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EFFECT OF SPATIAL VARIATION OF GROUND MOTION ON SURFACE SOIL AMPLIFICATION

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ABSTRACT

The spatial variation of the seismic ground motion is evaluated from the coherence function, using the records of seismic array at the site of Tohoku University, Sendai, Japan. Coherence functions show a remarkable decay with the increase in the frequency and the separation distance; the value of coherence for the separation distance over 300m is lower than 0.2 in the frequency higher than 3Hz. Next, a stochastic relation between the coherence and the fluctuation of surface soil amplification of the ground motion is discussed. It is illustrated that the observed coherence function can explain well the coefficient of variation of the surface soil amplification.

KEYWORDS

seismic array observation; differential ground motion; spatial variation; coherence function; surface soil amplification; transfer function; coefficient of variation

INTRODUCTION

It is known that seismic waves are changed in its amplitude and phase in the process of propagation because of the scattering of seismic waves in the deep and shallow ground (Toksoz *et al.*, 1992). Different wave forms are observed at two separated stations which are located on the sites with almost the same soil condition. It is important to take into account the effect of differential ground motion in the aseismic design of structures with widely extended foundations or structures with long spans. Generally, the spatial variation of the ground motion can be quantified by the coherence function, which is the frequency-dependent spatial correlation of the ground motion

In this paper, the spatial variation of the ground motion is evaluated as the coherence function using the seismic array records obtained at the site of Tohoku University, Sendai. The characteristics of the coherence versus the frequency and the separation distance is discussed. Moreover, it is shown that the surface soil amplification, defined as the transfer function between the records of a soil station and a rock station, shows a considerable fluctuation. A stochastic relation between the coherence of the ground motion and the fluctuation of surface soil amplification is discussed.

GROUND MOTION OBSERVATION IN THE TOHOKU UNIVERSITY ARRAY

Figure 1 shows the location of observation stations of seismic ground motion at the Tohoku University array. The array consists of four stations, denoted as KNSJ, ABKN, TUKN and ZKNZ in the figure, which are lying nearly on a straight line. The total length of the array is about 1km and the distances between two adjacent stations are 250-410m. Station KNSJ is located in the bedrock. The other three stations are on the soil site. The soil profile at the ABKN station is shown in Fig.2. A surface layer is diluvial sand and clay with gravel with a thickness of 18m. Beneath the surface layer, a bedrock of tuff and mudstone appears. Table 1 summarizes the data of seven earthquake events which are used in the present study. The magnitude of earthquake, M_J, and the hypocentral distance, Δ, are widely distributed. Figure 3 shows accelerograms recorded at the four stations by the event 5. NS components of the records are used in the analysis. The peak accelerations of the records are about 3-20 gal.

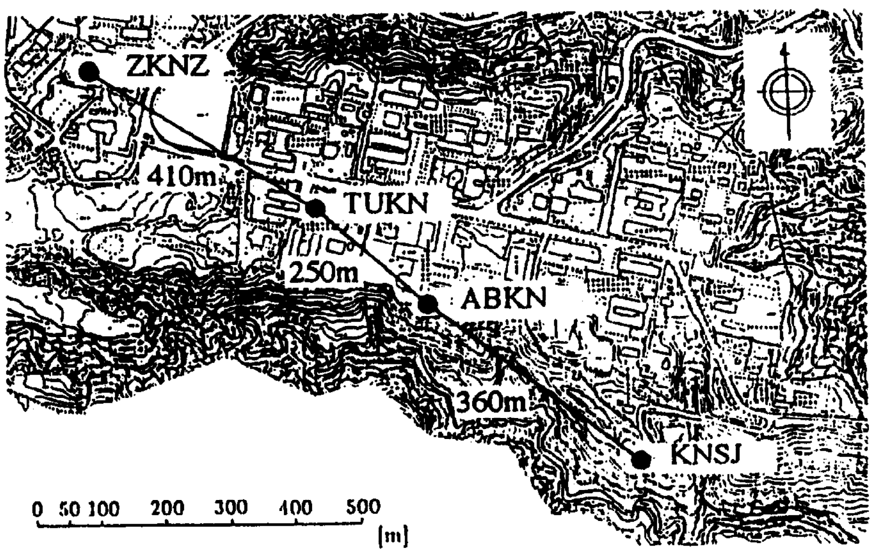

Fig. 1 Locations of observation stations in the Tohoku University array.

