SITE AMPLIFICATION EVALUATION IN THE CASE OF NON-HORIZONTAL AND NONLINEAR STRATIFICATION

Y. Furumoto
Nagano National College of Technology, Japan

A. Miyazawa
Shinshu University, Japan

M. Sugito
Gifu University, Japan

SUMMARY:
A simple method is proposed for modeling seismic transfer function of ground on inclined base layer by superposing one-dimensional transfer functions on upper and lower sides of the slope. By using FEM seismic response analysis, the typical ground model is analyzed for several cases of its geometrical conditions and input intensity of earthquake motion on the basement. Change of the SH wave transfer function of ground on inclined basement was examined by comparing with that by one-dimensional analysis. The result showed that the dominant frequency on the basement inclination is strongly affected by that on lateral sides. It was confirmed that the transfer function obtained by the proposed method is consistent with that based on the two-dimensional finite element method. An application for making seismic hazard intensity map for local area is examined by the interpolated transfer functions.

Keywords: Seismic Response Analysis, Soil layer on Inclined Basement, Seismic Hazard Intensity Map

1. INTRODUCTION

Generally, on seismic risk assessment by central or local governments, the seismic hazard intensity map is demonstrated based on the amplification of the earthquake motions from engineering base layer to ground surface applying the one-dimensional seismic response analysis for grid meshes of several hundred meter squares corresponding to the logging survey results, since the target area is very large. However, since the transfer function of an earthquake motion changes with the geometric conditions, in the case of embankments or grounds on inclined base layer, two or three-dimensional analysis is necessary.

On the other hand, Seismic response analyses for horizontally layered ground have been conducted for many years. The equivalent linearized method; for example SHAKE is commonly used. The frequency-dependent equivalent linearized method FDEL having improved SHAKE is being developed until now. FDEL converts the nonlinear relation of the shear strain rigidity and the damping characteristic of the ground into an equivalent relation considering the spectral amplitude of the strain, so that it does not underestimate earthquake motion amplification in the high frequency range.

The equivalent linearized method based on one-dimensional multiple reflection theory: SHAKE (Schnabel et al. 1972), for example, is generally used for engineering conveniently, compared with nonlinear analysis in time domain, which require detailed soil profiles. This method, operated in frequency domain, provides the transfer function that is regarded as the amplifying characteristics of the earthquake motion.

In this research, the seismic transfer functions of ground on inclined base layer and embankment are examined. Several parametric case studies are conducted to obtain the SH wave transfer functions from basement to the ground surface. The results by two-dimensional FEM analysis are compared with that by one-dimensional analysis. Subsequently, a simple modeling method for seismic transfer function of ground on inclined base layer is proposed by superposing one-dimensional transfer functions on upper and lower sides of the slope. It was confirmed that the transfer function obtained by the proposed technique is consistent with that based on the two-dimensional FEM analysis.

2. SEISMIC RESPONSE ANALYSIS FOR GROUND ON INCLINED BASE LAYER

Several parametric case studies are conducted to obtain the SH wave transfer functions from basement to ground surface by using two-dimensional FEM analysis with plane strain condition. Hypothetical ground models are analyzed by changing its geometrical conditions such as depth of the soil layers and inclination of the basement besides changing shear wave velocity of soil layer and input intensity of earthquake motion on the basement.

Subsequently, total change of the horizontal transfer function of ground on inclined basement is examined by comparing with that by one-dimensional analysis based on multiple reflection theory.

2.1. Definition of Frequency-Dependent Equivalent Strain

A FEM based seismic response analysis is formulated according to FLUSH (Lysmer,J. et al. 1975), and the definition of equivalent linearized strain is modified (Furumoto,Y. et al. 2002).

Generally, the equivalent linearized method is difficult to apply into soft ground, if the soil nonlinearity is not negligible, because it is operated in frequency domain through Fast Fourier Transformation. The frequency-dependent equivalent linearized method; FDEL, developed by Sugito,M. et al (1994), converts the nonlinear relation of the shear strain rigidity and the damping characteristic of the ground into an equivalent relation considering the spectral amplitude of the strain, so that it does not underestimate earthquake motion amplification in the high frequency range.

