STUDY OF NONLINEAR SOIL AMPLIFICATION CHARACTERISTICS OF THE ACCELERATION RESPONSE SPECTRUM

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SUMMARY

Estimation of seismic ground motion at ground surface requires an appropriate evaluation of the surface soil amplification. However, it is difficult to estimate surface soil amplification for a large area through detailed analysis, so a simplified method has been desired. This study proposed a method to determine earthquake ground motion on the ground surface, using the acceleration response spectrum on the bedrock and the acceleration response spectrum ratio representing nonlinear amplification characteristics on the surface layer of the ground. First, the relation between smoothed transfer function and acceleration response spectrum ratio for surface topography, type of earthquake and intensity of earthquake ground motion was researched by using SHAKE with many surface layer models. Second, a simple method of estimating acceleration response spectrum ratios was investigated.

INTRODUCTION

Estimating wide-area earthquake ground motion of the ground surface, based on the estimation on ground motion on the bedrock, demands an appropriate consideration of surface soil amplification, because the latter can greatly influence the estimation results. Dynamic response analysis using seismic waves on the bedrock may be an accurate way to consider the amplification of the surface soil. However, collecting soil profile parameters is difficult and the computation time is excessive for broad areas, as is usually the case for earthquake ground motion estimations used by governmental organizations and utility companies in their earthquake damage surveys.

For this reason, government organizations and others adopted the following method for estimating wide-area earthquake ground motion in their earthquake damage surveys [Aichi prefecture, 1993; Kawasaki city, 1998]. For a velocity response spectrum on the bedrock, which was easily obtained using an attenuation relation, a method of multiplication was employed for nonlinear transfer functions of hundreds of soil profile parameters previously allocated to the specific wide area.

This paper presents a simplified way to estimate a model of surface soil amplification for wide-area, what we termed as response spectrum ratio, of earthquake ground motion. Our amplification model of surface soil is similar to previous models for estimating wide-area earthquake ground motion in the earthquake damage surveys. However, the present study differs from previous studies in that it uses both the acceleration response spectrum on bedrock and the acceleration response spectrum ratio of surface soil amplification, and in that it proposes a new simple model of acceleration response spectrum ratio, taking into account surface topography, earthquake type, and intensity levels of earthquake ground motion.

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THE ACCELERATION RESPONSE SPECTRUM RATIO AND ITS USE FOR GROUND MOTION ESTIMATION

Recently, attenuation formulas have improved, as seen in the one proposed by Ohno et al. [Ohno et al., 1996] which considered the spread of the earthquake faults to estimate response spectra. The response spectrum on the bedrock, which has shear wave velocity V_s greater than about 500m/s, can be obtained by an attenuation formula referring to these studies. A wide-area earthquake ground motion on the ground surface can be estimated efficiently by multiplied by response spectrum ratio describing an amplification factor that includes characteristics of the surface layer of the ground [refer to Figure 1].

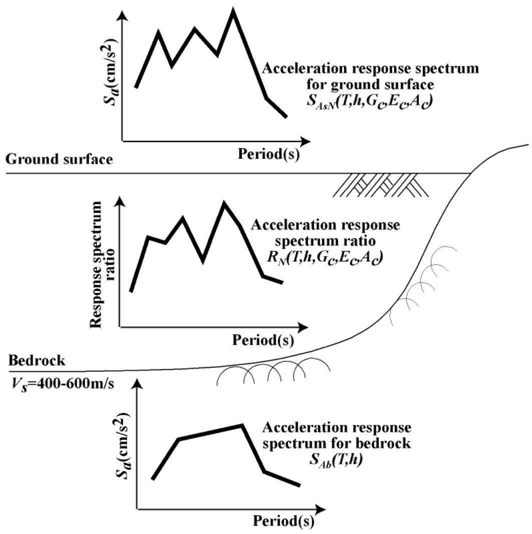

Figure 1: Simple model of estimating ground motion amplification

As diagrammed in Figure 2, the acceleration response spectrum ratio is represented by a model that incorporates the linear response transfer function of the ground, the types and intensities of earthquake ground motion, and the detailed topography of a wide area. It can predict the acceleration response spectrum on the ground surface if used in combination with an attenuation formula constructed to estimate the acceleration response spectrum on the bedrock.

