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Simplified Strong Ground Motion Prediction Method for Reflecting Nonlinear Site Effect Using Fault Model

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ABSTRACT

Strong ground motion prediction methods using fault models such as the empirical and stochastic Green's function methods overestimate short-period ranges at sites on soft soils because it cannot consider a nonlinearity of the soil. The authors proposed a detailed method that combined the empirical Green’s function method and dynamic response analysis considering soil nonlinearity but had difficulties in the case where there were numerous study sites because detailed data was required on soil characteristics. Then, the authors focus on the prediction of response spectrum, propose a simple method for estimating response spectrum considering the nonlinearity of soil using the natural period at the study site and verify the effectiveness of the method using observation records.

Introduction

The Empirical Green's Function Method (EGFM) (Irikura, 1986) and Stochastic Green's Function Method (SGFM) (Kamae et al., 1990) estimate ground motions during a large earthquake using fault models and small earthquake records as Green’s functions.

These methods express ground motions as linear synthetics of Green’s functions based on the law of similarity between large and small earthquakes and the law of spectral similarity. Ground motions can therefore be estimated accurately at the sites on hard soils with low nonlinearity. At the sites on soft soils where nonlinearity is outstanding during a large earthquake, on the other hand, synthetic waves are overestimated especially in the short-period range. Cities have mostly developed on soft alluvial deposits in Japan. If EGFM or SGFM is to be applied under such circumstances, the method should be enhanced to take the nonlinearity of soil into consideration. The authors focused on the reproducibility of S-wave-induced main shock, which is highly correlated to seismic damage, and proposed a method for synthesizing ground motions on hard bedrock subject to small effects of soil becoming nonlinear (hereinafter referred to as the engineering base), not at surface where nonlinearity of soil is outstanding, and computing surface ground motions based on the results of detailed seismic response analysis considering the nonlinearity of soil conducted separately (hereinafter referred to as the detailed method). The effectiveness of the detailed method has been verified after it was applied to several actual earthquakes (Ikeda et al., 2011).

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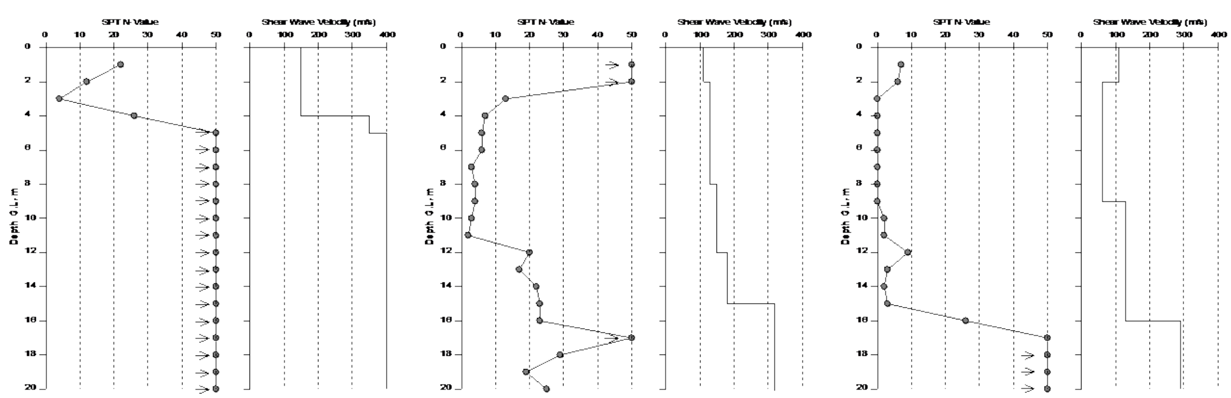
The detailed method has the advantage that soil characteristics can be estimated in detail at study sites. Detailed data on soil characteristics including nonlinearity is, however, required at each study site. With the development of seismographic network, seismographic observations have been conducted at an increasing number of sites, and conditions have been met for applying EGFM to the prediction of strong ground motions. Only inadequate data is, however, available on soil characteristics including nonlinearity, so there are restrictions in applying the method. Then, it is desired that a simple method with a certain level of accuracy is developed for predicting ground motions.

