6 – The average of $\mathrm{Coh_{ij}(f)}$ between Chiba and Hayakawa sites (separation distance: 5 m)



(1) Separation distance: 5 m

(2) Separation distance: 15 m

(3) Separation distance: 30 m

(4) Separation distance: 60 m

Fig. 7 – The average of $\mathrm{Coh_{ij}(f)}$ at adjacent observation points in Chiba site

In the previous studies, the authors inferred that the depth of subsurface soil that affects spatial variation of ground motion h_r increases as the separation distance between observation points becomes longer, and the frequency at which $Coh_{ij}(f)$ of ground motions begin to decrease f_c corresponds to the wavenumber of about 0.5 for h_r [8]. Fig. 9 shows the relation between separation distance and h_r which is estimated so that the wavenumber corresponding to f_c is around 0.5. On the other hand, assuming that the main cause of microtremor is the Rayleigh wave, the propagation velocity is almost equivalent to S-wave velocity, and the wavelength when propagating in the same subsurface soil should be almost the same.

On the basis of these presumptions, $Coh_{ij}(f)$ of microtremor records in Chiba and Hayakawa site, shown in Fig. 7 and Fig. 8 are transferred to the wavenumber domain for h_r ($Coh_{ij}(h_r)$). The results are shown in Fig. 10. Though $Coh_{ij}(h_r)$ at separation distance of 30 m in Chiba site begin to decrease at the wavenumber below 0.5, and there is not significant wavenumber that $Coh_{ij}(f)$ begin to decline in the results at separation distances of 30 m and 60 m in Hayakawa site, other $Coh_{ij}(h_r)$ begin to decrease at the wavenumber of around 0.5.

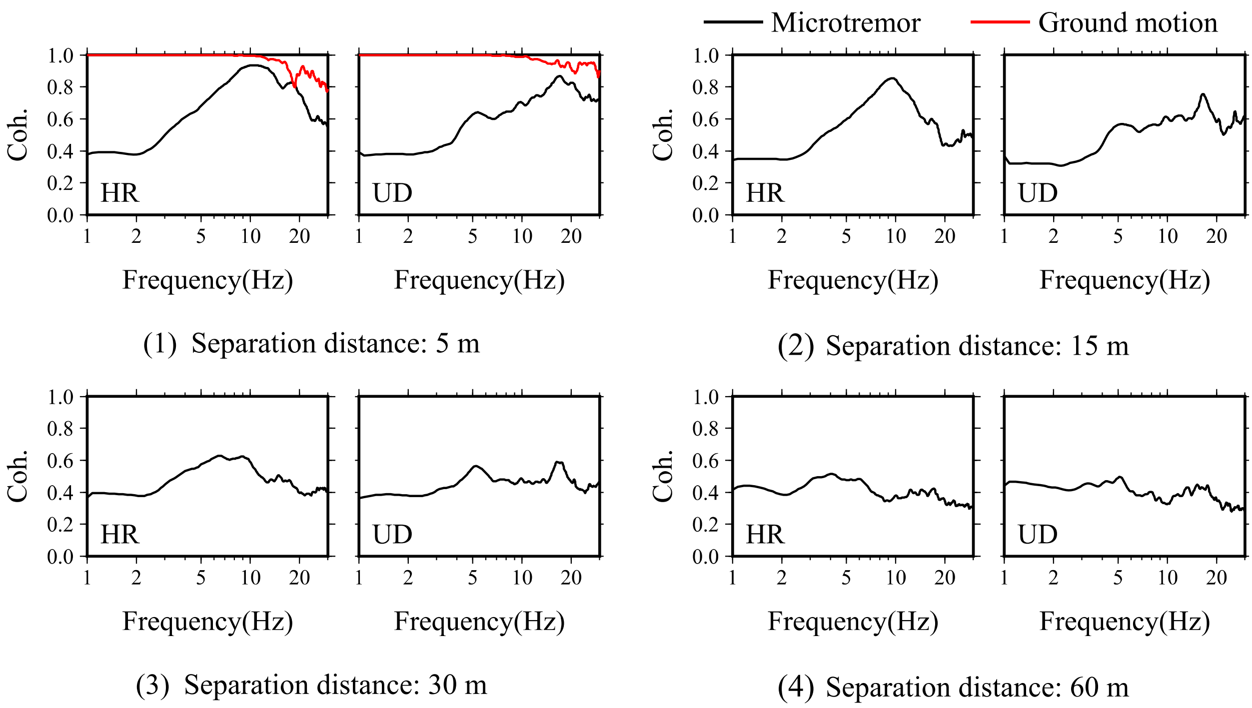


Fig. 8 – The average of $Coh_{ij}(f)$ at adjacent observation points in Hayakawa site