Following Figures. 1 and 2, the relations between the acceleration response spectrum of the bedrock and the response spectrum ratio of the ground surface are now described. First, the relation between the acceleration response spectra of the bedrock and those of the ground surface is

$$S_{AsN}(T,h,G_c,E_c,A_C) = S_{Ab}(T,h) \cdot R_N(T,h,G_c,E_c,A_C) \quad (1)$$

where $S_{AsN}(T,h,G_c,E_c,A_c)$ is a nonlinear acceleration response spectrum of the ground surface, $S_{Ab}(T,h)$ is the acceleration response spectrum of the bedrock, $R_N(T,h,G_c,E_c,A_c)$ is the acceleration response spectrum ratio with a nonlinear response characteristics of surface soil, T is the period, h is the damping ratio, G_c is topographical classifications, E_c is the earthquake type, and A_c is the earthquake ground motion intensity described by peak acceleration.

By using topographical classification, earthquake type and earthquake ground motion intensity, a simple estimate for the acceleration response spectrum ratio of surface soil with a nonlinear characteristics is

$$R_N(T,h,G_c,E_c,A_C) = \hat{H}_L(T) \cdot \alpha(T,h,G_c,E_c,A_C) \quad (2)$$

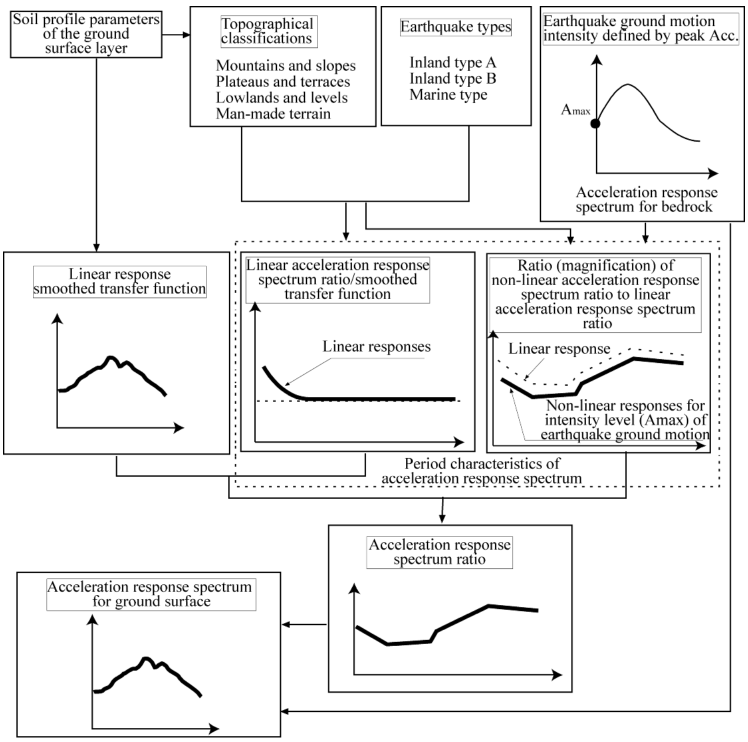

Figure 2: Simple method of estimating surface acceleration response spectra

where $\hat{H}_L(T)$ is the smoothed transfer function that represents a weighted average of the linear response transfer functions, and $\alpha(T, h, G_c, E_c, A_c)$ are coefficients deduced from topographical classifications, earthquake types, and earthquake ground motion intensities.

ASSESSMENT OF THE ACCELERATION RESPONSE SPECTRUM RATIO FOR THE NAGOYA REGION IN JAPAN

Outline

To run the above amplification model of surface soil, the acceleration response spectrum ratio (h = 5%) and the smoothed transfer function were calculated for each topographical classification, earthquake type, and earthquake ground motion intensity. Then individual characteristics and relations between the response spectrum ratio and the smoothed transfer function were analyzed according to the diagram in Figure 3. The ground response analysis program SHAKE was used for the calculation of the acceleration response spectrum ratio (h=5%) and the smoothed transfer function.