The frequency-dependent equivalent strain is proposed in the following equation:

$$\gamma_f(\omega) = C\gamma_{\max} \frac{F_\gamma(\omega)}{F_{\gamma_{\max}}} \qquad (2.1)$$

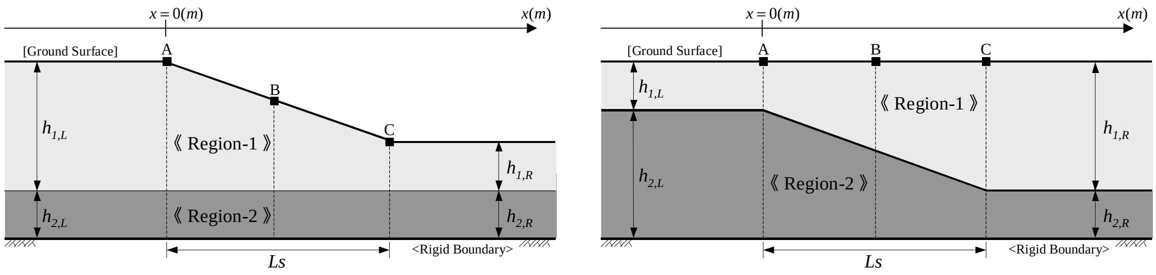
Where C is constant. γ_{max} is maximum shear strain in time-history, $F\gamma(\omega)$ is Fourier spectrum of the shear strain time-history, and $F\gamma_{max}$ represents the maximum of $F\gamma(\omega)$.

The definition of $F\gamma(\omega)$ in the left side of Equation 1 describe the equivalent strain, which controls equivalent shear modulus and damping factor, is given in proportional to the spectral amplitude of shear strain in frequency domain. The constant C controls the level of equivalent strain uniformly along the frequency axis. The condition $F\gamma$ (w)/ $F\gamma_{max}$ =1.0 and C =0.65 gives the same condition as SHAKE.

2.2. The Ground Model for the Analysis

Hypothetical ground models are analyzed by changing its geometrical conditions and input intensity of earthquake motion on the basement. The ground model is shown in **Figure 2.1** consists of 2 layers with inclined base layer. Angles of basement inclination are 1/5, 1/4, 1/3 and 1/2. Shear wave velocities of ground layers are 100 and 300 m/sec. Shear wave velocity of base layer is 650 m/sec for all models (**Table 2.1** and **2.2**). Viscous boundaries are set at the right and the left sides to absorb the reflection waves. The bottom is assumed as a fixed boundary in the calculation.

A total of 8 Input motions are generated by using EMPR-I model (Sugito et al.2000) that predicts strong earthquake motions from earthquake magnitude M on Richter scale and hypocentral distance R. Magnitude values of 8.0, 7.5, 7.0, 6.5 and 6.0, and hypocentral distances of 30, 60 and 100 km are used to simulate earthquake strong motions. The waves are input at the bottom of the target area (**Table 2.3**).



(a) Type-A (Embankment) (b) Type-B (Base Inclination)

Figure.2.1. Analytical Models

Table 2.1. Specifications of Analytical models

Case	h1,L	h2,L	h1,R	h2,R	Ls	Angle of Inclination
Case1(Type-B)	80m	40m	20m	20m	200m	1:5
					160m	1:4
					120m	1:3
					80m	1:2
Case2(Type-B)	120m	40m	20m	20m	400m	1:5
					320m	1:4
					240m	1:3
					160m	1:2
Case3(Type-A)	20m	80m	60m	40m	200m	1:5
					160m	1:4
					120m	1:3
					80m	1:2
Case4(Type-A)	20m	120m	100m	40m	400m	1:5
					320m	1:4
					240m	1:3
					160m	1:2
Case5(Type-A)	5m	80m	45m	40m	200m	1:5
					160m	1:4
					120m	1:3
					80m	1:2

Table 2.2. Specifications of Materials

	Shear Wave Velocity	Poisson's Ratio	Bulk Density
Region-1	100 m/s	0.48	1.5 gf/cm
	300 m/s		
Region-2	650 m/s	0.40	1.8 gf/cm

