Reduction in High-Frequency Component of Foundation Input Motion Caused by Spatial Variation of Earthquake Ground Motion

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SUMMARY:
Spatial incoherence of an earthquake ground motion may results in reduction in high-frequency components of the input motion for a building or a structure. In our study, two-dimensional finite element method is used for heterogeneous soil medium and the model is constructed with the parameters based on the data from a real site. Through Monte Carlo simulation, the ergodicity of a random field is confirmed showing stability of the statistic results as for the transfer functions. The spatially correlated soil model shows more reducing effect in the average input with increasing frequency and with increasing correlation distance. In case that the real information is limited, the conditional simulation technique is adopted to utilize as much data as possible. The profile just below the foundation of the structure may affect the amplification factor, so that the adopted method is effective in estimation of the foundation input motion.

Keywords: ground motion, spatial variation, incoherence, heterogeneous medium, foundation input motion

1. INTRODUCTION

For a building or a structure with horizontally spread configuration, the reduction effect of input motion may be expected in high frequency components caused by spatial incoherence of earthquake ground motion(EPRI(2006), Ostadan et al.(2007)). Such incoherence is due to spatial variation of earthquake ground motion as the result of obliquely incident body wave, propagating surface wave, complicated topography, heterogeneous soil medium and wave scattering. Especially, the last two factors are expressed in a stochastic manner. Among many researches focusing on spatial variation of ground motion, Abrahamson(2007) estimated the coherency function based on the observed data of high dense arrays. He suggested a functional form showing the correlation of motions at two points, which reflects decreasing coherency with increasing frequency and distance.

In this study, the heterogeneous soil is modelled and analyzed to see the influence of the variety of the medium to spatial variation of ground motion. For a hard rock site, such influence is evaluated as the effect of reducing input motion for a foundation of a building or a structure. The two-dimensional finite element method is used and a stochastic model is constructed to form a random field. In the sensitivity analysis, the properties of the soil medium are parameterized and the results are statistically estimated through Monte Carlo simulation. The soil data of a real site, such as the boreholes and the trench investigations are utilized in the model. The conditional simulation method is adopted to compensate the shortage of the data and information of the soil. The amplification factor of the soil and the foundation input motion are also estimated.

2. METHODOLOGY

2.1. Analytical method

The soil with a flat surface is expressed in a two-dimensional finite element model which can be analyzed in a broad-band frequency range. The average property is given with the coefficient of variation (C.O.V.) as a parameter of its variability. The concept of analysis is shown in Fig.1.

Defining earthquake ground motion on the surface of the free field, each model is studied to investigate its amplification factor and the transfer functions at some points on the surface against the bedrock or the surface of the free field. Those can show spatial variation of ground motion depending on frequency. By adding a rigid massless surface foundation to the soil model, foundation input motion is evaluated from its own response. Its response spectrum is compared with that of the defined motion. The transfer function (herein after, “TRF”) is smoothed by Parzen’s window with the band width of 0.2 Hertz.

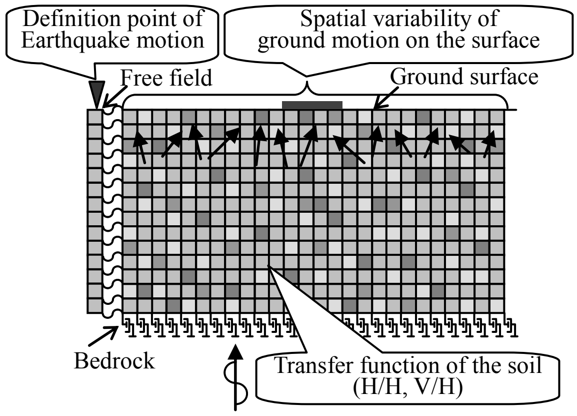

Figure 1. Concept of analysis and soil model

Table 1. Analytical cases of the heterogeneous soil model with and without a foundation

Model		Variation of the soil properties		Correlation function	ρ, Vs Correlation distance (Horizontal, Depth)
w/o foundation	w/ foundation				
G2U000	B2U000	C.O.V. =15%	Uniformly random	-	-
G2g040	B2g040		Correlated	Gaussian	40(m), 10(m)
G2g100	B2g100			Gaussian	100(m), 10(m)
G2e100	B2e100			Exponential	100(m), 10(m)
G2g140	B2g140			Gaussian	100(m), 40(m)