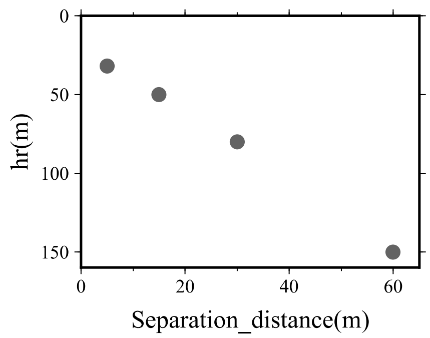
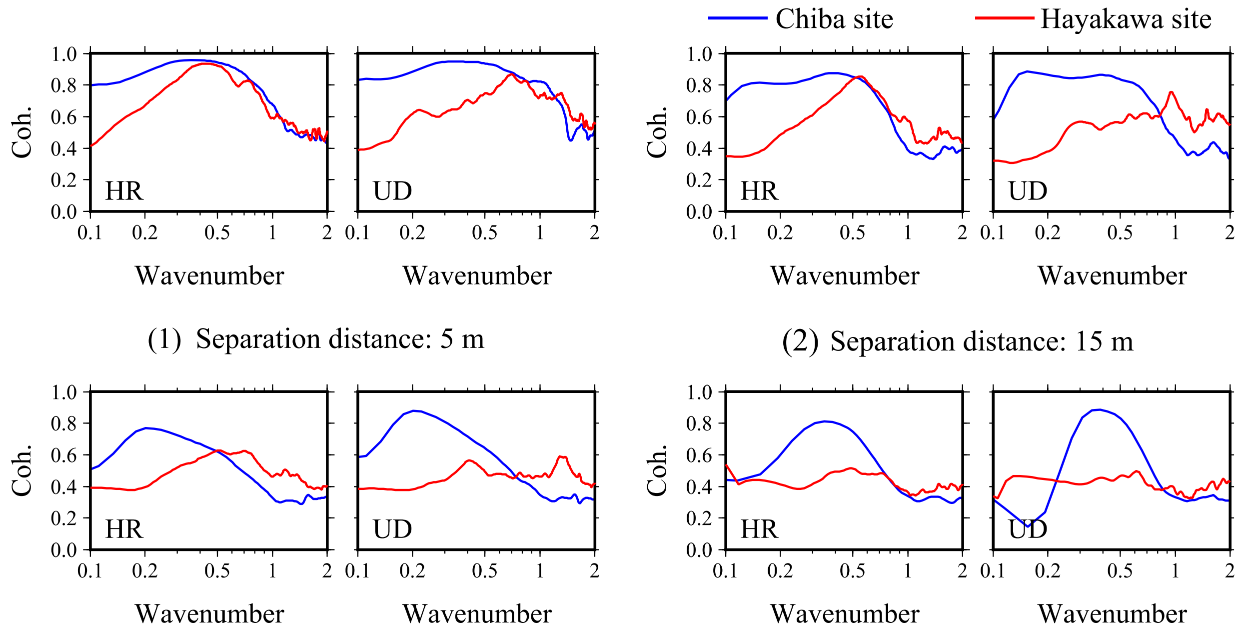


Fig. 9 – Relation between h_r and separation distance



(1) Separation distance: 5 m

(2) Separation distance: 15 m

(3) Separation distance: 30 m

(4) Separation distance: 60 m

Fig. 10 – The average of $Coh_{ij}(h_r)$ at adjacent observation points in Hayakawa site

4. Microtremor and Ground Motion Simulations Using Heterogeneous Soil Models

In order to verify the characteristics of spatial variation of microtremor and ground motion records shown in the previous chapter, microtremor and ground motion simulations were conducted using 2D FEM soil models of Chiba and Hayakawa sites.