Response spectra are sometimes used as a scale of strength of input ground motion in structural design. This paper proposes a method for simply estimating a ground motion response spectrum considering soil nonlinearity (hereinafter referred to as the simple method) from the ground motion response spectrum considering no soil nonlinearity that is directly estimated using a ground motion prediction method using fault models (hereinafter referred to as the synthesis method). Specifically, the response spectrum directly estimated using the synthesis method is corrected using the ratio between linear and nonlinear amplification of response spectrum between the engineering base and surface as a correction function. Used in this paper is a pseudo velocity response spectrum with a damping coefficient of 0.05.

Estimation of Ground Motions in Soft Soils Using the Detailed Method

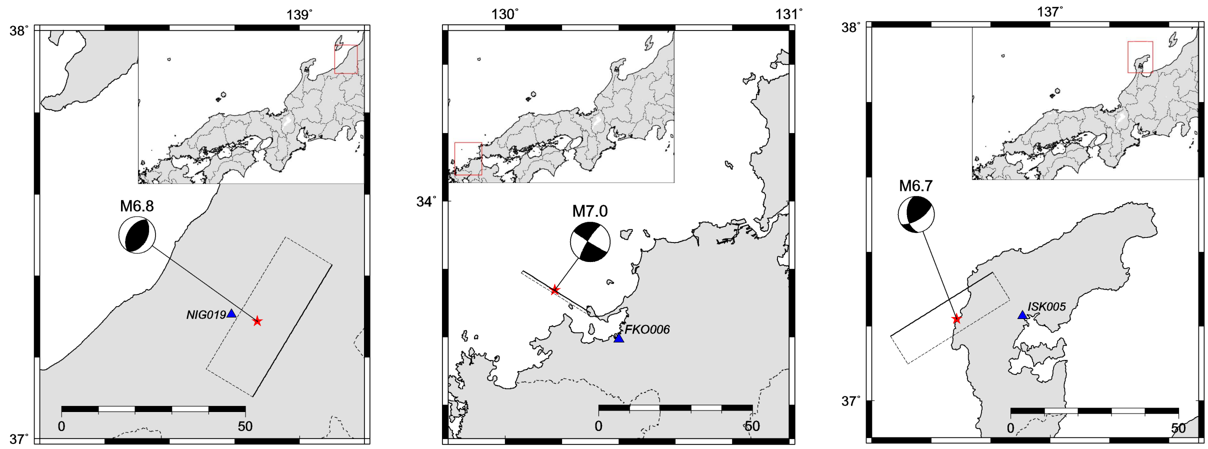
The detailed method first transfers the small ground motion observed at surface to the engineering base. A ground motion is synthesized using EGFM and the ground motion at surface is estimated again based on the results of dynamic response analysis considering soil nonlinearity. The results of application of the detailed method in soft soils are presented here by quoting existing works.

Studies were made at three points, NIGO19, FKO006 and ISK005, all of which are earthquake observation sites in soft soils. Figure 1 show depth distribution of SPT-N value and shear wave velocity (Vs) of each site. We can confirm that the surface layers are very soft.



(a) NIG019. (b) FKO006. (c) ISK005.

Figure 1: Soil conditions (depth distribution of SPT-N value and Vs) of NIG019, FKO006 and ISK005.



(a) NIG019
Mid Niigata prefecture earthquake in 2004 (M6.8).