Table 2. Common parameters of the soil model

Size of model (Horizontal, Depth)		1,000(m)× 500(m)
Size of finite element (Horizontal, Depth)		10(m),10(m)
No. of elements		5,000
Density (ρ)	Average	26.5(kN/m^3)
	C.O.V.	0.15
	No. of materials	8
S wave velocity (Vs)	Average	2,240(m/s)
	C.O.V.	0.15
	No. of materials	50
Poisson's ratio (ν)		0.35
Damping factor (h)		3%

2.2. Analytical model

Two kinds of models, uniformly random and spatially correlated models, are analyzed. The properties of the soil are given by the average values and C.O.V. of the density ρ and the shear wave velocity Vs. The correlation functions and the correlation distances of ρ and Vs are also the parameters. For each element of FE model, the shear rigidity G and the longitudinal wave Vp are determined given Poisson's ratio ν. The analytical cases are listed up in Table 1. The common parameters and conditions are in Table 2. The sample models of each cases are compared in Fig.2. The average Vs is 2,240m/s and C.O.V. of ρ and Vs is 15% based on the data obtained at a real hard rock site.

Model G2U000 and B2U000 have uniformly random soil properties with Gaussian distribution. The variation of the properties is not spatially correlated and the randomness does not depend on distance. The other models have correlation structure in space that is defined in terms of Gaussian-type or an exponential-type function. The correlation distance is different in a horizontal and a vertical direction. The free field has the uniform property of the average value and is connected to the random model through energy-transfer boundary in the side. At the bottom of the model is viscous damper.

3. VARIETY OF SOIL PROPERTIES AND SPATIAL VARIATION OF GROUND MOTION

3.1. Response characteristics of soil model in random field

Each soil model presents TRF against the surface of the free field as shown in Fig.3. The figure is the result at eleven points of the surface in each model without a foundation (G series). TRFs decrease with increasing frequency. They vary depending on the location, which implies spatial variation.

In the uniform model, TRF should be 1.0 on the surface. Model G2U000 of uniformly random medium presents various amplification factors and the deviation is detected in the range of frequency higher than 10 Hertz. The factors are almost less than 1.0 at frequencies more than 20 Hertz. The models of Gaussian correlation such as G2g040, G2g100 and G2g140 show more variation in the high frequency range and effective reduction in foundation input motion. If the correlation distance is longer, the frequency range broads wider and lower where TRF varies and fall below 1.0. The difference in the correlation function between Gaussian and exponential type, G2g100 and G2e100, is not clearly seen in TRF. Next, the amplification factor is investigated on the ground surface to the imaginary surface of the bedrock at the depth of 500m. Fig.4 shows the result of G2g100 with that of the uniform model G2. Model G2 shows smoothly decreasing amplification with increasing frequency that reflects the effect of material damping of 3 percents. On the other hand, TRF of the random models falls below that of G2 and shows deviation from it with fluctuation.

The coherences are shown in Fig.5, which are obtained from a pair of TRFs on the surface. Uniformly random model G2U000 has relatively high coherence to keep around 1.0 in frequencies less than 20 Hertz, whereas the correlated models present decreasing coherences with increasing frequency and correlation distance.

3.2. Monte Carlo simulation

The above are the results from only one sample for each model. In this section, Monte Carlo simulation (MCS) is performed to lead general conclusions for foundation input motion in the stochastic field. The soil parameters are described in the previous section. Using random generator, a 100 case of samples (G series) are constructed for each model. Likewise, the models with foundation (B series) are also studied assuming a rigid massless bar element of 100 meters at the center of a soil model.