Table 2.3. Specifications of Earthquake Motions

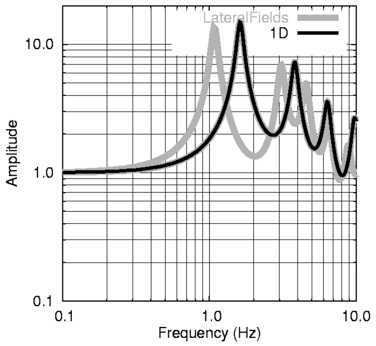
No.	M	R(km)	Amax(gal)	JMA Seismic Intensity Scale
Acc-1	6.0	100	32.4	3
Acc-2	6.0	60	55.7	3
Acc-3	7.0	100	94.3	4
Acc-4	7.0	60	152.3	4
Acc-5	6.5	30	197.6	5-
Acc-6	7.0	30	319.6	5+
Acc-7	7.5	30	547.3	6-
Acc-8	8.0	30	987.0	6+

2.3. Seismic Response Characteristics of Ground on Inclined Base Layer

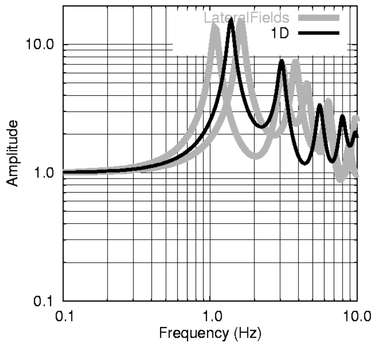
The transfer functions of the acceleration (horizontal component) from the basement to each point on the ground are shown in the **Figure 2.1**. Point A, B and C are the nodes on the surface of the model shown in **Figure 2.1**. Point A is located at right above the summit of the inclined base layer, Point B is above the halfway and Point C is right above the toe of the incline.

Figure 2.2 (a-1), (b-1) and (c-1) show the transfer functions by one-dimensional analysis based on converted 1D models, at the points of A, B and C respectively. The dominant frequency of the right free ground is about 1.0Hz and the dominant frequency of the left free ground is about 1.6Hz as shown in the figures by gray lines. The figure shows that in one-dimensional analysis, the transfer function of Point A is the same as the one of the left free ground, and the transfer function of Point C is the same as the one of the right free ground.

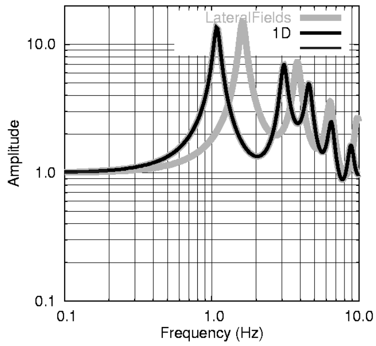
In the transfer function obtained from two-dimensional analysis, as shown in **Figure 2.2** (a-2), (b-2) and (c-2) by solid lines, there are at least two dominant frequencies around 1.0Hz and 1.6Hz approximately. One coincides with the left free ground and another coincides with right free ground. The resemblance is largely dependent on the distance from the point to the right or the left of free ground.



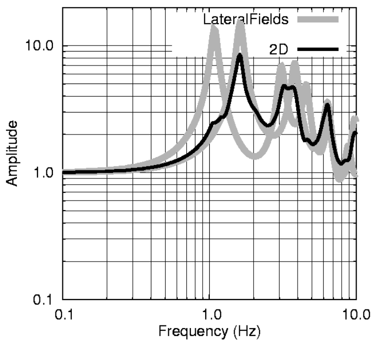
(a-1) Point-A



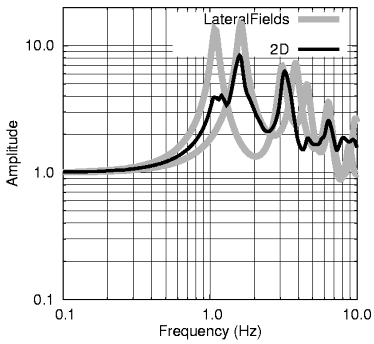
(b-1) Point-B



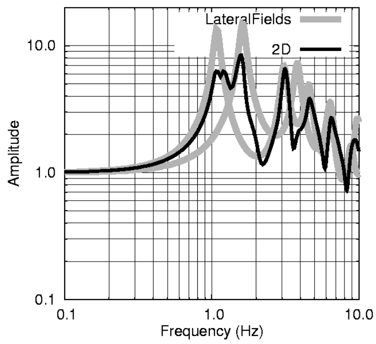
(c-1) Point-C



(a-2) Point-A



(b-2) Point-B



(c-2) Point-C

Figure.2.2. Examples of Seismic Transfer Functions (Case-3,Ls:200m,Vs:300m/s,Acc-3)

3. Modeling of Transfer Function of Ground on Inclined Base Layer

In the former section, FEM analysis showed that the dominant frequency of the ground above basement inclination is strongly affected by that on lateral sides. In the transfer function obtained from two-dimensional analysis, there are two dominant frequencies around both the dominant frequencies of the left and the right free ground.