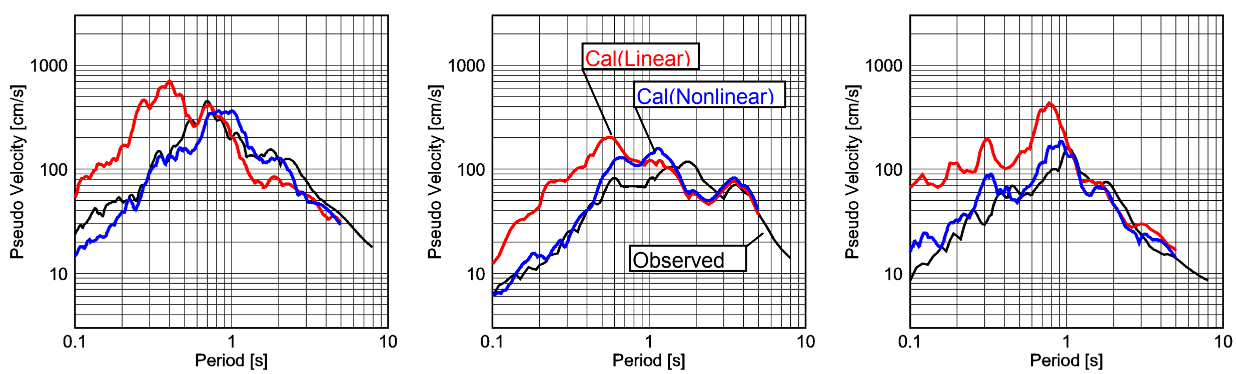
(b) FKO006
2005 West off Fukuoka prefecture earthquake (M7.0).

(c) ISK005
Noto Hanto Earthquake in 2007 (M6.9).

Figure 2: Location relationship with epicenter and examination site.

Earthquakes to use for this study are Mid Niigata prefecture earthquake in 2004 with M6.8 of NIG019, 2005 West off Fukuoka prefecture earthquake with M7.0 of FKO006 and Noto Hanto earthquake in 2007 with M6.9 of ISK005 respectively. Figure 2 show location relationship with epicenter and examination site.

Figure 3 shows spectra of observed ground motions and of ground motions directly estimated using EGFM (hereinafter referred to as the linear response spectra), and the spectrum of ground motions estimated using the detailed method considering soil nonlinearity (hereinafter referred to as the nonlinear response spectrum), at the above three points.



(a) NIG019.

(b) FKO006.

(c) ISK005.

Figure 3: Comparison between linear response spectra and nonlinear response spectra.

The linear response spectrum was overestimated in short-period range with approximately one second or shorter as compared with the response spectrum of observed ground motions (hereinafter referred to as the observed response spectrum). The nonlinear response spectrum was in better agreement with the observed response spectrum at all of the three points.

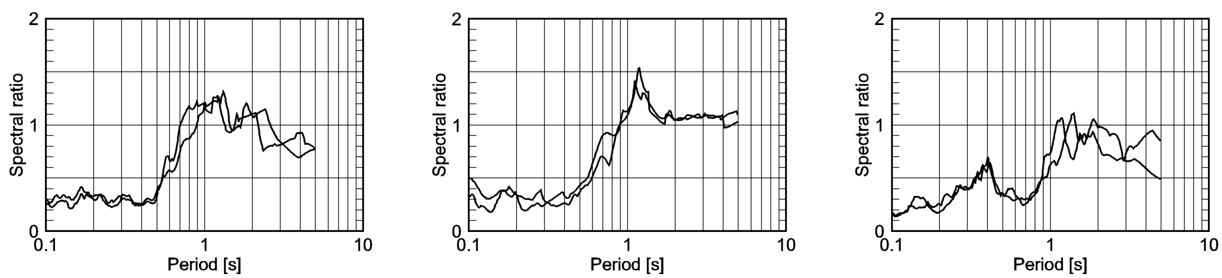
Relationship between Response Spectrum and Soil Nonlinearity

Figure 4 shows the results of division of nonlinear response spectrum by linear response spectrum (hereinafter referred to as the response spectral ratio). The response spectral ratio remains nearly constant in the short-period range up to a certain period, then increases rapidly to a certain period and remains constant thereafter. If the response spectral ratio can be defined based on the soil characteristics and input motion level, it can be used as a correction function to estimate the nonlinear response spectrum from the linear response spectrum directly estimated using the synthesis method.

Figure 5(a) shows superimposed response spectra at the three sites. The response spectral ratios evidently varied probably because of the difference in soil characteristics and input ground motion at respective sites. Then, the horizontal axis of Figure 5(a) was normalized using the natural period of surface layer at each site. Spectral ratios were reproduced accordingly (Figure 5(b)). The normalized period is estimated using equation (1) where t_{np} is the normalized period, t is the period (s) and t_p is the natural period of surface layer (s).