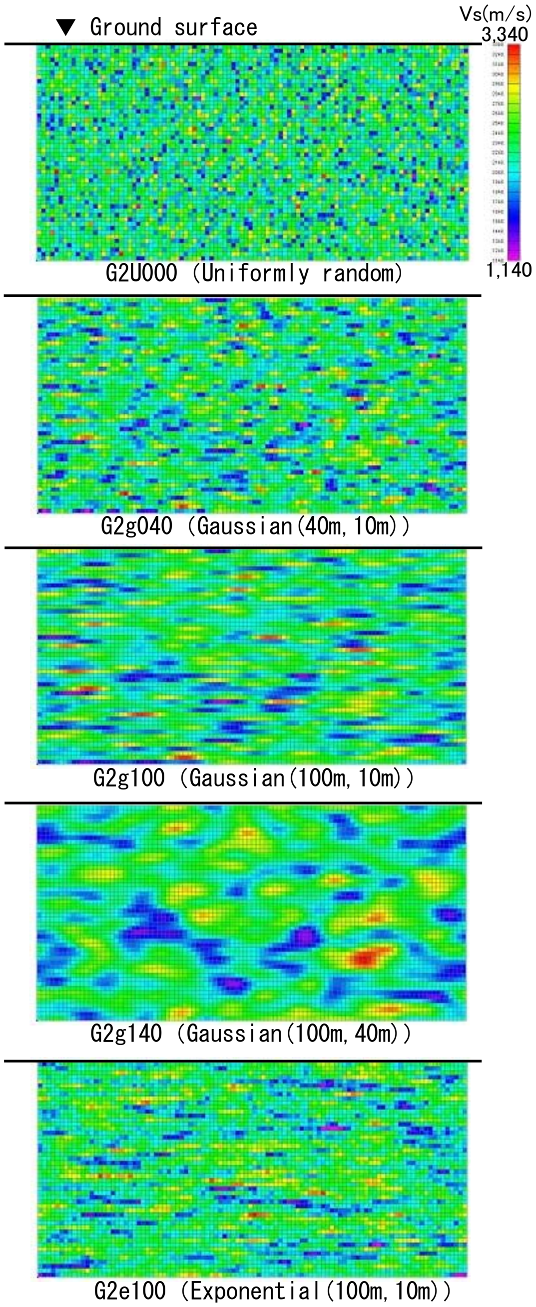

Figure 2. 2D-analytical soil model

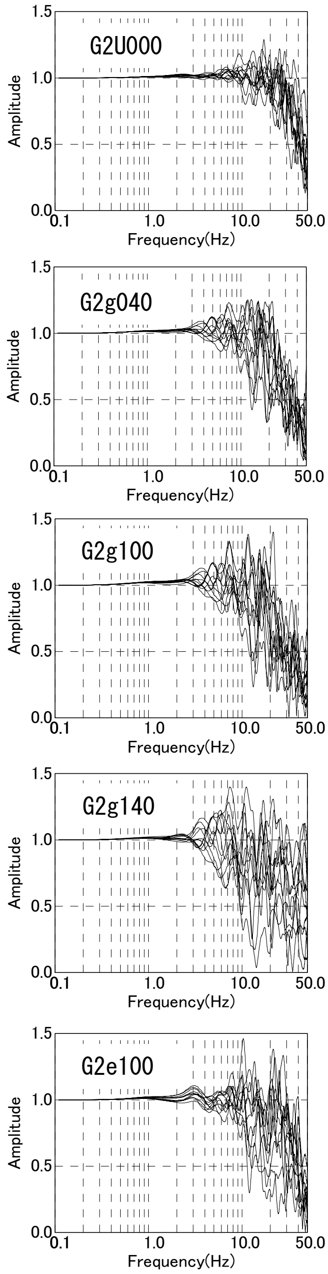

Figure 3. Transfer functions of the horizontal component on the ground surface against the surface of free field (H/H)

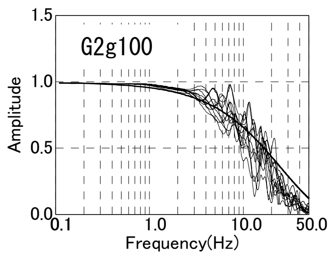

Figure 4. Transfer functions of the horizontal component on the ground surface against the bedrock (H/H) (Heavy line : Uniform model G2)

One hundred of lines of TRFs are shown in Fig.6 in the case of Model B2g100. In the figure, the average (red full line) and ±1σ (red dotted line) where σ is the standard deviation are drawn. Fig.7 compares the results of G and B series. The statistic results (Gave, Gave±1σ) of 10 samples multiplied by 101 points on the surface for each model are almost identical with those from 100 cases at the center of each model. That means “ergodicity” which implies coincidence of statistical characteristics between the whole points and the center on the surface. The number of MCS, 100 cases is proved to be enough.   In this model, the average TRF is less than 1.0 at higher frequencies than 10 Hertz.

TRFs of the models in B series are similar but their average is slightly smaller compared with the results in G series. The variance of the TRFs is smaller in the range higher than 10 Hertz. These are the effects of foundation input loss caused by constraint by a rigid foundation. It is remarkable in the frequency range higher than 20 Hertz which corresponds to one wavelength.