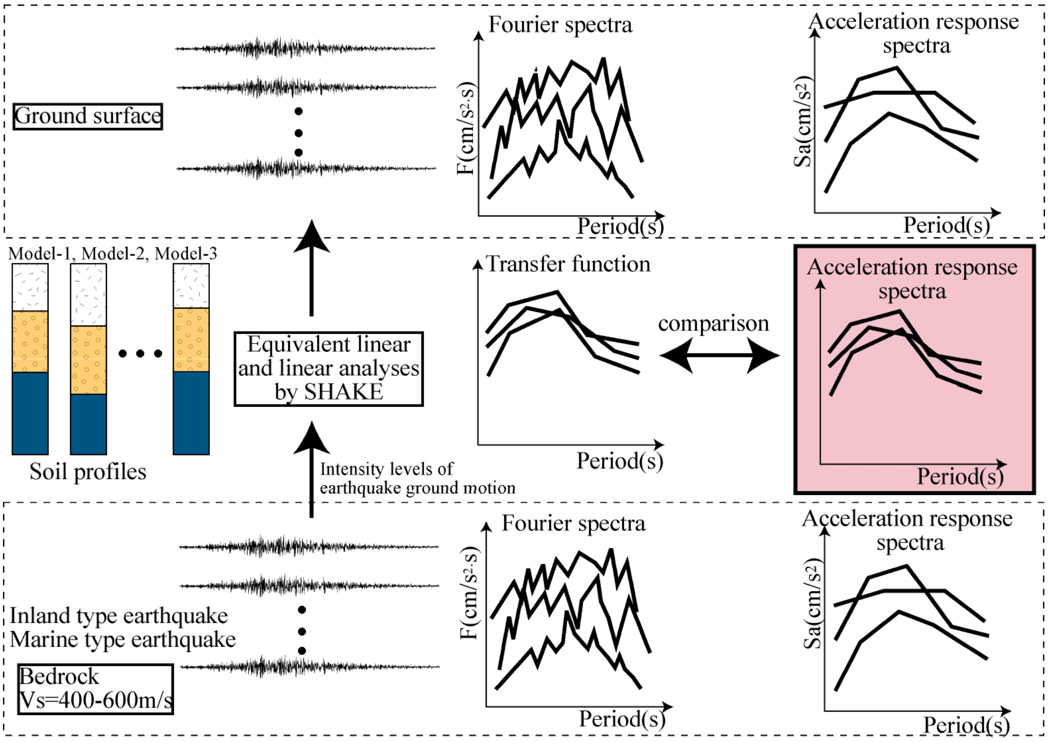

Figure 3: Analytical procedure of acceleration response spectrum ratio

The topography was classified into four groups: mountains and slopes, plateaus and terraces, lowlands and levels (includes deltas, coastal plains, valley floors, and flood plains), and man-made terrain (includes filled-in regions, reclaimed land). For each group, 5 to 10 types of soil profile parameters were selected based on boring data in the area [Japan Geotechnical Society, 1989].

Moreover, we selected eight sets of seismic waves of the inland type earthquakes with hypocenter under the affected areas, and four sets of seismic waves of the marine type earthquakes occurring at boundaries between plates to formulate a model of response spectrum ratio that includes the influence of period characteristics of seismic waves. The inland type earthquakes were divided into two groups, one describe by inland type A for the 1997 Aichi-ken Tobu and the 1997 Kagoshima-ken Hokuseibu earthquakes, and the other describe by inland type B for the 1995 Hyogo-ken Nanbu earthquake. According to the period characteristics of seismic waves, there were three types of earthquakes as described above. If available, we used seismic waves observed on exposed bedrock, but otherwise used waves obtained by analytically removing the effects of the surface layer. Table 1 lists the earthquake records used for this examination, Figure 4 has the accelerograms, while Figure 5 shows their acceleration response spectra (h = 5 %). The intensity of input earthquake ground motion for the response analysis were organized into seven cases with maximum amplitudes of 50, 100, 200, 300, 400, and 500 gals. A seventh case was added for the linear analysis of the intensity levels. Table 2 lists the topographical classifications, earthquake types, and intensity of earthquake ground motions.

Table 1: Earthquake records

Type of earthquake	Name of earthquake	Date	Magnitude (JMA)	Observation site	Direction	Peak acc. (Gal)
Inland type A	Aichi-ken Tobu	1997.3.16	5.8	Nagashino	NS	112.52
					EW	115.49
	Kagoshima-ken Hokuseibu	1997.3.26	6.3	Izumi	NS	535.79
					EW	410.79
Inland type B	Hyogo-ken Nanbu	1995.1.17	7.2	Kobe Univ.	NS	271.94
					EW	304.65
				Kobe	NS	818.02
					EW	617.29
Marine type	Hokkaido Nansei-oki	1993.7.12	7.8	Sutsutsu	NS	216.02
					EW	202.23
	Chile	1985.3.3	7.8	Las Tortolas	N26W	139.42
	Mexico	1985.9.19	8.1	Zihuatanejo	NS	102.99

Table 2: Grouping contents

Topography classifications	Earthquake type	Earthquake ground motion intensity
Mountains and Slopes	Inland type A	Linear
Plateaus and terraces	Inland type B	50cm/s^2
Lowlands and levels	(Hyogoken-nanbu)	100cm/s^2
Man-made terrain	Marine type	200cm/s^2
		300cm/s^2
		400cm/s^2
		500cm/s^2