4.1 Soil Models and Input Motions

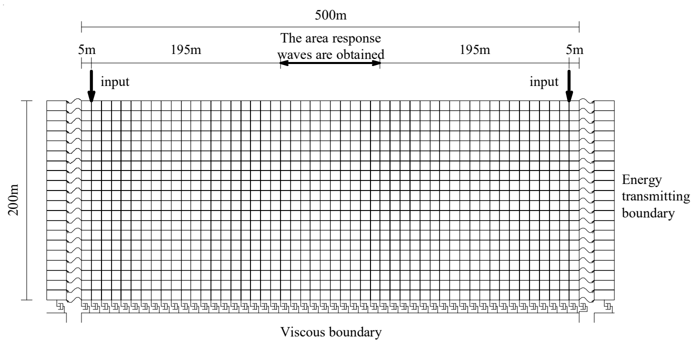
2D FEM models used for microtremor and ground motion simulations are shown in Fig. 11. All models are 500 m in length and 200 m in depth with energy transmitting boundary on the side and viscous boundary on the bottom. The mesh size of all the models is 1m x 1m.

S-wave velocity distributions of soil models are shown in Fig. 12. Soil layers are based on S-wave velocity structures of Chiba and Hayakawa sites, shown in Fig. 2. In this study, both homogeneous and heterogeneous soil models are used to evaluate the effects of phase velocity and heterogeneity of subsurface soil on the spatial variation of microtremor individually.

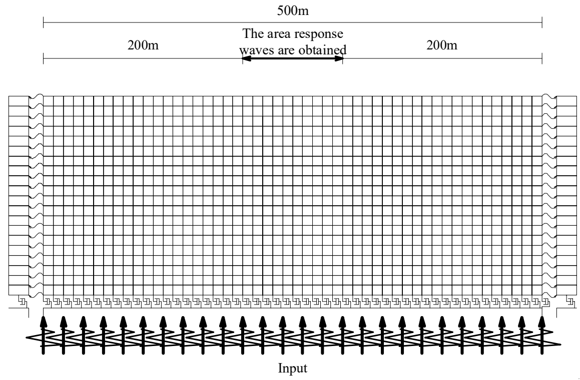
The heterogeneous soil models were built according to a Gaussian autocorrelation function with the correlation distance of 30 m in horizontal, 3 m in vertical, and the coefficient of variation of S-wave velocity of 20 %, referring to previous study [9, 10]. The average of S-wave velocity of each soil layer was set to S-wave velocity structure of Chiba and Hayakawa sites. To avoid being included peculiar characteristics in the result of simulations, five kinds of heterogeneous soil models were used for the simulations. Fig. 12 shows each one of the heterogeneous soil models of Chiba and Hayakawa sites.

The density of each mesh ($\rho(x_1, x_2)$) was defined by equation (2), linked with S-wave velocity.

$$\rho(x_1, x_2) = 2.5 \times \frac{v_s(x_1, x_2)}{\mu_s} \quad (2)$$

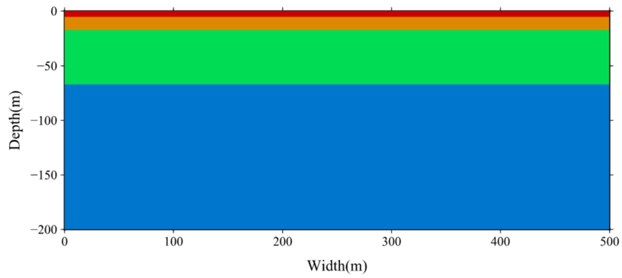


(1) Point source
(for microtremor simulations)

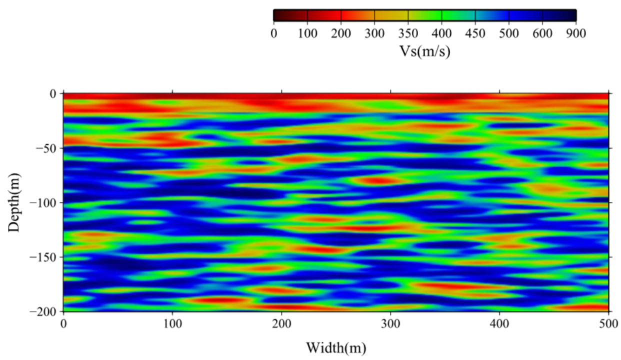


(2) Plain wave
(for ground motion simulations)