A simple modeling for seismic transfer function of ground on inclined base layer is proposed by superposing one-dimensional transfer functions on upper and lower sides of the slope. The linear interpolating polynomial is described on Gaussian plane with real weighting coefficient that is discussed in this section.

3.1. Simple Modeling of Seismic Transfer Function

Set the transfer function from the bottom of the target area to the ground surface as Ω_X, the transfer functions of the upper end of inclination by using a one-dimensional seismic response analysis as Ω_T and the transfer function of the lower end as Ω_B. Then Ω_X, complex number, is superposed by complex number operation as follows:

$$\Omega_x(\omega) = \Omega_T(\omega)^C \cdot \Omega_B(\omega)^{1-C} \qquad (0 < C < 1) \, . \tag{3.1}$$

Where C is real number and the weighting coefficients corresponding to the Ω_T.

The transfer functions by superposing are compared with the transfer functions by two-dimensional analysis, and the weighting coefficient C is determined by linear regression analysis so that the residual mean square of the amplifications should be least at dominant frequency. **Figure 3.1** (a), (b), (c) and (d) show the relationships between x/Ls, the dimensionless distance from the top of inclined basement divided by length of the inclination, and the weighting coefficient C for angles of inclinations respectively. The weighting coefficients C are determined by multiple linear regression analysis with x/Ls and θ as parameters. The regression is given by logistic equation as follows.

$$\ln\left(\frac{C}{1-C}\right) = 0.878 + 1.161\left(\frac{x}{Ls}\right) \cdot \ln(\theta) \tag{3.2}$$

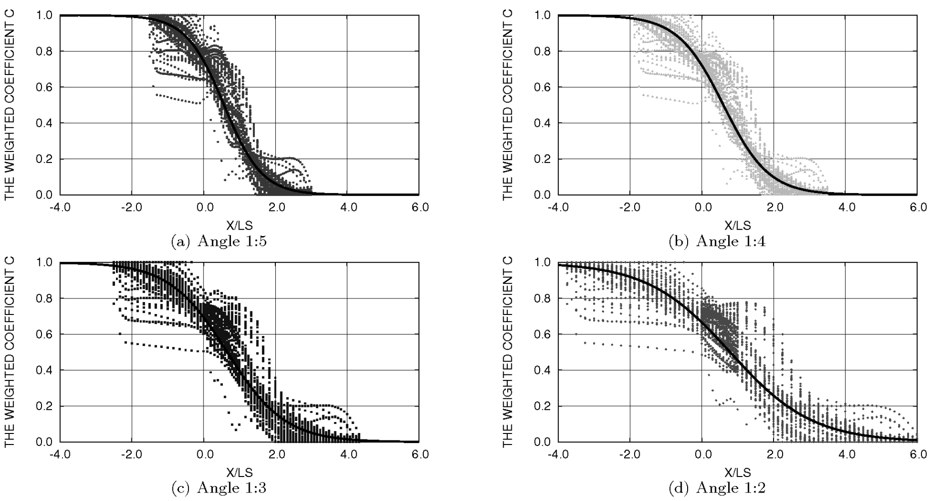


Figure 3.1 Weighting Coefficients and Regression Curve

Figure 3.2 (a), (b), and (c) show the transfer functions at the points of A, B and C respectively. The solid lines are obtained by superposing and the gray lines are by 2D-analyis. In the low and middle frequency area under 2Hz, the transfer functions by superposing almost agree with that by 2D-analysis. On the other hand, in the high frequency area above 4Hz, the transfer functions by superposing do not agree with that by 2D-analysis.

Figure 3.3 (a), (b), and (c) show the nyquist diagram form 0 Hz to 3Hz. At the point of A and B, vector loci by superposing almost agree with that by 2D-analysis. At the point of C, the change of phase is similar to each other; however, the amplitude by superposing is smaller than that by 2D-analysis.