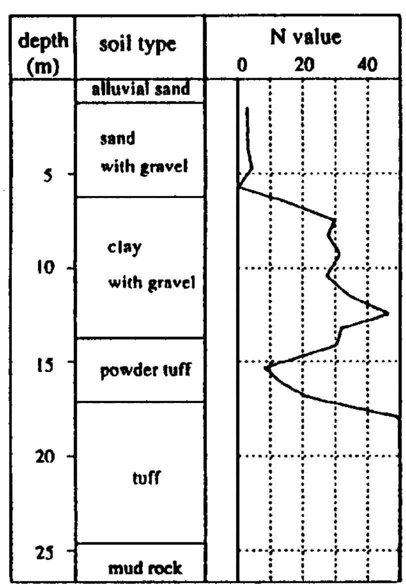

Fig. 2 Soil profile at the soil station, ABKN

Table 1 Earthquake data used in the analysis.

EVENT	DATE	M_J	H(km)	Δ(km)
1	1992. 6. 1	5.7	47	181
2	1992. 7.18	6.9	0	278
3	1992. 9. 1	4.7	8	35
4	1992.10. 7	4.7	76	122
5	1992.12.28	5.9	34	153
6	1992.12.31	5.8	30	154
7	1993. 1.15	7.8	107	598

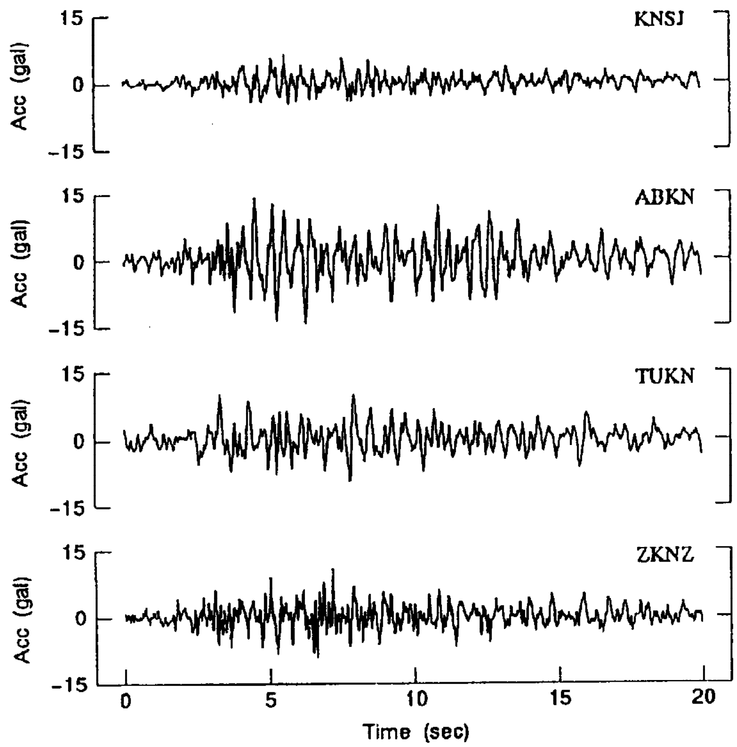

Fig. 3 Recorded accelerograms during the event 5.

COHERENCE ANALYSIS

The complex coherence function between two ground motion records, $x(t)$ and $y(t)$, is defined as

$$coh(f) = \frac{S_{xy}(f)}{\sqrt{S_x(f)S_y(f)}} \tag{1}$$

where S_x and S_y are the power spectra of $x(t)$ and $y(t)$, respectively, and S_{xy} is the cross spectrum between $x(t)$ and $y(t)$. The Parzen window with a band width of 0.4Hz is used for the evaluation of power and cross spectra. Prior to the calculation of the coherence, a length of time segment of the records for the analysis is examined using the evolutionary power spectrum. A five-second time segment of each record, including the strong motion part which is expected to be composed of body waves, is selected from the whole duration of the record. To keep the accuracy of the coherence, moreover, the time lag between two records is removed (Kawakami l.*et al*, 1986) by using the cross correlation analysis so that the phase of a filtered wave which passes lower than 1Hz agrees with each other. Coherence functions are calculated for all pairs of the records of the four stations. These are the frequency-dependent coherences for the specific separation distances.