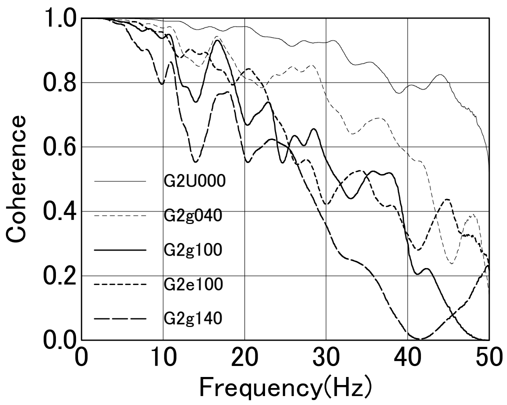

Figure 5. Coherence on the ground surface for the separation distance of 100m

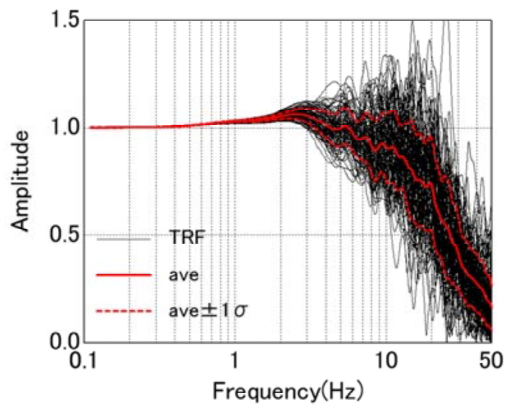

Figure 6. Transfer functions of the horizontal component o the foundation to the surface of free field. The average and the standard deviation of the results of MCS for B2g100 (B:model w/ foundation).

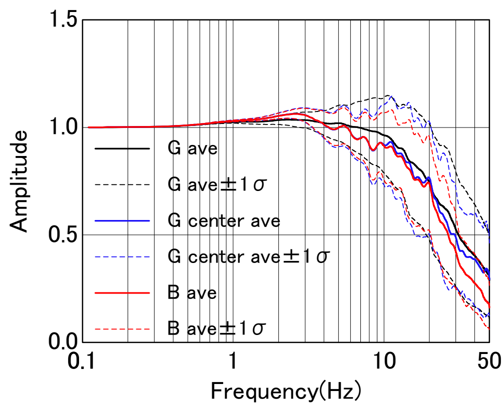

Figure 7. Transfer functions of the horizontal component on the ground surface and the foundation to the surface of free field. The average and the standard deviation of the results of MCS for B2g100 (B:model w/ foundation) and G2g100 (G:model w/o foundation).

G	: whole points	101×100cases
G center	: center of surface	1×100cases
B	: foundation	1×100cases

4. SENSITIVITY ANALYSIS TO HETEROGENEOUS PARAMETER

4.1. Influence by soil profile and correlation distance

The main factor of spatial variation of earthquake ground motion and resultant loss of foundation input motion in a random field is wave scattering. The quantity of those effect should be discussed not in the frequency but in the wavelength. In this section, it is investigated how the frequency range shifts, in which TRF varies and decreases, for different soil profiles such as shear wave velocity Vs. It is also studied how the correlation distance contributes to TRF. The wavelength λ (=Vs/*f*, *f*:frequency) is inferred to relate with the correlation distance *a*. On the other hand, the range *R* and the resolution *r* (*r*: descretized element size) of FE model are also parameters concerning randomness and heterogeneity of a field.
As the result of MCS, Figs.8 and 9 show the averages and the coefficients of variation (C.O.V.) of the TRFs for the parametric cases of the soil model, the shear wave velocity Vs of which is 2,240m/s or 700m/s. In the latter case, the density of 19.6N/mm^2 and Poisson’s ratio of 0.3 is different from those of the former. Both cases of Vs, the TRFs have similar trend. With increasing frequency, the average

decreases below 1.0 and C.O.V. increases. With increasing correlation distance, the frequency decreases at which TRF show the above trend. Comparing the results for Vs 700m/s with those for 2,240m/s, TRFs clearly shift in the lower frequency range. Here, to be noted is that the results for soil profiles coincide with each other by transforming the horizontal axis from frequency to wavelength. Fig.10 shows the relation between correlation distance and C.O.V. with the parameter of λ. Not Vs but λ controls the results.