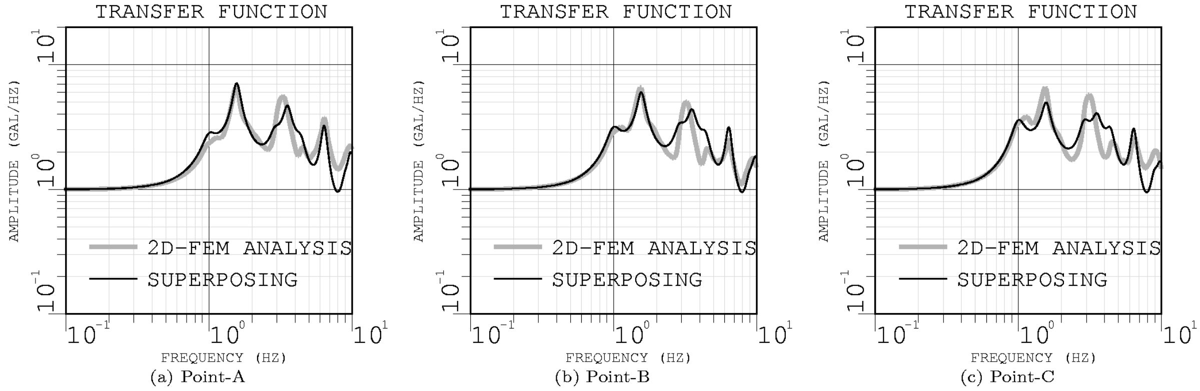


Figure 3.2 Seismic Transfer Functions Estimated by This Study (Case-3,Ls:200m,Vs:300m/s,Acc-8)

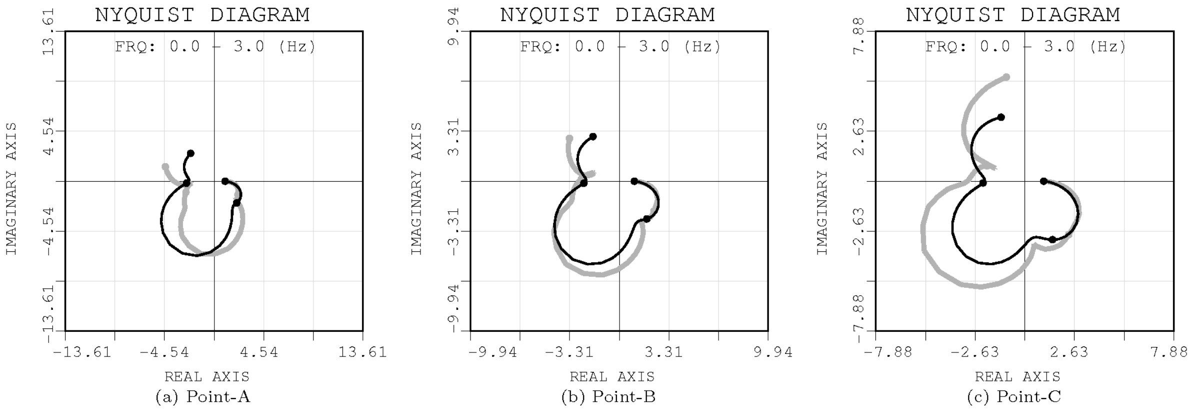


Figure 3.3 Nyquist Diagram Estimated by This Study (Case-3,Ls:200m,Vs:300m/s,Acc-8)

4. AN APLICATION FOR MAKING SEISMIC HAZARD INTENSITY MAP

Generally, the earthquake motion is predicted considering a propagation process of seismic wave from an earthquake fault to the ground surface which is modeled as horizontally layered soil stratums in each quadrate mesh on several hundred meters. In the conventional earthquake prediction, since seismic response analysis for each soil mesh is conducted individually, the interaction between laying side-by-side mesh is neglected. Therefore, the reflection and refraction of the wave is not considered in the case of embankments or grounds on inclined base layer.

In this chapter, some case studies conducted to make seismic hazard intensity map considering nonlinear seismic responses of the ground on inclined base layer.

4.1 Interpolation of Seismic Transfer Function of The Ground

The weighting coefficients corresponding to the transfer function in the **Equation 3.1,** in the former chapter, is proposed in the following equations (**Equation 4.1** and **4.2**). Where x represents the distance from the beginning point of interpolation shown in **Figure 4.1**.

