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STRONG GROUND MOTION PREDICTION METHOD USING FAULT MODEL REFLECTING NONLINEAR SITE EFFECT

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ABSTRACT

For mitigating damage of structures during disastrous earthquakes, we have to improve both the procedure for constructing source models for future earthquakes and the method for estimating broad-band strong ground motions. The empirical Green's function method (Irikura, 1986, hereafter EGFM) is one of the most appropriate methods for predicting broad-band strong ground motions near source area. However, EGFM is known to overestimate an observation record on the soft soil layers site because it could not consider a nonlinear characteristic of the soil during the earthquake. We attempted expansion to be able to apply EGFM to a soft soil layers site, combining it with the nonlinear dynamic response analysis of a surface layer. As a result, the calculated motions on the ground surface underlain by soft soil layers agree reasonably well with the observed ones. It means that the EGFM is one of the most effective methods for predicting a borad-band strong ground motions at both soft soil layers sites as well as hard rock sites.

INTRODUCTION

The inland crustal earthquake may cause strong ground motion in the near source area. Furthermore, it often becomes the characteristic ground motion due to the source heterogeneity and forward rupture directivity effect. In the 1995 Hyogo-Ken Nanbu earthquake, Japan with Mw6.9 pulse wave with a period of around 1.0 second were generated in the near source area and gave a devastating damage to many structures and take a heavy toll. Therefore, for the mitigation of the earthquake damage, it is necessary to improve prediction accuracy of characteristic ground motion generated in the near source area for future earthquake. We have to make an effort for development of the source modeling procedure and extend the applicability of the strong ground motion prediction method.

Forward modeling method using EGFM is known as method to evaluate the source model of the earthquake (Kamae and Irikura, 1998). This method places strong motion generation areas (hearafter SMGA) on the fault plane based on a wave inversion analysis result and quantifies size and stress drop of each SMGA. This modeling procedure is simple, but can consider non-homogeneity and a forward directivity effect of the ground. The effectiveness of this procedure was clarified by strong motion simulation analyses for past earthquakes (e.g. Kamae and Irikura, 1998 and Ikeda et al., 2004).

The strong ground motion is influenced by a source characteristic and a propagation characteristic and a site characteristic. It is necessary to evaluate three characteristics appropriately for predicting strong ground motion with a high accuracy. EGFM can evaluate a site characteristic and a

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propagation characteristic automatically by using the appropriate small earthquake record as empirical Green's function (hearafter EGF). In this method, the strong ground motion is evaluated by linear synthesis of the empirical Green's function according to the similarity law of earthquake and the similarity law of source spectra. Therefore, EGFM is known to overestimate an observation record on the soft soil layers site that becomes a nonlinearity during an earthquake.

In this study, we expanded procedure of the strong ground motion prediction using EGFM. Specifically, we have tried to evaluate the strong ground motion of soft soil layers by a combination of EGFM and nonlinear dynamic response analysis. And we evaluated applicability of the proposed method through the strong ground motion simulation on the soft soil -layers site of past earthquakes.

PROPOSED METHOD

The non-linear strong ground motion simulation of soft soil layers using EGFM was carried out in the following procedures. Firstly, we calculated strong ground motion by EGFM. The source model was constructed by forward modeling using EGFM for the hard ground sites. As previously described, EGFM cannot consider a nonlinearity of the ground, the calculated strong ground motion should be overestimated for an observation record. Next, we calculated base motion of the small motion which use as EGF by deconvolution analysis. The base here is the engineering base which have a S wave velocity more than 400m/s (hereafter engineering base). Next, we synthesised strong ground motion on the engineering base by EGFM. Finally, we calculated surface strong ground motion reflecting non-linear site effect using non-linear dynamic response analysis.

This procedure was already applied for earthquake damage estimation, but applicability was not clarified. So, we applied this method to past earthquake and confirmed the applicability of this procedure. In this study, we selected 2 inland crustal earthquake that were the 2007 Noto-Hanto earthquake (Mw6.7), Japan and the 2005 West Fukuoka prefecture earthquake (Mw6.5), Japan as target earthquakes. We assume that the ground motions should be generated only from the SMGA.

THE 2007 NOTO-HANTO EARTHQUAKE (Mw6.7)

On 25th March 2007, Noto-Hanto earthquake (Mw6.7) struck the Noto peninsula in Hokuriku district, Japan. Maximum acceleration more than 900cm/s^2 was observed in the near source area, and many houses were collapsed. Figure 1 shows location of the epicenter and centroid moment tensor (hereafter CMT) solution. Table 1 shows parameters of main-shock.