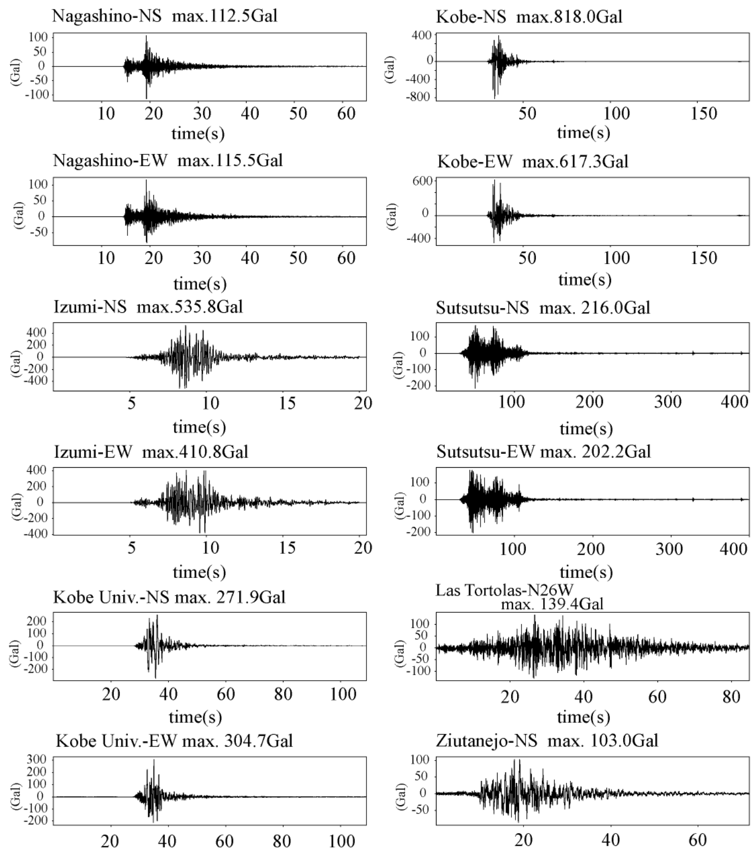

Figure 4: Time histories of accelerograms of the accelerograms

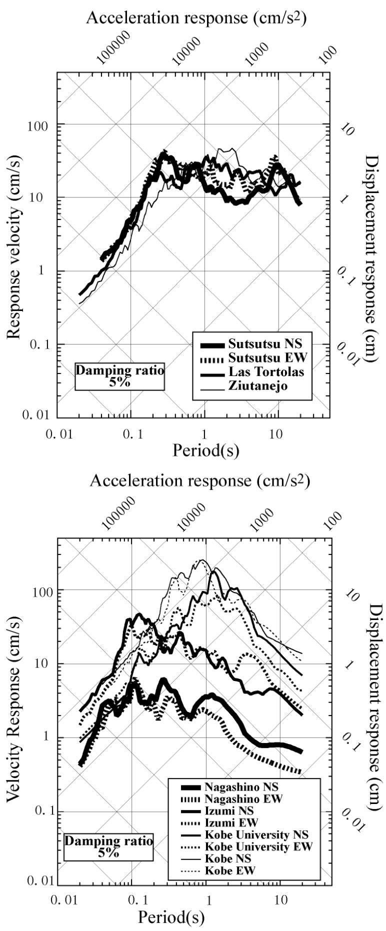

Figure 5: Response spectra

Results of the acceleration response spectrum ratio analysis

The acceleration response spectrum ratio was calculated for each topographical classification and earthquake type, which is shown in Figure 6 together with the average values by earthquake ground motion intensity. The analytical results based on the figure are discussed below.

For all earthquake types, the acceleration response spectrum ratios for the mountains and slopes; and the plateaus and terraces varied less with ground motion intensity than the lowlands and levels, and man-made terrain. In particular, this ratio decreased with rise in ground motion intensity of short-periods for both the lowlands and levels, and the man-made terrain. In addition, the extent of the decrease was particularly large for man-made terrain. The periods at which their ratios decreased the most were about 0.05 seconds for inland type A earthquakes, about 0.5 seconds for inland type B earthquakes, and about 0.2 seconds for marine type earthquakes. Summing all earthquake types, the ratios for the mountains and slopes, and the plateaus and terraces; that for the lowlands and levels, and that for the man-made terrain peaked for periods between approximately 0.1 to 0.3 seconds, 0.5 to 1 second, and 1 to 2 seconds, respectively.