(a) θ > 0

$$C = \frac{\exp(0.878 + 1.161 \cdot X1)}{1 + \exp(0.878 + 1.161 \cdot X1)} \text{ , } X1 = x / XLS \cdot \log \theta \quad (0 \le x \le 500m) \tag{4.1}$$

(b) θ = 0

$$C = 1 - x / XLS \quad (0 \le x \le 500m) \tag{4.2}$$

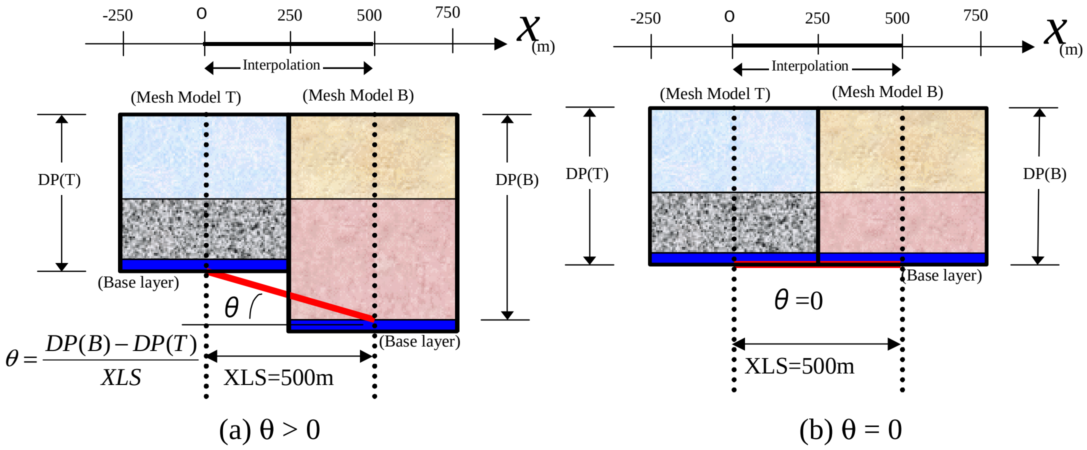


Figure 4.1. Modeling of the Ground on Inclined Basement

4.2 A Case Study Based on Hypotheses Ground Structure

A case study based on hypotheses ground structure is conducted to verify the proposed modeling technique in the former section. The JMA seismic intensity scale on the ground surface by superposing technique is compared with that by conventional 1-D analysis.

Figure 4.2 shows the analytical model with inclined base layer. Shear wave velocity of layer-1 is 300 m/s and that of layer-2 is 650m/s on average. The dimension of the inclination is shown in the Figure. An acceleration wave of supposed Tokai earthquake (Amax=152gal, JMA Seismic Intensity Scale=4.37) is input at the bottom of the area. In **Figure 4.2**(a), the seismic intensity is interpolated between the topside and the bottom side on the slope. In **Figure 4.2(b)** the seismic intensity is represented by conventional method. JMA Seismic Intensity Scale for each meshes are shown in both figures. The seismic intensity of the surface ground is very different around the border of the meshes.