Several inverted source models have already been estimated from strong ground motion data (e.g. Asano and Iwata, 2008; Nozu, 2008). These results have several features in common such as relatively large slip exists near the hypocenter. In this study, we initially referred to these inverted results to determine the locations of the SMGAs which generate strong ground motion. Resultantly, as shown Figure 2, the first SMGA (SMGA1) is located near the hypocenter, the second SMGA (SMGA2) in the relatively shallow part of south-west direction and third SMGA (SMGA3) in the relatively shallow part of north-east direction.

We adjusted the locations, sizes and stress parameters of these sub-events to fit the simulated motions to the observed ones using a forward modeling approach. The dimensions of these SMGAs specifying basically the waveform have been determined by the number of divisions and the areas of the small event used as the empirical Green’s functions. The aftershock with Mw4.0 happened at 15:43 on March 25, 2007(JST) was selected as EGF. The epicenter and CMT solution shows in Figure 1. The CMT of the aftershock is similar to a mainshock.

Here, the number of divisions and the stress parameters specifies the levels of the synthetic high and low frequency ground motions. We searched the parameters to obtain a better fit of the envelope and high frequency level between synthetics and observed broad-band ground motions. We assume an S-wave velocity of 3.5km/s along the wave propagetion path and a rupture velocity of 2.5km/s on the fault plane. Furthermore, we assumed that the rupture should start from the center bottom inside SMGA1 and propagate radially. The rupture of SMGA2 and SMGA3 should restart after the rupture reaches that point respectively and propagate radially.

After several trials, we obtained the best fit source model shown in Figure 1 and Figure 2. The source parameters for each SMGA are summarized in Table 2. The synthesized motions at ISK003 and ISK005 are compared with the observed ones in Figure 3. Figure 4 shows the comparison between the synthetic and observed pseudo velocity spectra (PVRS) with damping factor of 0.05. ISK003 is located on the hard ground and ISK005 is located on the soft soil layers. From Figure3 and Figure 4, we can see that the synthetic at ISK003 is in good agreement with the observed one. On the other hand, we can point out easily that the synthetic acceleration and velocity ground motion at ISK005 is extremely overestimated compared with the observed one.

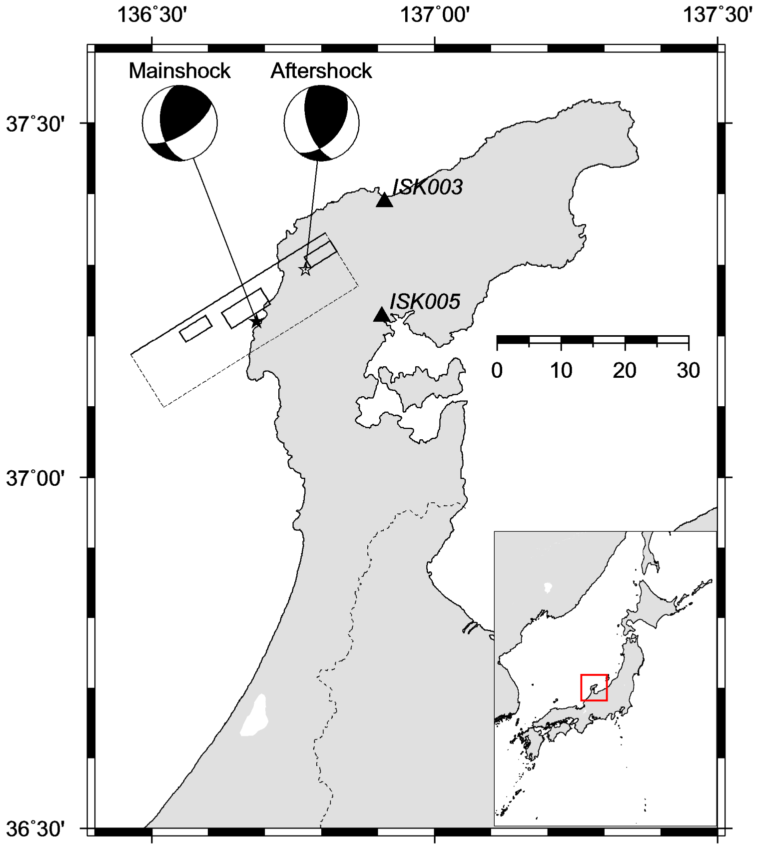


Figure 1. Location of the 2007 Noto-Hanto earthquake (Mw6.7), Japan and target site of strong ground motion simulation.