In order to obtain an average coherence as a function of separation distance as well as frequency from the individual coherences with different separation distances, an averaging scheme (Harichandran et al., 1986) , expressed as

$$coh(\nu, f) = \frac{\sum_i \sum_j coh(\nu_i, f_j) \cdot \kappa\left(\frac{\nu - \nu_i}{\Delta\nu}\right) \cdot \kappa\left(\frac{f - f_j}{\Delta f}\right)}{\sum_i \sum_j \kappa\left(\frac{\nu - \nu_i}{\Delta\nu}\right) \cdot \kappa\left(\frac{f - f_j}{\Delta f}\right)} \tag{2}$$

in which $\kappa(x)=exp(-x^2/2)$, is used. Parameters Δf and $\Delta\nu$ are chosen to be 1Hz and 40m, respectively.

Figure 4 shows the absolute of average coherence functions for the event 4 with the earthquake magnitude M_J=4.7 *and* event 5 with M_J=5.9. It is found that the tendency of coherence decay with the separation distance is quite different between the two events. The coherence for the events 4 shows a rapid decay regardless the frequency even in the low frequency range whereas the coherence for the event 5 shows a slower decay in the lower frequency. To examine the above phenomenon, the Fourier amplitude spectrum of the record for each event is plotted. Figure 5 shows normalized Fourier amplitude spectra of the records at KNSJ for the seven events. The left figure is the spectra for the events with relatively small earthquake magnitudes and the right figure is the spectra for the events with relatively large earthquake magnitudes. It is seen that the spectra for the small magnitudes show quite small amplitude in the frequency lower than 1Hz. It is considered that the accuracy of coherence in the low frequency range for the events with small earthquake magnitudes is poor because of the low signal-noise ratio. Therefore the records of these events are excluded in the evaluation of coherence for the array site.

Figure 6 shows the ensemble average of coherence from the four events with relatively large earthquake magnitudes. It is found that the coherence decays with the increases in the separation distance and in the frequency. Figure 7 shows the coherence for the SMART-1 array site obtained by Harichandran et al.(Harichandran *et al.*, 1986). The tendency of decay of the coherence for the Tohoku University site is slightly stronger than that for the SMART-1 array site. This is considered to be caused by the complicated topography of the Tohoku University site (Fig. 1).

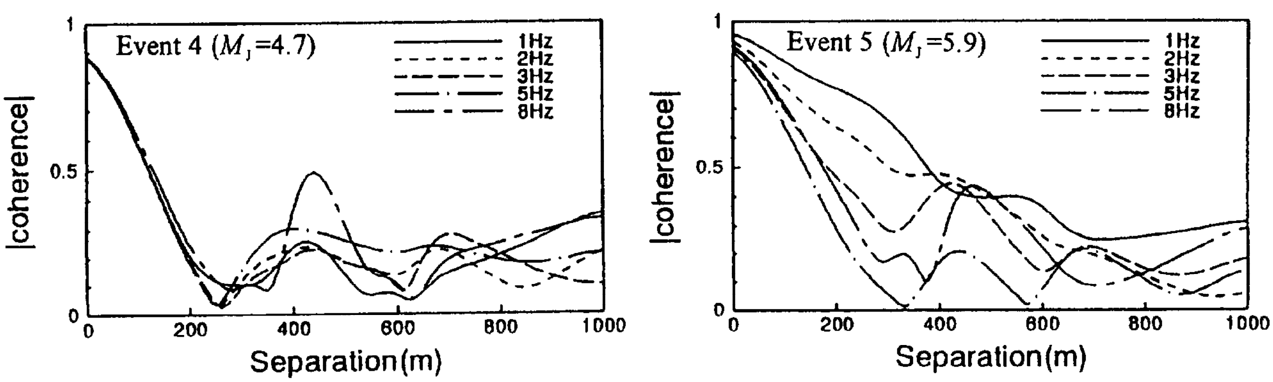

Fig. 4 Average coherence functions for event 4(left) and event 5(right).