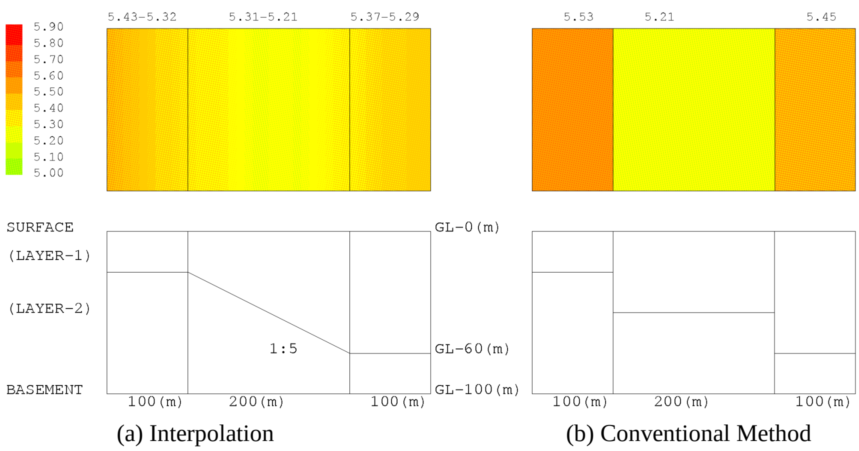
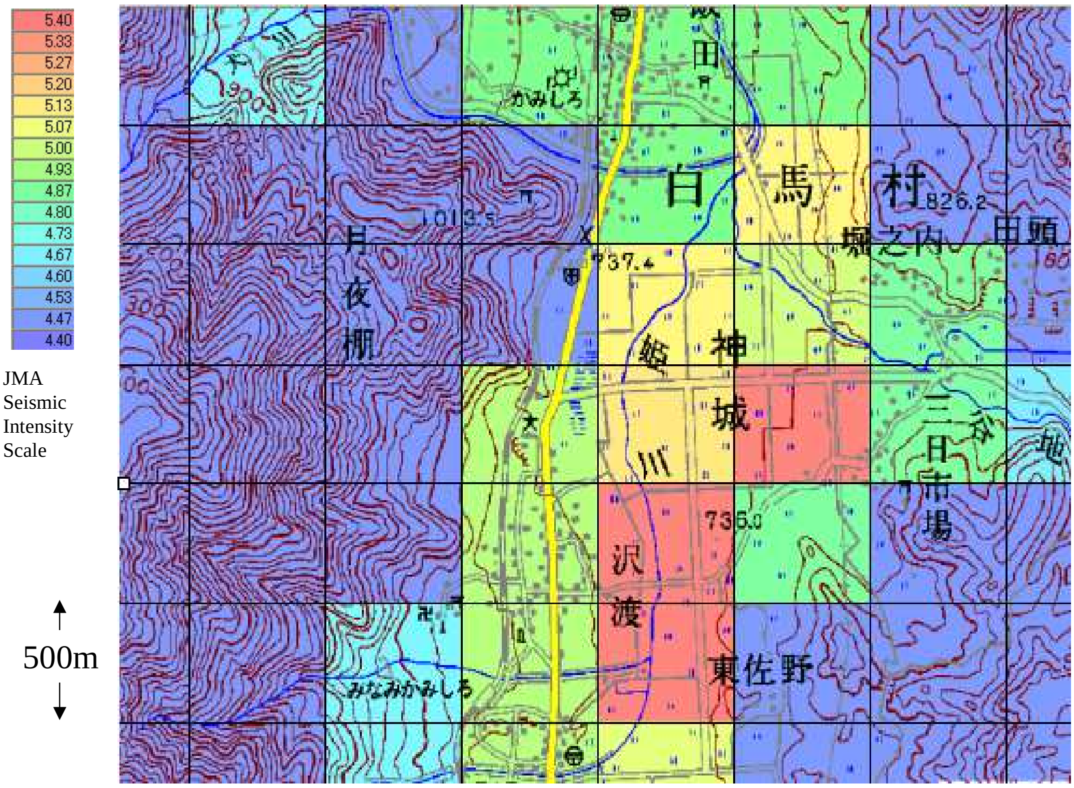
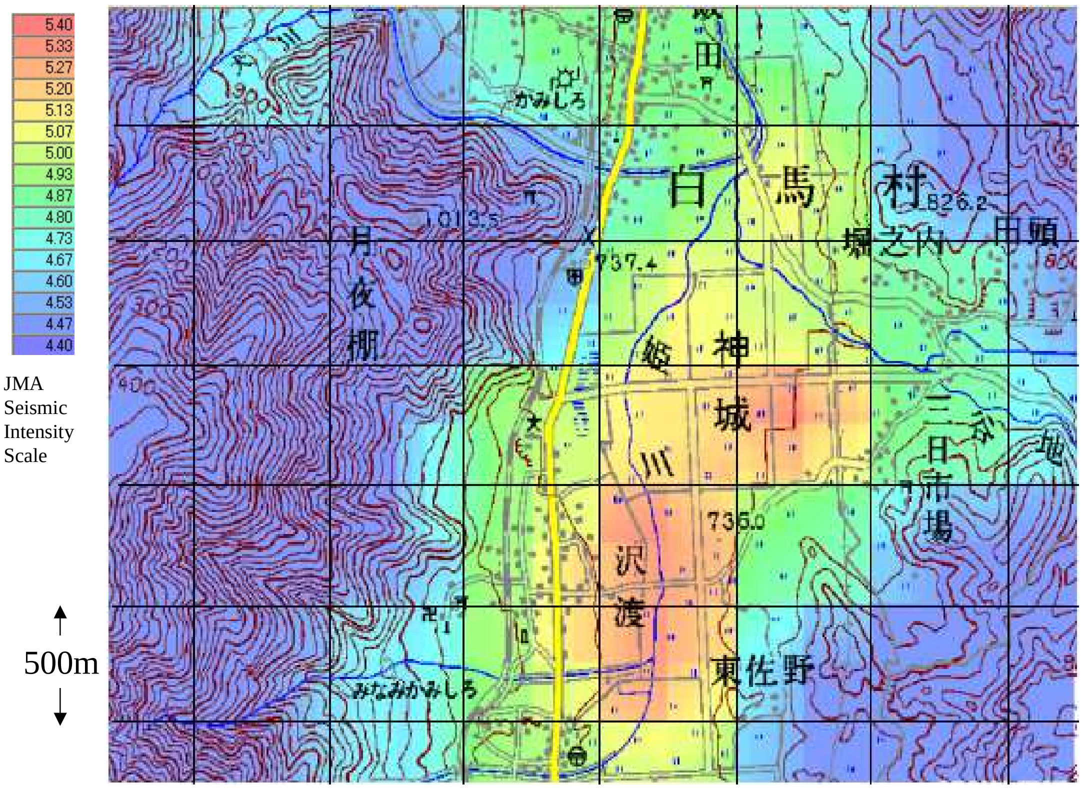