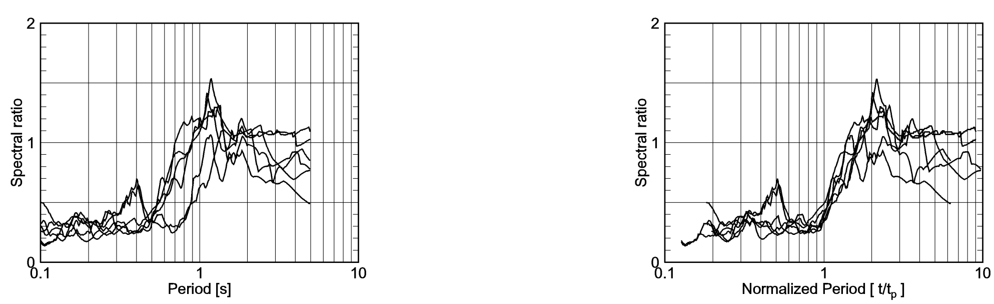
$$t_{np} = t / t_p \tag{1}$$

Figure 5(b) shows that the soil characteristics obtained by normalization at the three sites using the horizontal axis as the normalized period exhibit a similar shape, which suggests that modeling the spectral ratio is possible.



(a) NIG019. (b) FKO006. (c) ISK005.

Figure 4: Ratio of response spectra by dividing nonlinear response spectrum by linear response spectrum.



(a) Rearranging in the period. (b) Rearranging in the normalized period.

Figure 5: Response spectral ratio at 3 sites.

Figure 6 shows a model of response spectral ratio. Emphasis was placed on the increase of accuracy near t_{np} of 1.0 and as simple a shape as possible was developed as the effect on structural damage and the benefit obtained by the application of the method were both taken into consideration. The spectral ratio was kept constant in the normalized periods shorter than *T1* and longer than *T2*. A straight line was interpolated between *T1* and *T2*. The constant value on the T1 side was set at *CA1* and the one on the *T2* side at *CA2*. This function is referred to as the spectrum correction function below.

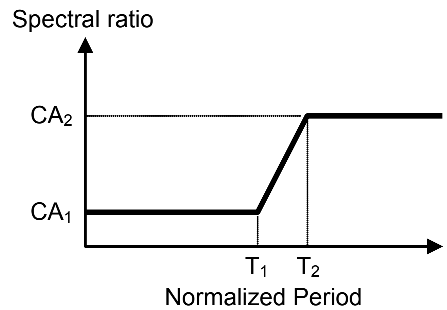


Figure 6: Model of response spectral ratio (spectral correction function).

Proposal of Simple Method Considering Soil Nonlinearity

The nonlinear response spectrum is estimated by estimating the spectrum correction function based on the soil characteristics and input motion at the study site, and multiplying the estimate by the linear response spectrum computed using the synthesis method. Equation (2) is used for estimation.

$$S_{NL}(t_{np}) = C(t_{np}) \times S_L(t_{np}) \tag{2}$$

where $S_{NL}(t_{np})$, $C(t_{np})$ and $S_L(t_{np})$ are nonlinear response spectrum, spectrum correction function and linear response spectrum, respectively.

The nonlinear ground motion is computed based on the results of soil nonlinear dynamic response analysis using the ground motion synthesized in the engineering base as the input motion. The linear ground motion is based on the results of soil linear dynamic response analysis using the same ground motion as the input ground motion. Then, the spectrum correction function can be computed by dividing the soil response spectrum obtained based on the results of soil nonlinear dynamic response analysis using the same input ground motion in the same soil by the response spectrum obtained based on the results of linear dynamic response analysis.

The spectrum correction function is considered to vary according to the soil characteristics and input ground motion level. Multiple soil models and input ground motion levels were therefore specified, and the spectrum correction function was computed based on the results of linear and nonlinear seismic response analyses to develop a model by statistical processing.

Estimation of Spectrum Correction Function

Spectral ratio was computed by developing multiple soil models with a layer thickness of 30 m and making linear and nonlinear dynamic response analyses. It was assumed that the soil structure was composed alternately of cohesive, sandy and cohesive deposits. The average shear wave velocity was varied from 100 to 300m/s at 10m/s intervals. Two types of input motions of inland and subduction earthquakes were used. The maximum acceleration was varied from 100 to 1,000cm/s^2 at 100cm/s^2 intervals.