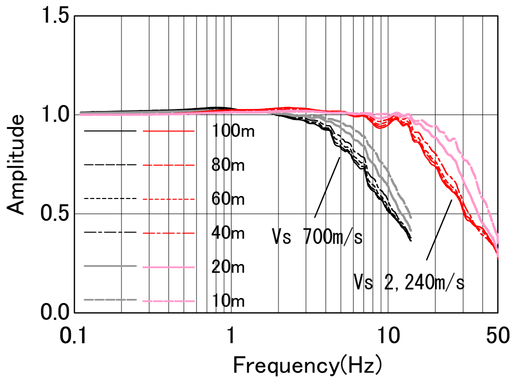

Figure 8. Comparison of the average transfer function on the ground surface. (Effect of soil properties and correlation distance)

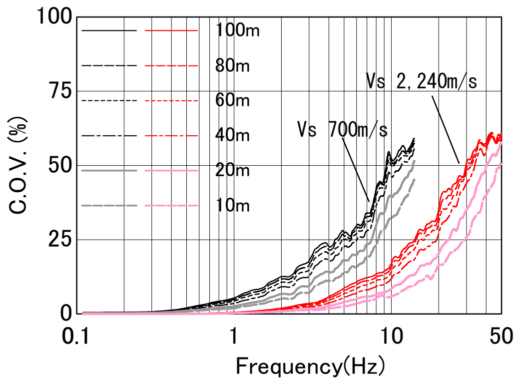

Figure 9. Comparison of C.O.V. of transfer functions on the ground surface. (Effect of soil properties and correlation distance)

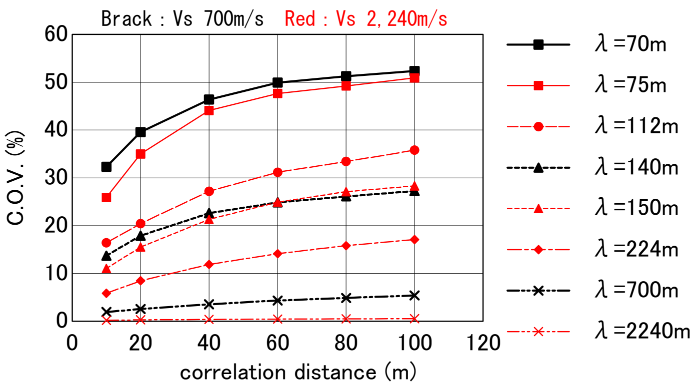

Figure 10. Comparison of C.O.V. of transfer functions on the ground surface. (Effect of wavelength and correlation distance)

4.2. Influence by range and resolution of FE model

Similarity of the model in a random field is studied. Three models are compared as shown in Fig.11 with the similarity ratio of 4:2:1 for modeling range (horizontal R_b, in the depth R_h), resolution ($1/r_b$, $1/r_h$) and correlation distance (a_b, a_h). Except for the scaling factor, the other profiles are the same. So the contour map of them is in the same pattern. The three TRFs shown in Fig.12 are identical if they are re-drawn by multiplying a scaling factor in the horizontal axis. Fig.13 shows comparison in acceleration response spectra for damping of 3%.

Next, three sample models are introduced by changing the range of modeling from unique large sample. As shown in Fig.14, Model 1b is cut off from Model 1a which is cut off from Model 1. The frequency content of three TRFs is quite similar, that is different from the case for similar models above. However, the amplitudes of TRFs and response spectra vary depending on the size of the model as shown in Figs. 15 and 16. This implies predominance of the longest wavelength which is determined by the range of the model and the correlation distance. On the other hand, the amplitude of the TRF and the response spectrum increases for smaller size of an element with higher resolution. By increasing resolution, the medium can be considered to become more uniform.

4.3. Discussions

To investigate parameters' contribution to heterogeneity in a random field, the additional cases are analyzed by MCS (10 samples times 101 points on the surface for each model) to obtain average TRFs. The coefficient of variation δ of the shear wave velocity Vs is also a parameter as shown in Table 3. All the results are compared in Fig.17 with the horizontal axis of frequency, and in Fig.18 for a new parameter suggested to quantify heterogeneity of a field as shown in the following formula.

$$\text{(Heterogeneous Parameter) } P(f) = \delta \cdot (R \cdot r \cdot a)^{1/3} / \lambda$$

As indicated in the above, wave scattering effect depends on correlation distance a and wavelength λ. Fig.17 clearly shows the relation between a, λ and the reduction factor on foundation input motion. Some research says that the correlation distance of an exponential type of correlated model may proportional to the size of the region *R* of a model (Gelher(1993)). Others say that the standard deviation σ (or C.O.V. δ) quantifying variety of the property of the medium is related with the region *R* and the resolution 1/*r* in FE model (Saito and Kawatani(2001)). To verify the result shown in Fig.18, more intensive and parametric study is required.