Standard deviations of the ratio, calculated according to intensity levels of earthquake, had a wide dispersion: about 0.1 to 0.3 seconds for mountains and slopes, and plateaus and terraces; about 0.5 seconds for the lowlands and levels, and greater than 1 second for the man-made terrain. The period ranges with wide dispersion of standard deviation agreed with the period ranges in which the acceleration response spectrum ratios peaked.

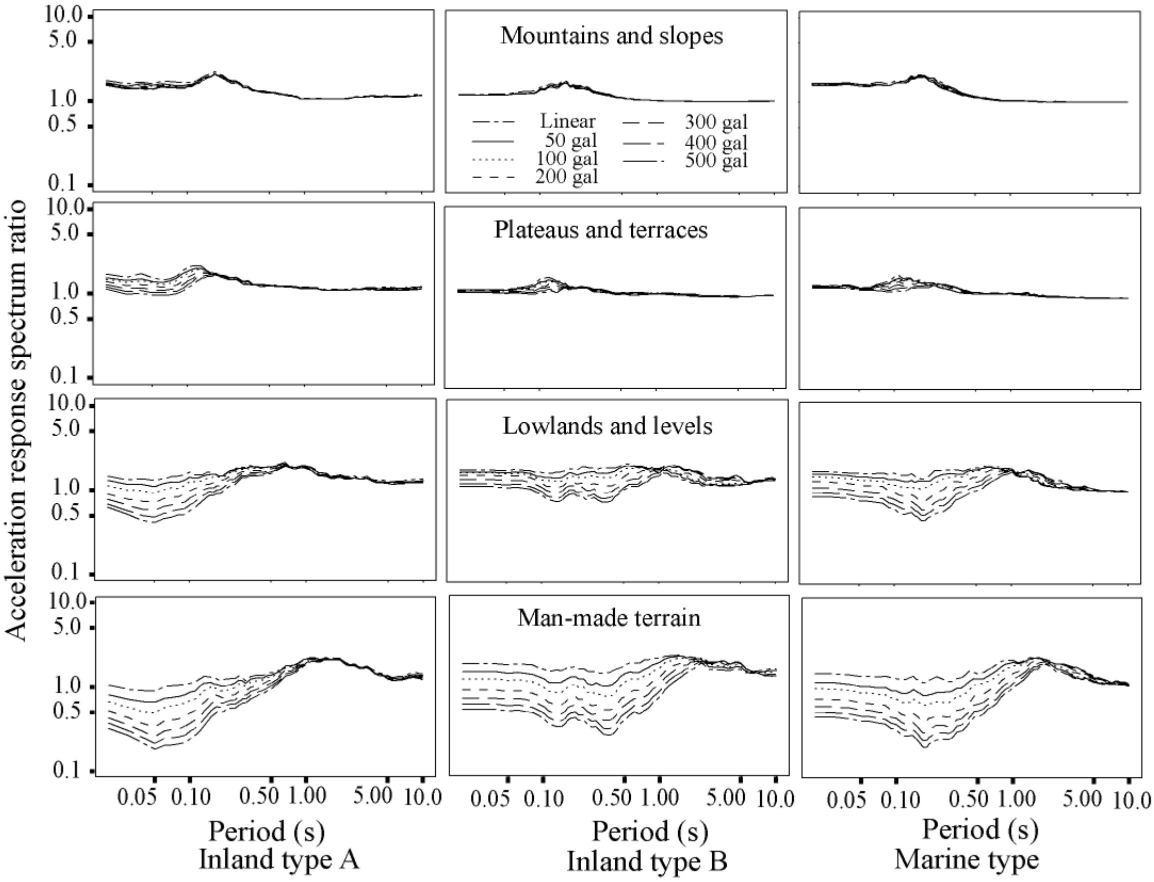

Figure 6: Acceleration response spectrum ratio

Comparison between the acceleration response spectrum ratio and the smoothed transfer function

The ratio of the acceleration response spectrum ratio to the smoothed transfer function were calculated, hereinafter referred to as coefficient $\alpha(T,h,G_c,E_c,A_c)$, for each topographical classification and earthquake type, which is shown in Figure 7 together with the average values by earthquake ground motion intensity.