Fig. 11 – Soil model, input points and observation area

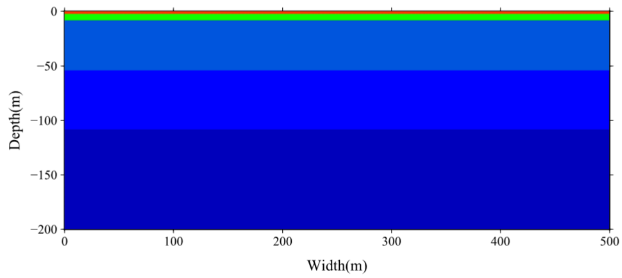


Homogeneous model

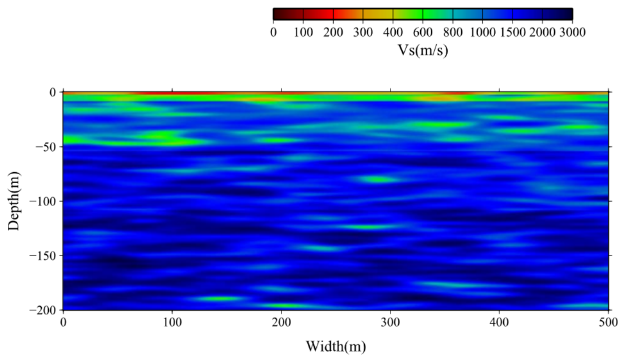


Heterogeneous model

(1) Chiba site



Homogeneous model



Heterogeneous model

(2) Hayakawa site

Fig. 12 – Homogeneous and heterogeneous soil models of Chiba and Hayakawa sites

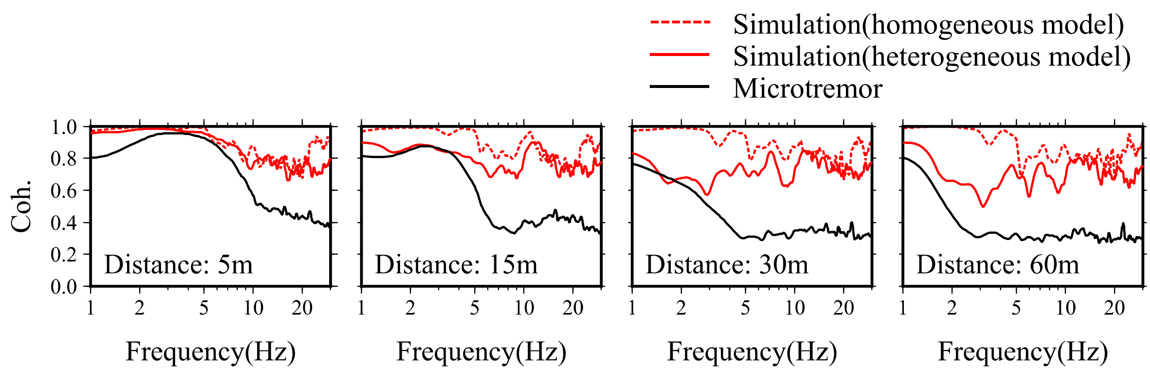
Where $v_s(x_1, x_2)$ is S-wave velocity of the mesh (x_1, x_2), μ_s is the average of S-wave velocity. Note that the non-linearity of the soil property was not considered, and the damping constant was set to 0.5 % in all meshes.

To simulate microtremor and ground motion on the surface of the model, two kinds of input motions were set in this study. The one is vertical motion at 5 m from both ends of the surface of the model as shown in Fig. 11(1), to simulate the spatial variation of microtremor on the surface using both homogeneous and heterogeneous models (hereinafter referred to as “microtremor simulation”). The other is the horizontal motion (SH wave) from all over the bottom of the model just like a plane wave as shown in Fig. 11(2), so that the spatial variation of ground motion could be simulated using heterogeneous models (hereinafter referred to as “ground motion simulation”). A triangular function with 0.02 seconds were used for all the input motions in order to give an impulse-like wave. The response of SV wave in microtremor simulations and the response of SH wave in ground motion simulations were extracted at 1 m intervals in the central area of 200 m on the surface of soil models.