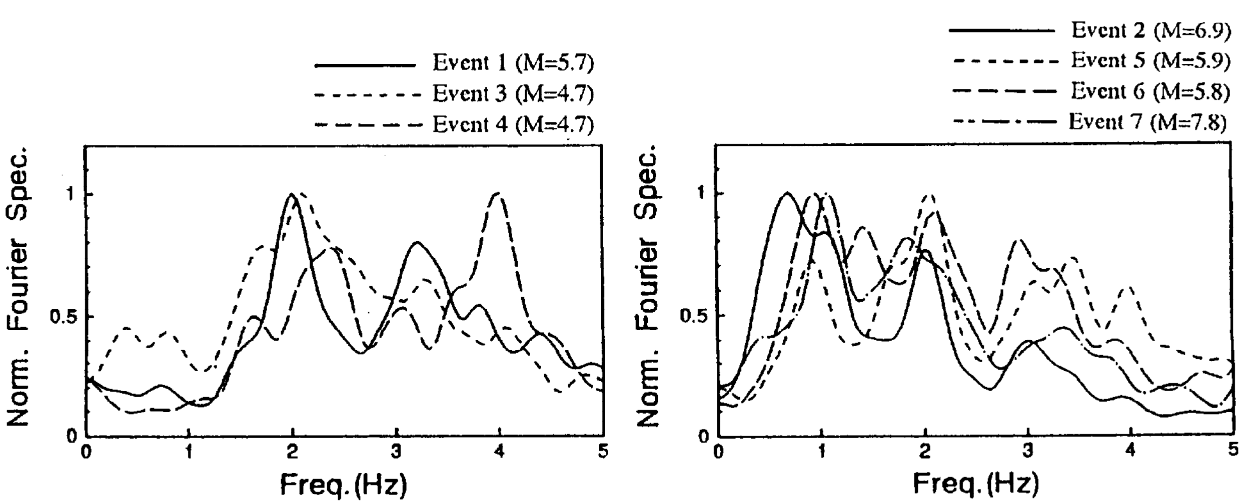

Fig. 5 Normalized Fourier amplitude spectra for small earthquake magnitude(left) and large earthquake magnitude(right).

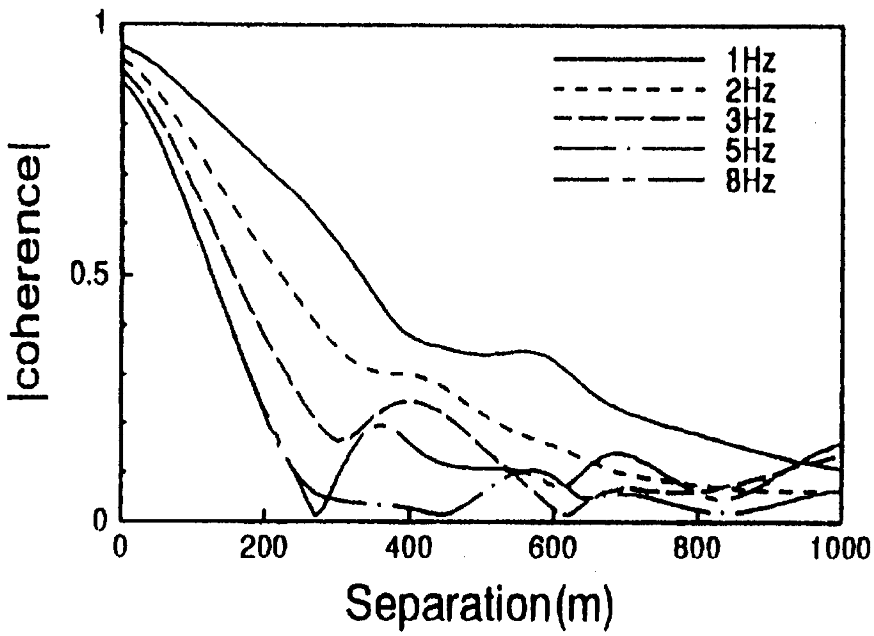

Fig. 6 Average coherence function of the ground motion in the Tohoku University array.