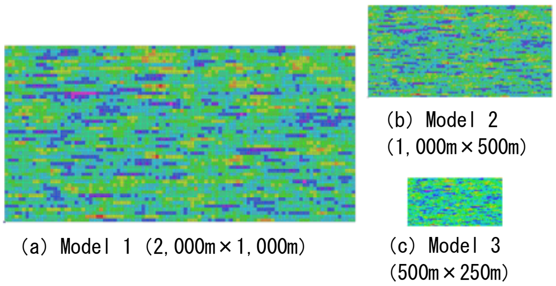

Figure 11. 3 similarity models

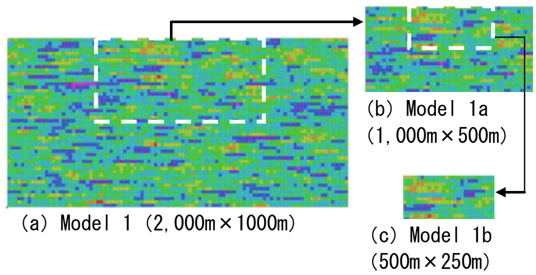

Figure 14. 3 different scale of models

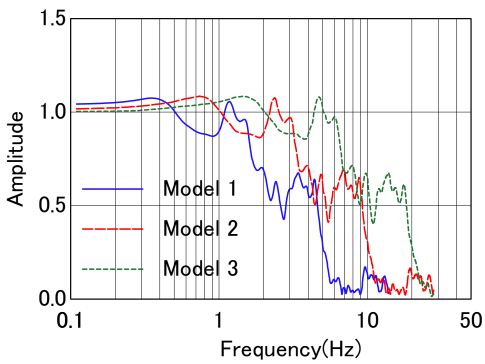

Figure 12. Transfer functions at the foundation to the surface of free field for 3 similarity models.

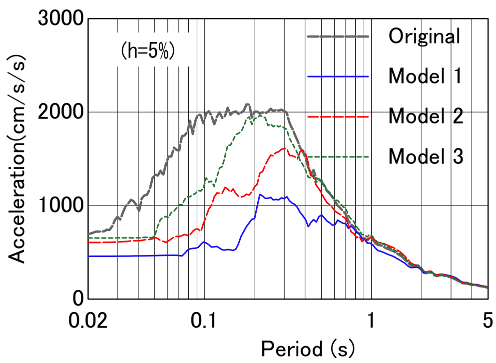

Figure 13. Acceleration response spectra at the foundation of 3 similarity models.

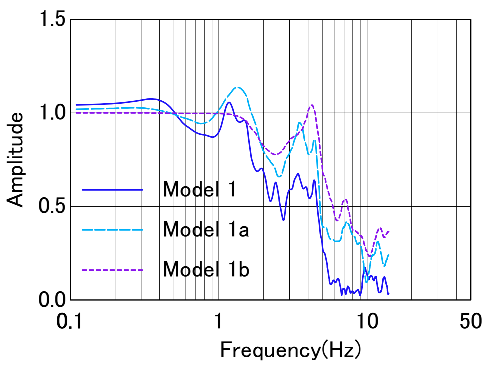

Figure 15. Transfer functions at the foundation to the surface of free field for 3 different scale of models.

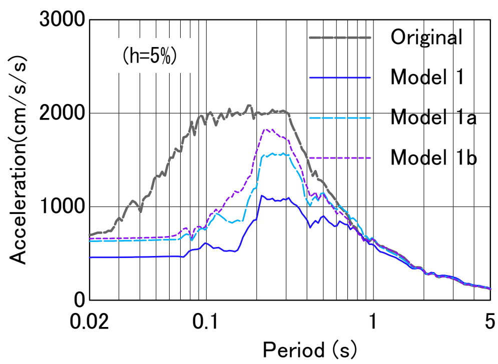

Figure 16. Acceleration response spectra at the foundation of 3 different scale of models.