Figure 4.2. Distribution of JMA Seismic Intensity of Ground Surface on Inclined Basement



(a) Conventional



(b) Interpolation

Figure 4.3 Distribution of JMA Seismic Intensity Hazard Map (Hakuba village, Nagano)

4. 2 Case Study of Seismic Hazard Intensity Map

A case study based on a real ground structure is conducted to verify the proposed modeling technique in the former section. An application for making seismic hazard intensity map for local area is examined by the interpolated transfer functions.

Figure 4.3(a) and **Figure 4.3(b)** show examples of the seismic hazard maps with JMA seismic intensity scale. An acceleration wave, which is equivalent to the inland earthquake motion of M 7.4, is input at the bottom of the area. In **Figure 4.3(a)** the seismic intensity is represented by conventional method. In **Figure 4.3(b)**, the seismic intensity is interpolated between the topside and the bottom side on the slope. The seismic intensity of the surface ground is very different around the border of the meshes.

5. CONCLUSIONS

The characteristic of the seismic response on the ground with inclined base layer is examined and the results by two-dimensional analysis are compared with one-dimensional analysis. Major conclusions derived from this study may be summarized as follows.

(1) In the horizontal transfer function on the basement inclination, the dominant frequency is strongly affected by that on lateral sides.
(2) A simple modeling method for seismic transfer function of ground on inclined base layer is proposed by superposing one-dimensional transfer functions on upper and lower sides of the slope.
(2) The weighting coefficients are determined by multiple linear regression analysis with the distance from the top of inclined basement and the length of the inclined basement as parameters.
(3) Transfer function obtained by the proposed method is consistent with the analytical result using the two-dimensional finite element method.
(4) An application for making seismic hazard map for local area is examined by the interpolated transfer functions.

REFERENCES

Schnabel, P. B., Lysmer, J. and Seed, H. B. (1972). SHAKE a computer program for earthquake response analysis of horizontally layered sites, Proc. of EERC: 72-12.

Lysmer, J., Udaka, T., Tsai, C.-F. and Seed, H.B. (1975). FLUSH a computer program for approximate 3D-analyisis of soil structure interaction problem, Proc. of EERC: 75-30.

Furumoto,Y., Sugito,M., and Yashima,A. (2002). A Seismic Response FEM-Analysis of Ground with Inclined Base Layer by using Frequency-Dependent Equivalent Linearized Technique, Proc. of 1st International Workshop on New Frontiers in Computational Geotechnics, Banff, Canada, pp.155-162.

Sugito,M., Goda,H. and Masuda T. (1994). Frequency-dependent equi-linearized technique for seismic response analysis of multi-layered ground, Proc. of JSCE, No.493/III-27: 49-58 (in Japanese).

Sugito,M., Furumoto,Y. and Sugiyama, T. (2000) Strong Motion Prediction on Rock Surface by Superposed Evolutionary Spectra, 12WCEE in Auckland, New Zealand (CD-ROM).

Furumoto,Y. ,Saiki,Y. and Sugito,M. (2006). On A Simple Modeling for Seismic Transfer Function of Ground on Inclined Base Layer, Third International Symposium on the Effects of Surface Geology on Seismic Motion, Grenoble, France, Paper Number: 98 (CD-ROM)