The figure shows that in surface soil that showed almost linear response, such as mountains and slopes, coefficient $\alpha(T,h,G_c,E_c,A_c)$ in all period approached 1.0 regardless of earthquake type and ground motion intensity. Hence, there was approximate agreement between the nonlinear response transfer function and the nonlinear acceleration response spectrum ratio. Moreover, for all earthquake types, coefficient $\alpha(T,h,G_c,E_c,A_c)$ increased with rise in earthquake ground motion intensity in the short-period range for the plateaus and terraces, the man-made terrain, and the lowlands and levels, while it decreased for ground showing a linear response. For inland type A earthquakes, coefficient $\alpha(T,h,G_c,E_c,A_c)$ was near 1.0 for plateaus and terraces, lowlands and levels, and man-made terrain in the period range of about 0.1 to 10 seconds regardless of earthquake intensity. For inland type B and marine type earthquakes, coefficient $\alpha(T,h,G_c,E_c,A_c)$ was near 1.0 for plateaus and terraces in the period range of 0.2 to 10 seconds; and also near 1.0 for lowlands and levels, and man-made terrain in the period range of about 1.0 to 10 seconds regardless of earthquake intensity.

The standard deviations of coefficient $\alpha(T, h, G_c, E_c, A_c)$ for linear response were obtained to examine the statistic dispersion of the smoothed transfer function. The standard deviations of coefficient $\alpha(T, h, G_c, E_c, A_c)$ for inland type A earthquakes showed that all topographical classifications had a small dispersion in the entire period range. This was also found for inland type B earthquakes in mountains and slopes, plateaus and terraces, and the lowlands and levels. However, those for the man-made terrain were dispersed widely in the range of periods less than about 0.02 seconds.

The above results show that the smoothed transfer function in the current form cannot replace the acceleration response spectrum ratio. Particularly when the surface soil showed nonlinear response in the short-period range and the smoothed transfer function was near 0.0, coefficient $\alpha(T, h, G_c, E_c, A_c)$ increased greatly and the difference between the smoothed transfer function and the acceleration response spectrum ratio became noticeable. When the surface soil showed linear responses, the value of coefficient $\alpha(T, h, G_c, E_c, A_c)$ was comparatively small and near 1.0, suggesting that the smoothed transfer function approximated the acceleration response spectrum ratio.