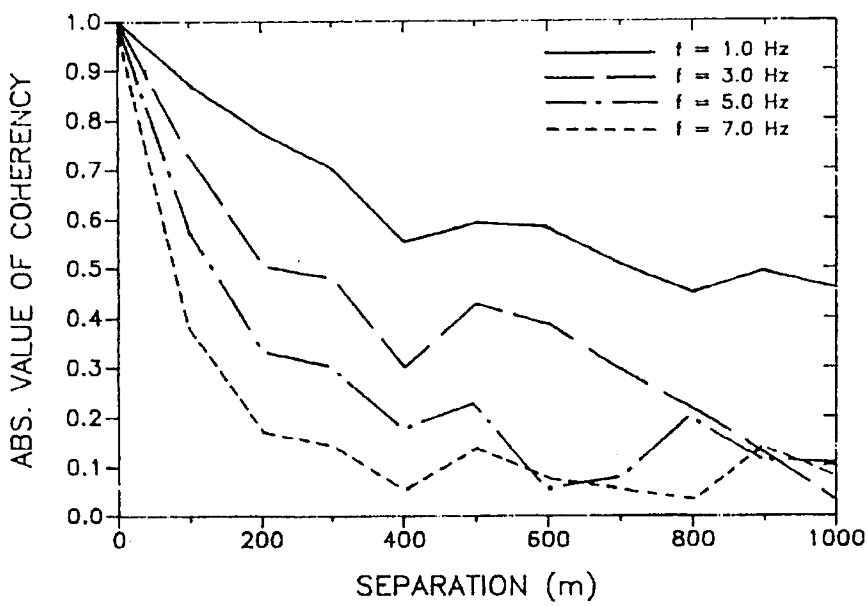

Fig. 7 Average coherence function of the ground motion in the SMART-1 array (after Harichandran *et al.*, 1986)

EFFECT OF SPATIAL VARIATION ON SURFACE SOIL AMPLIFICATION

In this section, the effect of the spatial variation of ground motion on the fluctuation of the surface soil amplification is discussed. Here, the surface soil amplification is defined as the transfer function of the record of the soil station to the record of the rock station, KNSJ, as

$$H(f) = \frac{S_{xy}(f)}{S_x(f)} \tag{3}$$

where S_x is the power spectra of the record at the rock station and S_{xy} is the cross spectra between the records at the rock and the soil stations. Figure 8 shows absolute soil amplifications of the three soil stations for the seven events. As surface soil properties of each station can be assumed constant, the soil amplification characteristics is expected to be independent of events. But actually obtained soil amplifications, as shown in Fig.7, have a significant fluctuation. Figure 9 shows the average and the standard deviation of the soil amplification of the three stations. The coefficient of variation of the soil amplification reaches to the order of 50-100%. One of main reasons of the fluctuation is considered that the input motion in the bedrock is different from station to station.

A theoretical relation between the fluctuation of the soil amplification and the coherence of the ground motion is examined using a model shown in Fig10. Input motions at the rock and soil stations, denoted as $X(f)$ and $X'(f)$, respectively, are assumed as Gaussian random variables with a zero mean and a certain standard deviation. The coefficient of correlation between $X(f)$ and $X'(f)$ is assumed to be γ. A surface motion $Y(f)$ at the soil station is the result of multiplication of $X'(f)$ and the deterministic soil amplification factor $\alpha(f)$. The stochastic parameters of the amplitude ratio between the soil station and the rock station $|Y(f)|/|X(f)|$, which is the definition of the surface soil amplification $|H(f)|$ in this study, are of concern.