Table 3. Additional models for sensitivity analyses depending on heterogeneous parameters

Model No.	S wave velocity		Size of model		1/Resolution		Correlation distance	
	Vs(m/s)	δ	R_b(m)	R_h(m)	r_b(m)	r_h(m)	a_b(m)	a_h(m)
11 ∼16	2,240	0.15	1,000	500	10	10	100 ∼10	10
21 ∼26	700	0.15	1,000	500	10	10	100 ∼10	10
31	700	0.10	1,000	500	10	10	100	10
32	700	0.20	1,000	500	10	10	100	10
41	700	0.15	500	500	10	10	100	10
42	700	0.15	1,000	1,000	10	10	100	10
51	700	0.15	1,000	500	5	5	100	10

※The shaded area shows the different values for the basic model (21).

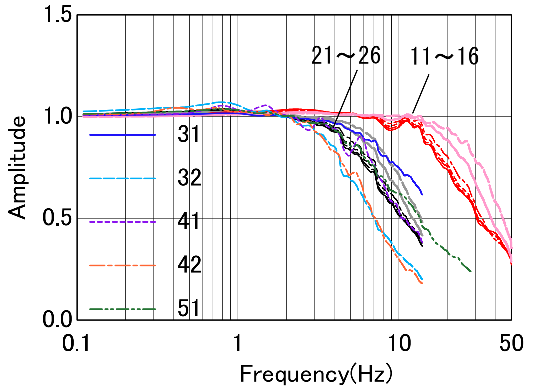

Figure 17. Comparison of transfer functions at the foundation to the surface of free field for all models versus frequency.

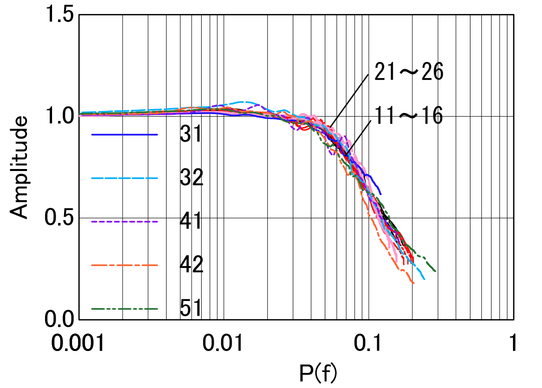

Figure 18. Comparison of transfer functions at the foundation to the surface of free field for all models versus heterogeneous parameter $P(f)$.

Table 4. Soil profile and analytical model

Density (ρ)	Average	26.5(kN/m^3)
	C.O.V.	2%
S wave Velocity (Vs)	Average	2,760(m/s)
	C.O.V.	12%
Poisson's ratio (ν)	Average	0.28
	C.O.V.	15%
Size of model (Horizontal,Depth)		1,000(m)× 500(m)
Size of finite element (Horizontal,Depth)		10(m),10(m)
No. of elements		5,000
Correlation func.		Exponential
Correlation distance (ρ,Vs,ν)	Horizontal	100(m)
	Depth	10(m)
No. of materials		500
Damping factor (h)		3%

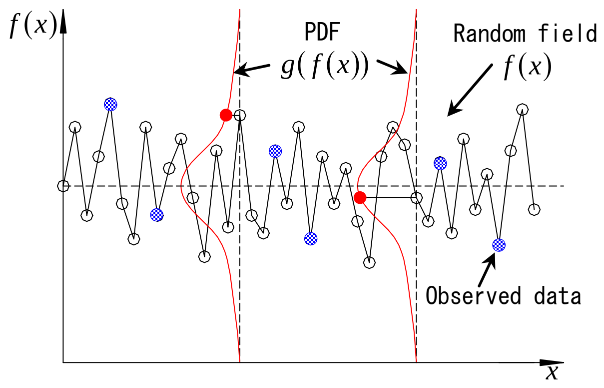

Figure 19. Schematic figure explaining conditional simulation for random field.