For linear dynamic response analysis, frequency response analysis based on the one-dimensional multiple reflection theory was used. For nonlinear dynamic response analysis, a time-history response method of successive integration method type was employed.

Figure 7 shows spectral ratios in the case where input ground motion of an inland earthquake was used. The figures in Figure 7 indicate the maximum linear response spectra. The horizontal axis indicates the normalized period. The natural period of soil was computed from the average shear wave velocity of soil (Vs_{ave}) using equation (3).

$$t_p = 4H / Vs_{ave} = 120 / Vs_{ave} \qquad (3)$$

When the maximum input ground motion (A_{max}) was small, response spectral ratios exhibited a nearly similar shape regardless of Vs_{ave}. As A_{max} increased, the shape of response spectrum changed and *T2* increased. The tendency was outstanding where Vs_{ave} was low (the soil was soft). When A_{max} was large, on the other hand, *T2* did not increase so much if Vs_{ave} was high. Thus, A_{max} had a small effect on the response spectral ratio. It was verified that similar tendency was found also in the case where ground motion of an ocean-trench earthquake was input.

The physical implication of spectrum correction function is discussed below. *T1* and *T2* are the normalized natural periods of linear and nonlinear soils, respectively. Accordingly, *T1* is 1.0 regardless of the input ground motion level and soil characteristics. *T2* becomes closer to 1.0 as the input ground motion level decreases or Vs_{ave} increases. *T2* exceeds 1.0 as the input ground motion level increases or Vs_{ave} decreases. *CA1* and *CA2* are the ratios for nonlinear and linear amplification characteristics. Both become closer to 1.0 if the input ground motion level is low or Vs_{ave} is high owing to low soil nonlinearity. As the input ground motion level increases or Vs_{ave} decreases, soil nonlinearity increases and *CA1* that indicates amplification characteristics in the short-period range becomes considerably lower than 1.0. In the long-period range on the other hand, *CA2* is approximately 1.0 regardless of the input ground motion level and Vs_{ave} because the long-period range is unlikely to be affected by the nonlinearity of soil.

T1, *T2*, *CA1* and *CA2* were specified based on the physical implication of spectrum correction function. As is obvious from Figure 7, *T1* and *CA2* fluctuate less than *T2* and *CA1*. *T1* ranges from 0.9 to 1.0 and *CA2* from 1.0 to 1.2. These values are in agreement with the physical implications of *T1* and *CA2* described above. In this study, *T1* and *CA2* were fixed at 0.9 and 1.1, respectively as they were not affected by the input ground motion and soil characteristics. *T2* and *CA1* were specified as functions dependent on the input ground motion and soil characteristics. Based on the physical implication, *T1* was 1.0. *T1* was, however, specified at 0.9 because the natural period of soil (t_p) was computed for normalizing the period using equation (3) and estimated longer than the natural period of soil estimated based on the seismic response analysis. Figures 6 and 7 show the relationships of *T2* and $PVRS_{max}$ and of *CA1* and $PVRS_{max}$ at Vs_{ave} of 100, 150, 200, 250 and 300 m/sec. $PVRS_{max}$ is the maximum nonlinear response spectrum and used as an index of input ground motion level instead of A_{max}. Equations expressing the *T2* - $PVRS_{max}$ and *CA1* - $PVRS_{max}$ relationships were obtained (equations (4) and (5)). The relationships are shown in Figures 6 and 7 using solid lines.