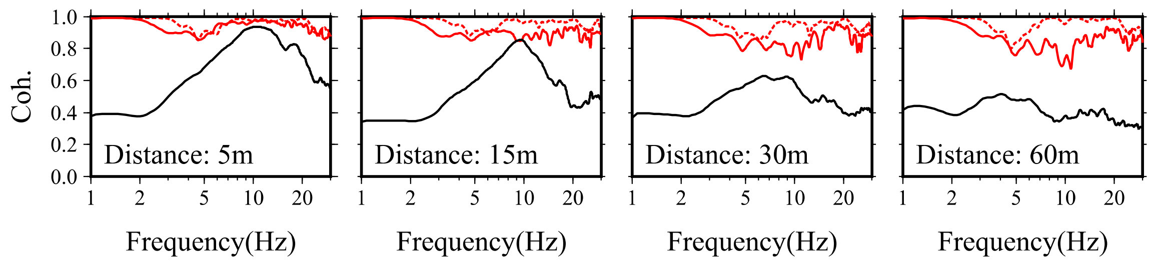
Every $Coh_{ij}(f)$ at adjacent points whose separation distances of i and j are 5 m, 15 m, 30 m and 60 m were evaluated. In calculating $Coh_{ij}(f)$, cross spectra and power spectra were smoothed with Parzen window at 1.0 Hz, just like evaluating the spatial variation of microtremor and ground motion records in Chapter 3. $Coh_{ij}(f)$ were averaged for each separation distance. In addition, in the evaluation of $Coh_{ij}(f)$ using heterogeneous models, $Coh_{ij}(f)$ of all the heterogeneous models were averaged.

4.2 Results

$Coh_{ij}(f)$ of microtremor simulations are shown in Fig. 13, with respect to the separation distances of 5 m, 15 m, 30 m, and 60 m. The red dotted lines are $Coh_{ij}(f)$ of the homogeneous model, and the solid red lines are $Coh_{ij}(f)$ of the heterogeneous model. For comparison, $Coh_{ij}(f)$ of the average of microtremor records are shown by black solid lines.



(1) Chiba site



(2) Hayakawa site

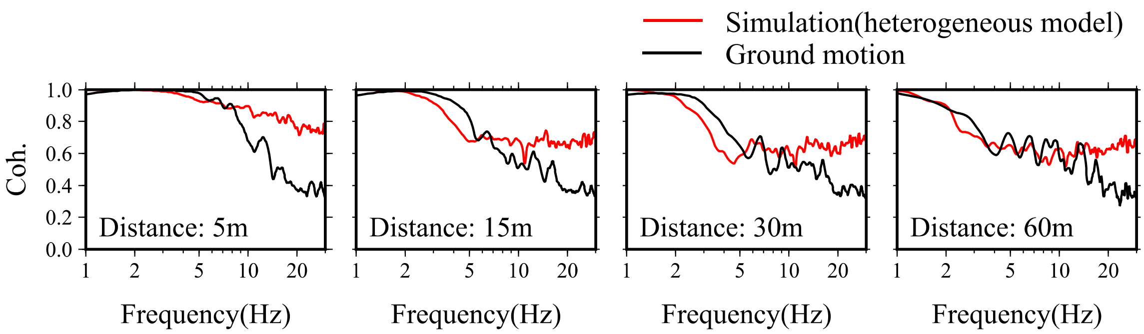
Fig. 13 – The average of $Coh_{ij}(f)$ of microtremor simulations at adjacent points

$Coh_{ij}(f)$ using the heterogeneous model is lower than $Coh_{ij}(f)$ using the homogeneous model. It could be thought that the difference of $Coh_{ij}(f)$ between the heterogeneous and the homogeneous model is due to the effect on spatial variation of heterogeneity of soil. $Coh_{ij}(f)$ of the simulations of Chiba site is lower than $Coh_{ij}(f)$ of the simulations of Hayakawa site at every separation distance. $Coh_{ij}(f)$ using the heterogeneous model of Chiba site corresponds well in lower frequencies with $Coh_{ij}(f)$ of microtremor records, and the frequency that $Coh_{ij}(f)$ begins to decline is almost the same between them. On the other hand, $Coh_{ij}(f)$ of the simulations of Hayakawa site is not in good agreement with $Coh_{ij}(f)$ of microtremor records almost in all frequencies.