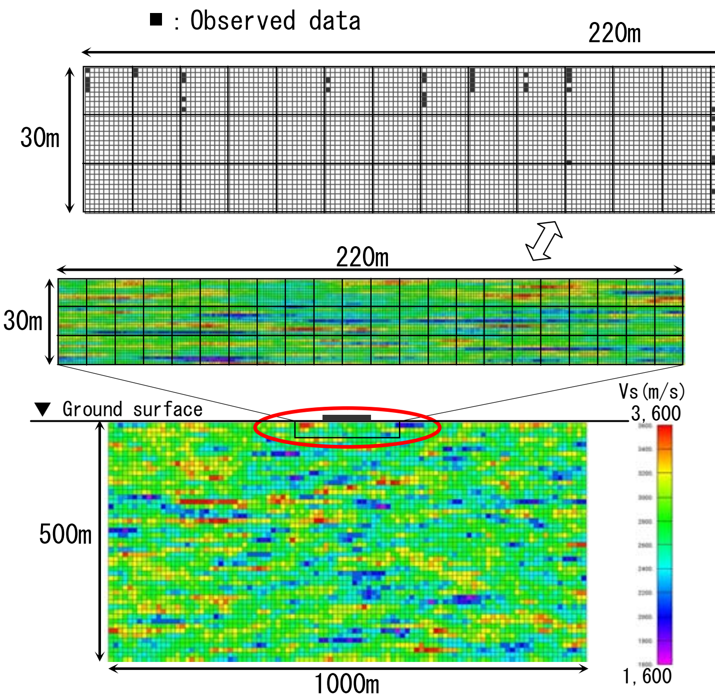

Figure 20 Data at the real site and a sample of a 2D-FE model.

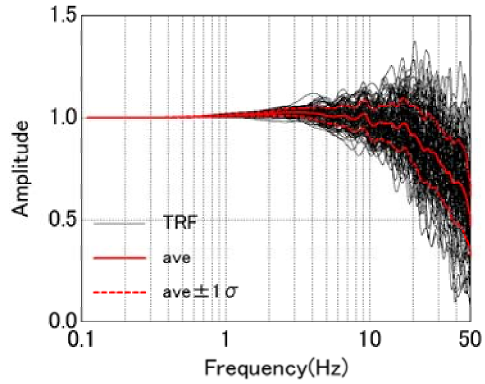

Figure 21. Transfer functions as a result of conditionally simulated models

5. STUDY ON REAL DATA BY CONDITIONAL SIMLUATION

Conditional simulation is one of the best ways to construct a stochastic model taking into account information and data at a real site. At our site, PS data and the rock profiles are obtained by investigation in some boreholes and multiple trenches. The soil profile and the parameters of an analytical model are listed in Table 4. The average value and C.O.V. of the shear wave velocity Vs or the density ρ are based on the data at the site. Although the number of the data exceeds 50, it is not enough to determine the correlation distance in a horizontal direction. The distance of 100m is just assumed.
The conditional simulation method is referred by Hosiya(1993) and Hosiya and Kuwana(1993). Its concept in a random field with the probability density function is schematically explained in Fig.19. The adopted data is limited in the range of horizontal width of 220 meters and the depth of 30 meters. The location of the points at which the data is obtained is shown in Fig. 20, with a sample of 2D-FE model. Compared with the size of a model, the range where the given data exist is rather small. However, the properties just beneath and near the foundation may affect foundation input motion, so that such method as conditional simulation is rational and effective.
As a result of conditional simulation, Fig.21 shows TRFs at 101 points on the surface and their average with ±1σ(σ: standard deviation). The reduction of foundation input motion is confirmed but its effect is not drastic and limited in high frequency range. That is partly because the shear wave velocity is quite high (2,760m/s) and the variation of the density is small.

6. CONCLUSIONS

For a rock site, spatial variation of earthquake ground motion and the resultant reduction of foundation input motion are investigated through two-dimensional finite element analysis using a stochastic model of a random field. Based on the data from a real site, sensitivity analyses are performed with the parameters of the average value and the coefficient of variation of the shear wave velocity, its correlation function and the correlation distance. The results of Monte Carlo simulations are estimated with a frequency and the new index introduced to quantify the heterogeneity. The following lines are identified as conclusions.

1) A heterogeneous soil model presents variance of amplification properties which reflect spatial variation of ground motion caused by wave scattering.
2) The response on the surface decreases with increasing frequency showing variation depending on the model and the location.
3) The spatially correlated model shows more reducing effect in the average input with increasing correlation distance and with increasing frequency.
4) Wave scattering effect depends on the correlation distance and the wavelength, and the reduction factor of foundation input motion is determined by the relationship of these factors.
5) The properties' variation of the medium is related with the region and the resolution in FE model. To clarify their relation, more intensive and parametric study is required.
6) In case that the real information is limited, the conditional simulation technique is effective to construct a stochastic model with as much data as possible. The profile just below the foundation of the structure may affect the amplification factor and the estimates of the foundation input motion.

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