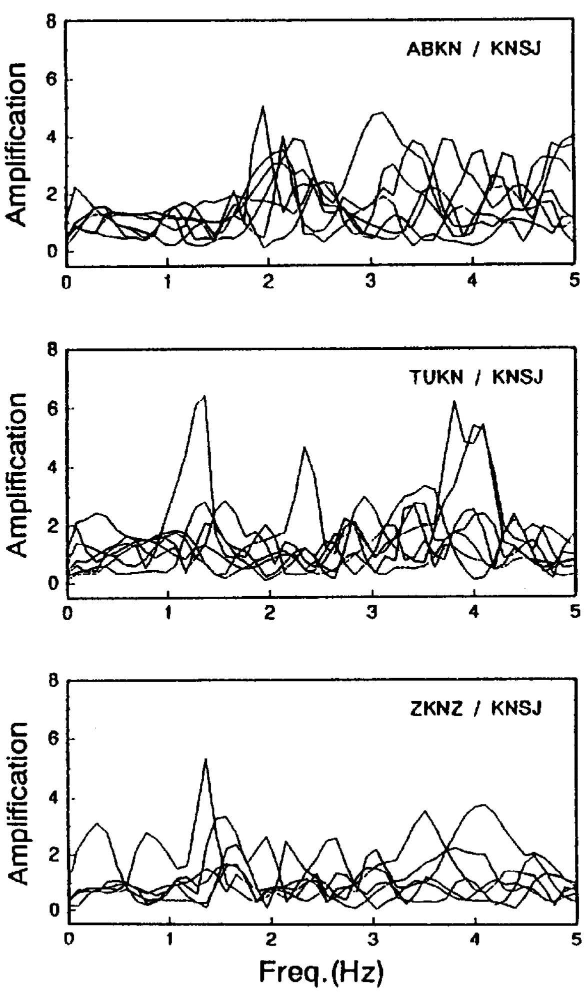

Fig. 8 Surface soil amplification of three soil stations for seven events.

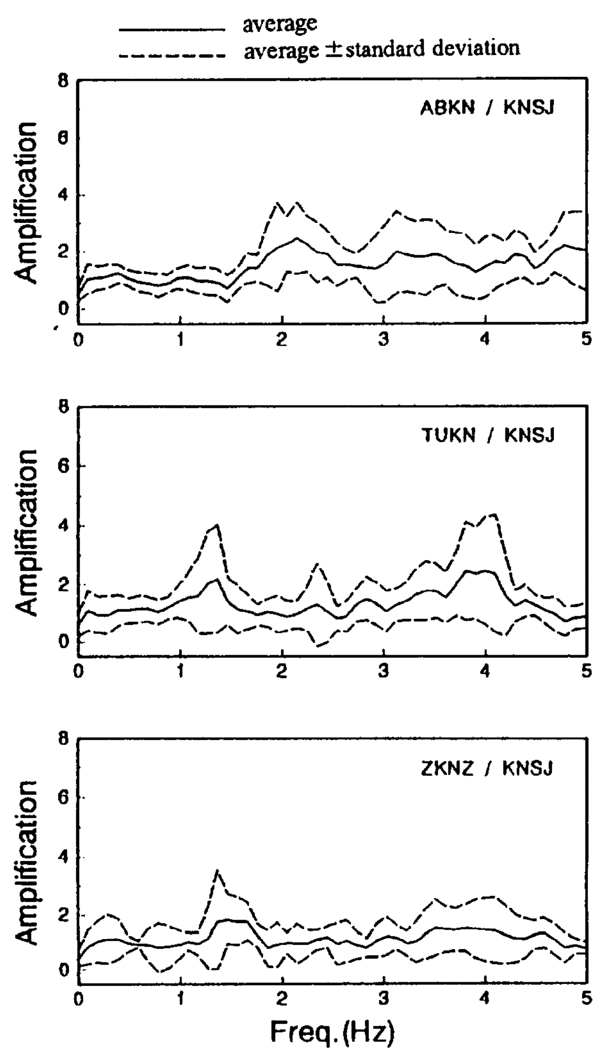

Fig. 9 Average and standard deviation of surface soil amplification.