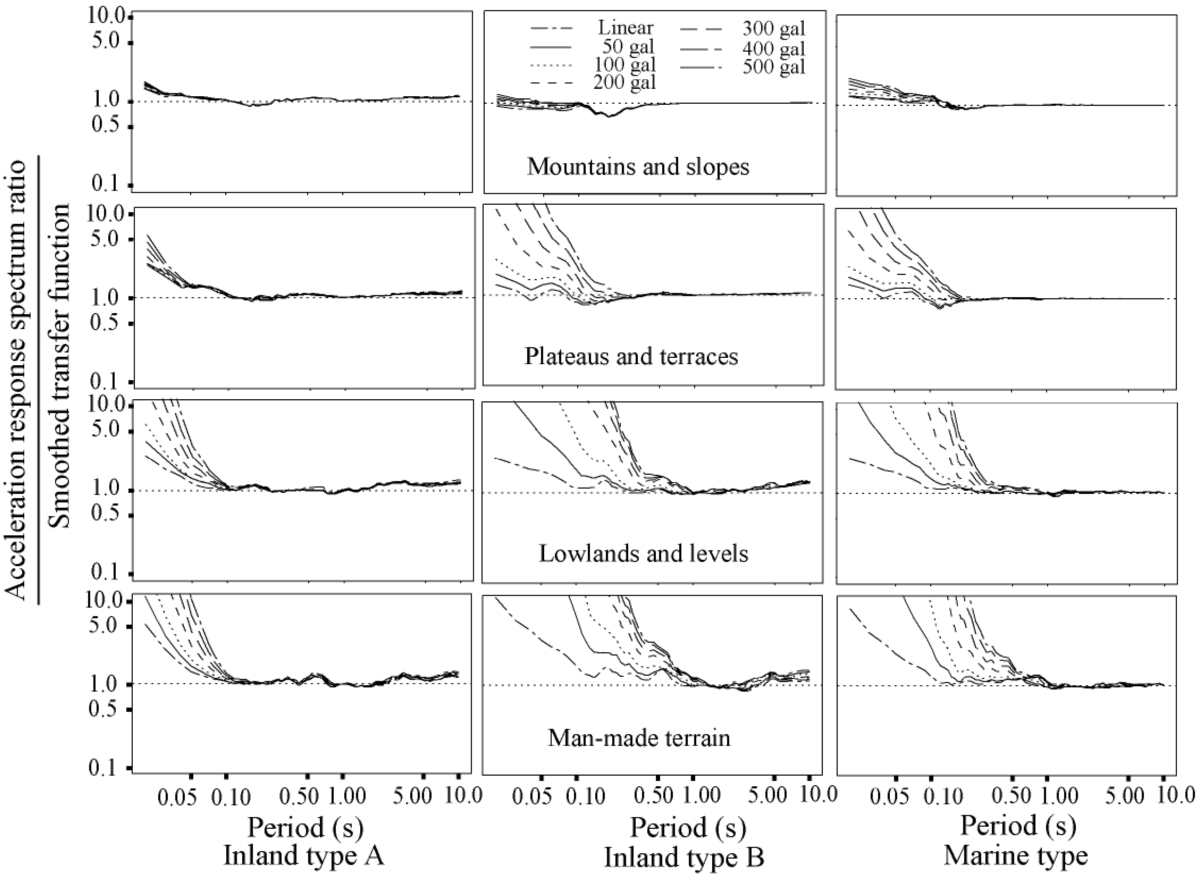

Figure 7: Ratio of acceleration response spectrum ratio to smoothed transfer function

Formulation of a surface soil amplification model

The authors examined methods to determine coefficient $\alpha(T, h, G_c, E_c, A_c)$ in Eq. 2 based on the acceleration response spectrum ratio in 3.2 and coefficient $\alpha(T, h, G_c, E_c, A_c)$ from 3.3. The formulation for a simple estimation model is described below.

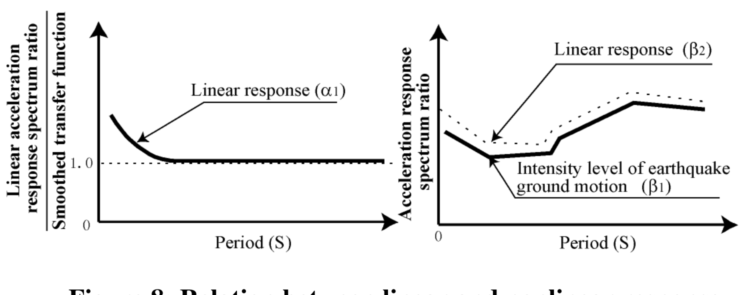

Figure 8: Relation between linear and nonlinear response spectrum ratio

First, the acceleration response spectrum ratio for linear response was estimated, based on the ratio α_1 of the acceleration response spectrum ratio to the smoothed transfer function obtained in 3.3 [refer to Figure 8].

$$R_L(T,h,G_c,E_c,A_c) = \alpha_1 \cdot \hat{H}_L(T) \tag{3}$$

where $R_L(T,h,G_c,E_c,A_c)$ is the linear acceleration response spectrum ratio of the surface soil, and $\hat{H}_{L(T)}$ is the linear-response smoothed transfer function of the surface soil.

Next, the magnification factor against a linear response was obtained using the acceleration response spectrum ratio β_1 for the earthquake intensity on the ground, and the acceleration response spectrum ratio β_2 for linear response [refer to Figure 8].

$$\frac{R_N(T,h,G_c,E_c,A_c)}{R_L(T,h,G_c,E_c,A_c)} = \frac{\beta_1}{\beta_2} = \alpha_2 \tag{4}$$

where $R_N(T,h,G_c,E_c,A_c)$ is the nonlinear acceleration response spectrum ratio.

From Eqs. 3 and 4, the nonlinear acceleration response spectrum ratio is

$$\begin{aligned} R_N(T,h,G_c,E_c,A_c) &= \alpha_N \cdot R_L(T,h,G_c,E_c,A_c) \\ &= \alpha_L \cdot \alpha_N \cdot \hat{H}_L(T) \end{aligned} \tag{5}$$

Therefore, coefficient $\alpha(T,h,G_c,E_c,A_c)$ established according to topographical classification, earthquake type, and earthquake ground motion intensity, which were assumed in Eq. 2, is given by

$$\alpha(T,h,G_c,E_c,A_c) = \alpha_1 \cdot \alpha_2 \tag{6}$$

NUMERICAL EXAMPLE OF EARTHQUAKE GROUND MOTION ESTIMATION USING THE RESPONSE SPECTRUM RATIO

The applicability of the proposed response spectrum ratio was examined using data on the Aichi-ken Tobu earthquake of March 16, 1997 of the seismological observation network "K-NET" of the Science and Technology Agency, the National Research Institute for Earth Science and Disaster Prevention.. Table 3 lists some parameters for the earthquake event.