$$T_2 = a1 \times PVRS_{\max} + b1 \tag{4}$$

$$CA_1 = a2 \times PVRS_{\max} + b2 \tag{5}$$

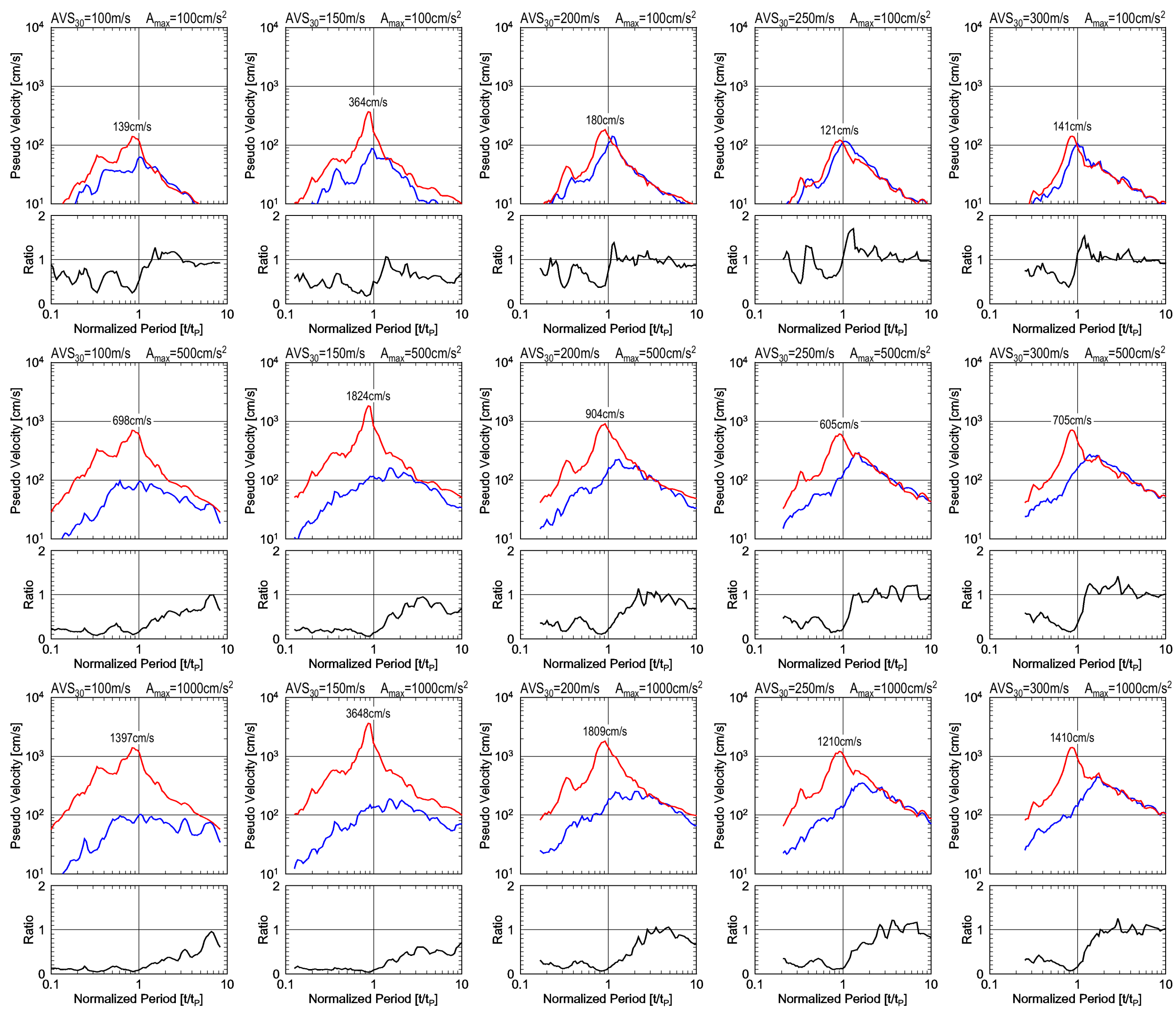
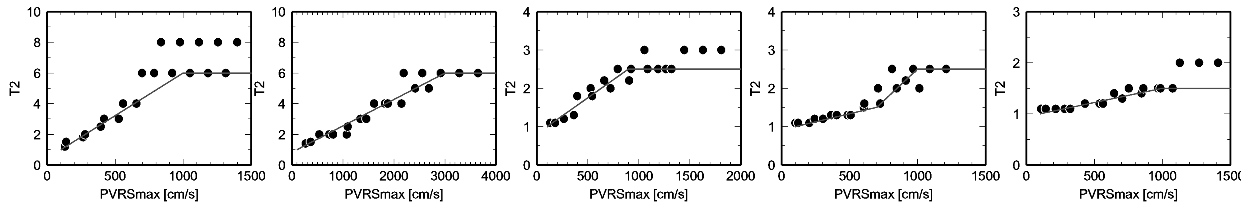