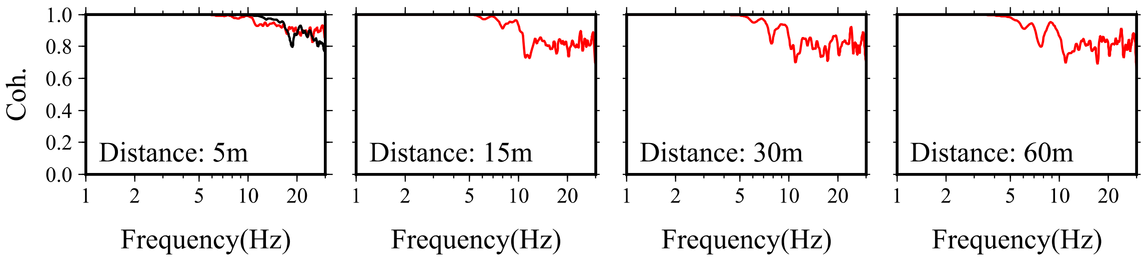
$Coh_{ij}(f)$ of the ground motion simulations are shown in Fig. 14. The solid red line is $Coh_{ij}(f)$ using the heterogeneous model. Also, $Coh_{ij}(f)$ of the average of ground motion records are shown with the solid black line.

In both simulations at Chiba site and Hayakawa site, $Coh_{ij}(f)$ of the ground motion simulations correspond well with $Coh_{ij}(f)$ of ground motion records except for high frequency bands. Also, the frequency that $Coh_{ij}(f)$ begins to decline is almost the same between ground motion simulations and ground motion records. $Coh_{ij}(f)$ of the simulations of Chiba site is lower than that of Hayakawa site, just like $Coh_{ij}(f)$ of ground motion records.

From the results of Fig. 13 and Fig. 14, it could be seen that $Coh_{ij}(f)$ of microtremor simulations are not in good agreement with $Coh_{ij}(f)$ of microtremor records compared to $Coh_{ij}(f)$ of ground motion simulations and $Coh_{ij}(f)$ of ground motion records, particularly at Hayakawa site. The reason of differences of $Coh_{ij}(f)$ between microtremor simulations and microtremor records could be thought that the amplitudes of microtremor records tend to be small especially at low frequency bands of hard subsurface soil sites, shown in Fig. 5, and it's difficult to ensure high accuracies to evaluate $Coh_{ij}(f)$ in such soil condition.



(1) Chiba site



(2) Hayakawa site

Fig. 14 – The average of $Coh_{ij}(f)$ of ground motion simulations at adjacent points

5. Conclusion

The characteristics of spatial variation of microtremor at adjacent observation points were examined by analyzing $\mathrm{Coh_{ij}(f)}$ of microtremor records obtained from the Chiba and Hayakawa site, Japan, as well as $\mathrm{Coh_{ij}(f)}$ of microtremor and ground motion simulations using 2D FEM homogeneous and heterogeneous soil models. It was found that $\mathrm{Coh_{ij}(f)}$ depends on subsurface soil structure, and low S-wave velocity of subsurface soil causes a reduction of $\mathrm{Coh_{ij}(f)}$. We also found that the longer the distance between observation points, the subsurface soil depth that effects to the spatial variation of ground motions $\mathrm{h_r}$ gets deeper, and $\mathrm{Coh_{ij}(f)}$ rapidly decreases at the frequency which is equivalent to around 0.5 wavenumbers to $\mathrm{h_r}$, just like spatial variation of ground motions.

6. Acknowledgements

We would like to thank Prof. Yoshiaki Nakano and Mr. Haruki Yoda of Institute of Industrial Science, University of Tokyo, for support to perform microtremor in the Chiba Array site. We also acknowledge Hayakawa Town Board of Education for support to perform microtremor survey in Hayakawa Town, Yamanashi Prefecture. Sayaka Igarashi of Taisei Corporation, Hideyuki Kanamori and Yuya Oki of Taisei-Yuraku Real Estate, cooperated with us in the microtremor survey. Ground motion records of K-NET and KiK-net by NIED, and that of the Chiba Array System distributed by the Association for Earthquake Disaster Prevention [11] are used for this study. some of the figures were drawn using the GMT.

7. References

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