If the distributions of $|X(f)|$ and $|Y(f)|$ are approximated to the log-normal distribution, the distribution of $|Y(f)|/|X(f)|$ is also the log-normal. Then the coefficient of variation, COV, of $|H(f)|=|Y(f)|/|X(f)|$ is expressed as a function of the coefficient of correlation of the input motions, γ.

$$\text{C.O.V. of } |H(f)| = \sqrt{\exp\left\{2 \cdot \ln\left(\frac{\pi}{2}\right) \cdot (1-\gamma)\right\} - 1} \tag{4}$$

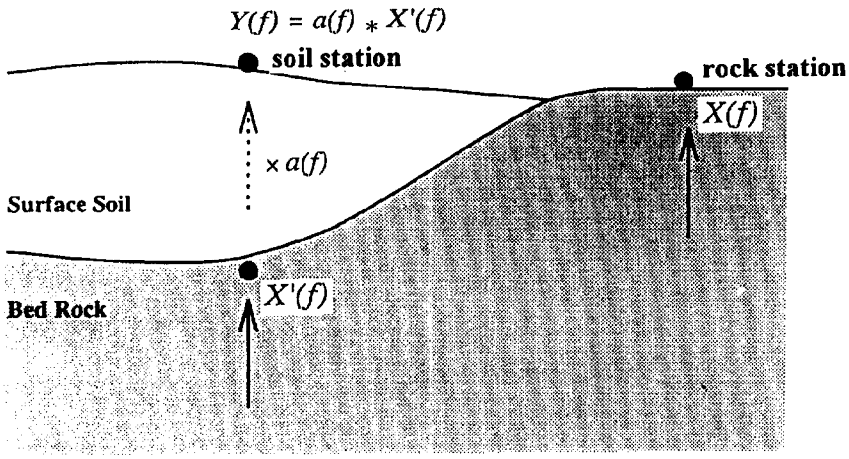

Fig. 10 Model of input motions and surface motion at a rock station and a soil station.

The theoretical COV of the soil amplification based on the Eq.(4) and the measured COV based on the transfer function in Fig.8 is compared in the following. The theoretical COV of the soil amplification is obtained from Eq.(4), in which the average coherence between the rock station and each soil station is used as γ. Figure 11 shows the average coherence for seven events between the rock station, KNSJ, and the soil stations. Figure 12 shows the comparison of the COVs of the surface soil amplifications. In the figure, a solid line indicates the COV obtained from the transfer function shown in Fig8, and a dashed line indicates the theoretical COV from Eq.(4). It is found that the measured and the theoretical COVs show a similar tendency, although the theoretical COVs are slightly larger than the measured ones. Both of the COVs show a tendency of increase with the increase in the frequency in the frequency range lower than 3Hz.

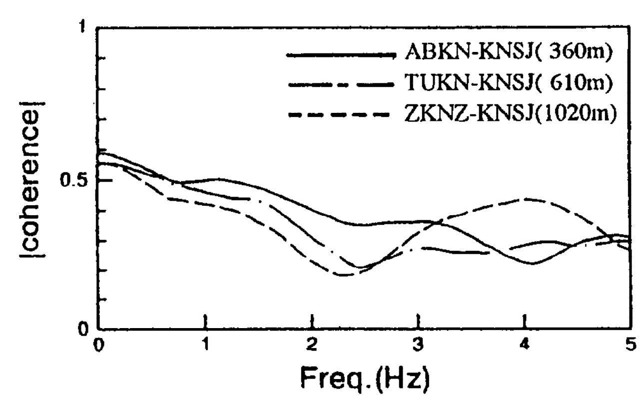

Fig. 11 Average coherence functions of the ground motions between the rock station, KNSJ, and each soil station.