This evaluation compared acceleration response spectra from K-NET records observed at AIC012 (hereinafter referred to as Point A) and AIC005 (hereinafter referred to as Point B), with acceleration response spectra on the ground surfaces that we estimated by the attenuation formula and acceleration response spectrum ratio at these two points. Input soil data were determined by referring to the boring data of the K-NET's observation points and other sources. Table 4 lists soil profile parameters for Points A and B. The authors judged this earthquake to be an inland type A earthquake, Point A to be a lowlands and levels region, and Point B a mountains and slopes region. Acceleration response spectra on the bedrock at Points A and B were estimated based on attenuation formula [Ohno et al., 1996] and the earthquake ground motion intensity was determined according to the peak acceleration estimated from acceleration response spectra at the period of 0.02 seconds. These determined α_1 and α_2 in Eq. 6, and accordingly, the acceleration response spectrum ratios for the surface soil at Points A and B.

Table 3: Parameters of the 1997 Aichi-k Tobu earthquake

Date of occurrence	1997.3.16
Epicenter	34.9N, 137.5E
Depth	39 km
JMA magnitude	5.8
Length of fault	10 km
Breadth of fault	5 km
Strike direction of fault	164 K
Dip of fault	37 K
Seismic moment	$1.8\text{x } 10^{24}$ dyn·cm

Table 4: Soil profile model

(a) Point A

Depth (m)	Layer thick. (m)	S-wave vel. (m/s)	Unit weight (t/m^3)
0	2	130	1.8
2	5	370	2.2
7	∞	1000	2.4

(b)Point B

Depth (m)	Layer thick. (m)	S-wave vel. (m/s)	Unit weight (t/m^3)
0	10	140	1.8
10	10	230	2.0
20	20	230	2.1
40	∞	600	2.1

Figure 9 shows a comparison of the observed and estimated acceleration response spectra (damping ratio 5%) at the ground surface of Points A and B. At point A there are differences between the two spectra in some period ranges; however, as a whole, there is qualitative agreement. On the other hand, at Point B, the estimated spectra reproduced the observed features in form and scale.

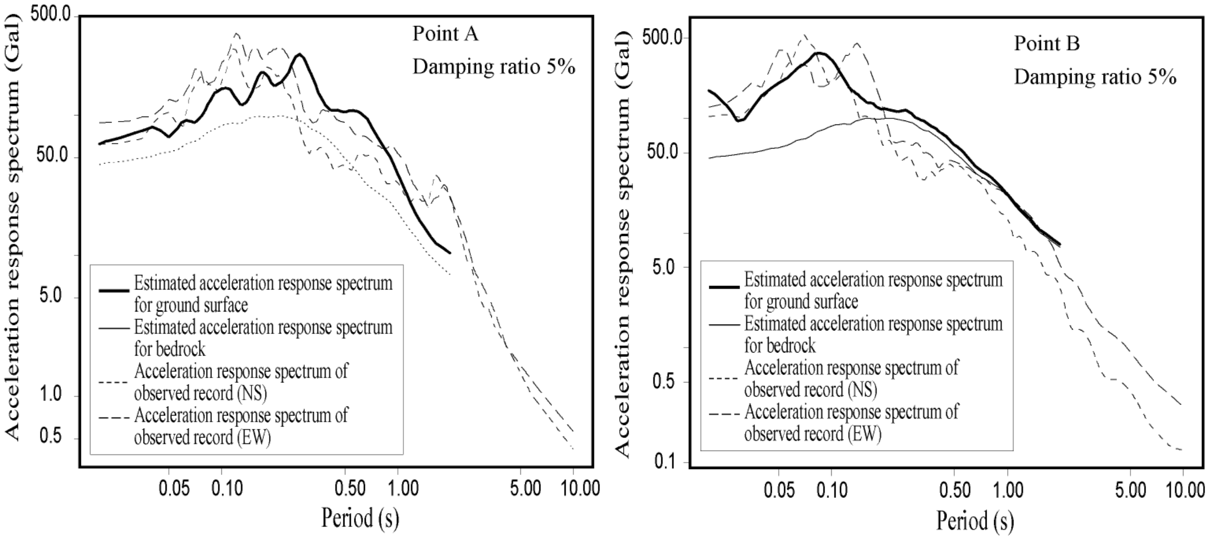

Figure 9: Comparison of the observed and estimated acceleration response spectra

CONCLUSIONS

This study has proposed a method to use acceleration response spectrum ratio, which was determined based on the smoothed transfer function for linear response, as the amplification characteristic of surface soil, to be applied to the estimation of surface earthquake ground motion in a wide area. Through the analysis on particular cases, the method was able to generally reproduce acceleration response spectrum of the ground surface.

The use of soil profile parameters was limited and could be increased to evaluate possible improvement in model performance. By dividing the inland type earthquakes into two, we examined a total of three types of earthquakes, although the use of two types, the inland type and the marine type, probably gives sufficiently good results with less effort, more studies on modeling earthquake types should be done.

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