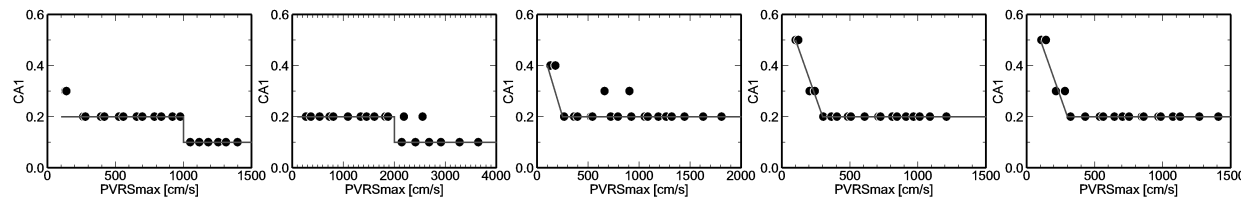
Figure 7: Comparison between nonlinear response spectra and linear response spectra.

Coefficients *a1*, *b1*, *a2* and *b2* are dependent on Vs_{ave} and $PVRS_{max}$. Table 1 shows the values of *a1*, *a2*, *b1* and *b2* at Vs_{ave} of 100, 150, 200, 250 and 300m/s. *T2* and *CA1* can be obtained at Vs_{ave} of 100 through 300m/s at 50m/s intervals using Table 1 and equations (4) and (5). *T2* and *CA1* at a given Vs_{ave} are therefore interpolated from the values. *T2* and *CA1* at Vs_{ave} of 100 m/s are applied at Vs_{ave} of less than 100m/s. *T2* and *CA1* at Vs_{ave} of 300m/s are applied at Vs_{ave} of more than 300m/s.



(a) VS_{ave}=100cm/s. (b) VS_{ave}=150cm/s. (c) VS_{ave}=200cm/s. (d) VS_{ave}=250cm/s. (e) VS_{ave}=300cm/s.

Figure 8. Relationship between input level index ($RVRS_{max}$) and *T2*.



(b) VS_{ave}=100cm/s. (c) VS_{ave}=150cm/s. (d) VS_{ave}=200cm/s. (d) VS_{ave}=250cm/s. (e) VS_{ave}=300cm/s.

Figure 9: Relationship between input level index ($RVRS_{max}$) and *CA1*.

Verification of Proposed Method

The proposed method was applied to actual earthquakes for verifying its effectiveness. Verification was made at three sites, NIG019, FKO006 and ISK005 shown in Figure 1. Table 2 shows Vs_{ave}, t_p and $PVRS_{max}$ at respective sites and *T1*, *T2*, *CA1* and *CA2*, parameters of the spectrum correction function.

Table1: Constant a1, a2, b1 and b2.

AVS_{30} (m/s)	$PVRS_{max}$ (cm/s)	a1	b1	$PVRS_{max}$ cm/s	a2	b2
100	100-1000	1/18	4/9	100-1000	0	0.2
	1000-	0	6	1000-	0	0.1
150	100-3000	5/2900	24/29	100-2000	0	0.2
	3000-	0	6	2000-	0	0.1
200	100-900	3/1600	13/16	100-250	-1/750	8/15
	900-	0	2.5	250-	0	0.2
250	100-700	1/1200	11/12	100-300	-3/2000	23/20
	700-1000	1/300	-5/6	300-	0	0.2
	1000-	0	2.5	-	-	-
300	100-800	1/1600	15/16	100-300	-3/2000	23/20