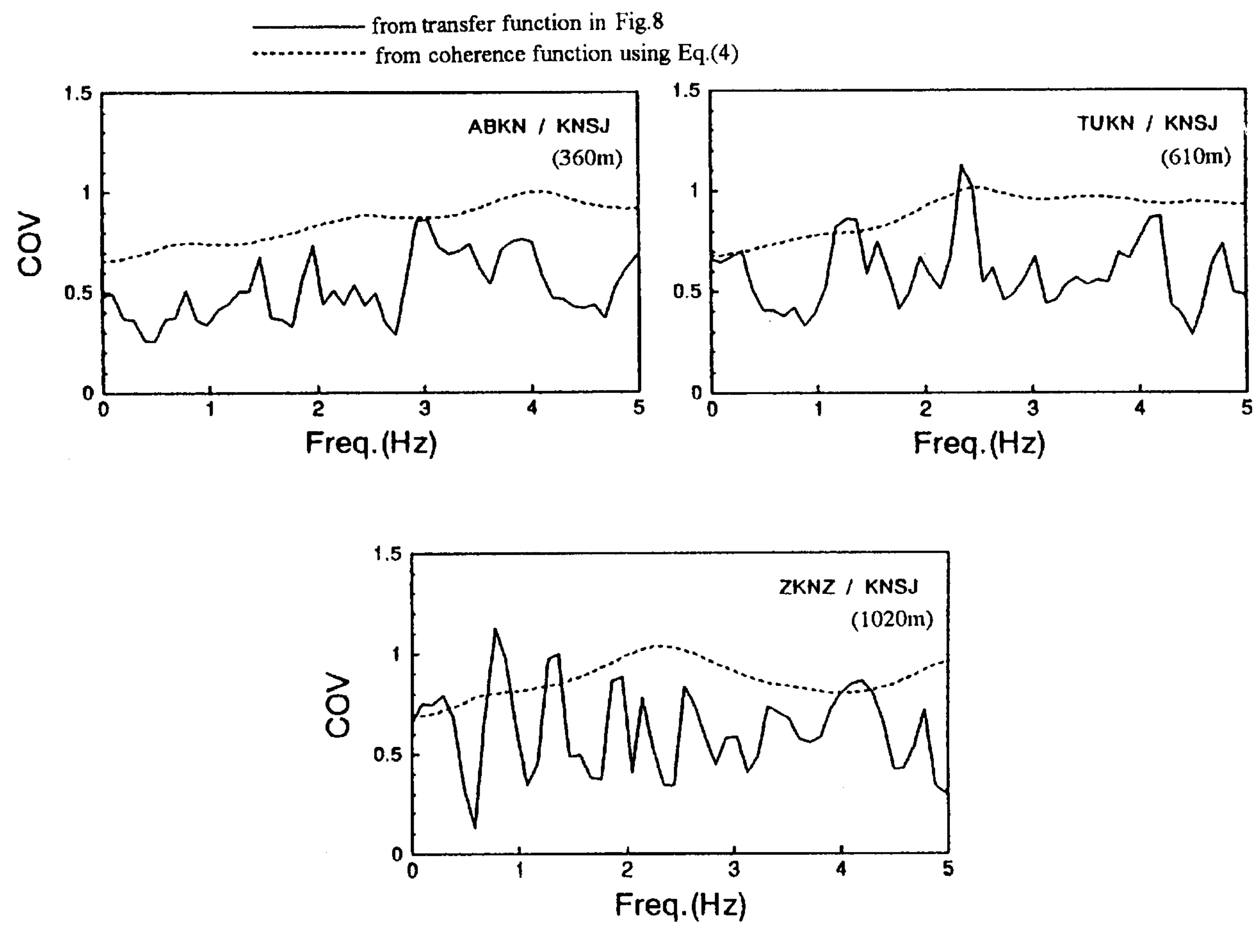

Fig. 12 Comparison of COVs of surface soil amplification of three soil stations.

CONCLUSIONS

The spatial variation of the ground motion and its effect on the fluctuation of soil amplification are studied, using the records of seismic array in the Tohoku University site. Following conclusions are obtained.

1) The average coherence of the ground motion of the site shows a rapid decay with the increase in the frequency and the separation distance. Coherence for the separation distance over 300m is lower than 0.2 in the frequency higher than 3Hz.

2) The surface soil amplification, defined as the transfer function between the records of soil and rock stations, shows a remarkable fluctuation. The coefficient of variation of the soil amplification can be explained by the coherence of the ground motion using a stochastic model of correlated input motions.

REFERENCES

Harichandran, R. S. and E. H. Vanmarcke (1986). Stochastic variation of earthquake ground motion in space and time, *Journal of Engineering Mechanics, ASCE*, 112, No.2, pp.154-174

Kawakami, H. and Y. Sato (1986). Characteristics of coherence function and its modified computation method, *Journal of Structural Engineering, Japan Soc. of Civil Eng.*, 32A, pp.749-762 (in Japanese)

Toksoz, M. N. and A. M. Danity and R. Coates (1992). Effects of lateral heterogeneities on seismic motion, *Proc. Int. Sympo. on the Effects of Surface Geology on Seismic Motion, Odawara, Japan*, 1, pp.33-64