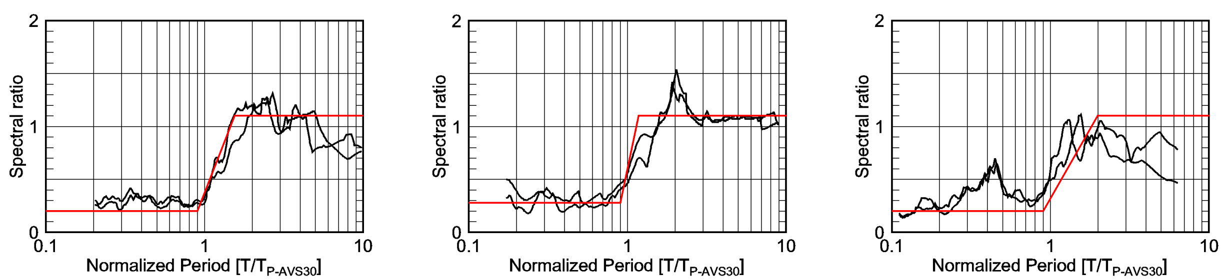
800-	0	1.5	300-	0	0.2

First, the validity of the spectrum correction function was verified. Figure 10 compares the assumed spectrum correction function and response spectral ratio. The spectrum correction function and response spectral ratio were in good agreement with each other.

Figure 11 compares the nonlinear response spectrum estimated using the simple method with observation-record-based spectrum and with the linear response spectrum. As a result of consideration of the effect of soil nonlinearity using the simple method, overestimation in the short-period range was moderated and the nonlinear spectrum was in better agreement with the response spectrum of observed waves. *T1* and *T2* were overestimated at ISK005 and the degree of agreement was low near the natural period. The response spectrum was nearly reproduced in the short-period range. The above results suggest that the simple method enables the assessment of the effect of soil nonlinearity as well as the detailed method.

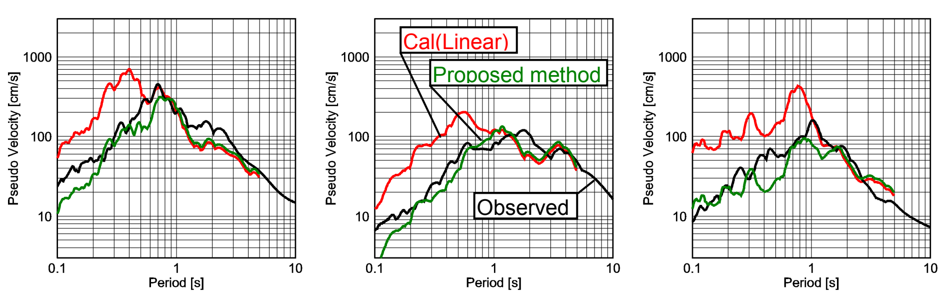
Table 2. Spectral correction functions at 3 sites

Site AVS_{30}(m/s)	t_p(s) $t_{p\text{-}AVS30}$(s)	Component	$PVRS_{max}$ (cm/s)	T_1	T_2	CA_1	CA_2
NIG019	0.51	NS	698	0.9	1.6	0.20	1.1
245	0.49	EW	879	0.9	2.1	0.20	1.1
FKO006	0.56	NS	203	0.9	1.2	0.28	1.1
209	0.58	EW	221	0.9	1.2	0.25	1.1
ISK005	0.79	NS	430	0.9	2.0	0.20	1.1
133	0.90	EW	775	0.9	3.0	0.20	1.1



(a) NIG019. (b) FKO006. (c) ISK005.

Figure 10: Comparison between observed response spectra ratio and estimated response spectra ratio.



(a) NIG019. (b) FKO006. (c) ISK005.

Figure 11: Comparison between calculated pseudo velocity response spectra and observed one.

Conclusions

In order to improve the applicability of strong ground motion prediction methods in soft soils using fault models, a method was proposed for simply considering the nonlinearity of soil at sites where no detailed soil investigation results were available. The following conclusions were reached.

(i) A simple method was proposed for estimating response spectrum considering the nonlinearity of soil using fault models and spectrum correction function.

(ii) The spectrum correction function is specified based on the soil characteristics and input ground motion level.

(iii) It was shown that the spectrum correction function can be modeled by normalizing the natural period of response spectrum (normalizing the frequency axis of response spectrum using the natural period of soil).

(iv) The proposed method was applied to actual earthquakes and its effectiveness was verified.

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