Table 1 Source parameters of 2007 Noto-Hanto earthquake

		Main-Shock	Small-event
Origin time	(JST)	2007/03/25 09:41:57.9	2007/03/25 15:43:30.5
Latitude	(deg.)	37.2200N	37.2933N
Longitude	(deg.)	136.6850E	136.7717E
Depth	(km)	11.0	9.0
Mw		6.7	4.0
Seismic moment	(Nm)	1.36×10^{19}	1.25×10^{15}
Strike/Dip/Rake	(deg.)	173/48/34	161/60/51
Stress drop	(MPa)	-	2.0
Area	(km^2)	-	1.44

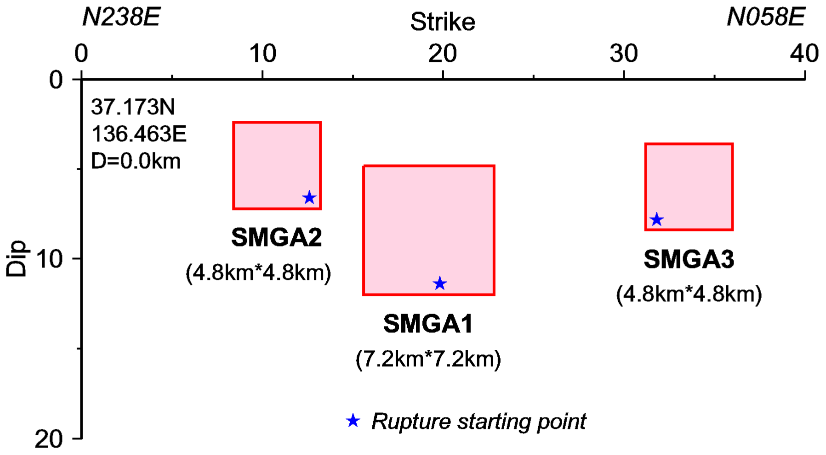
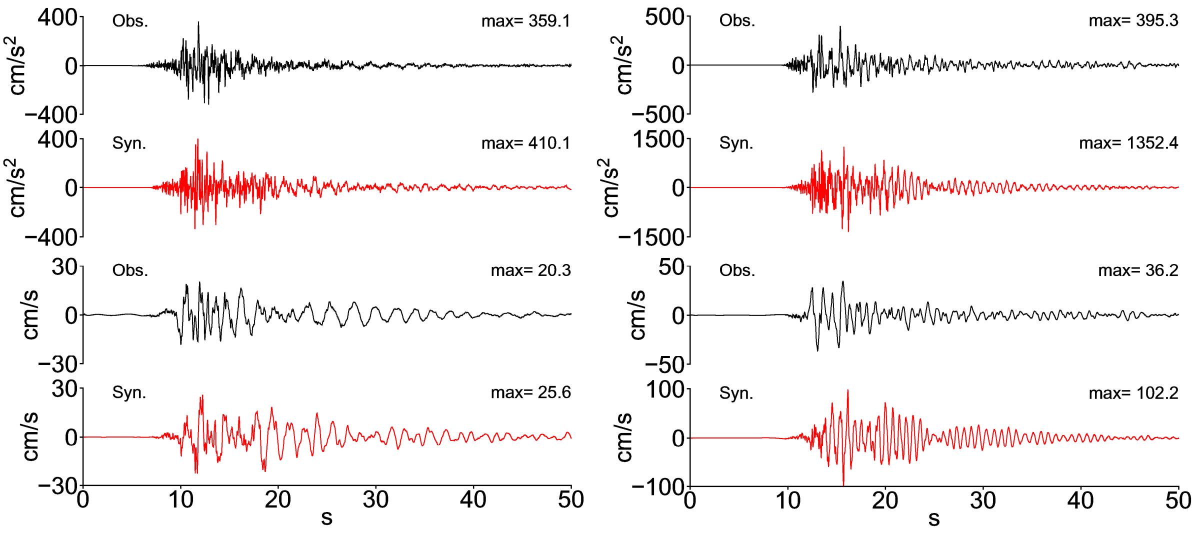


Figure 2. Source model of 2007 Noto-Hanto earthquake (Mw6.7) which consist of 3 strong motion generation areas (SMGA)

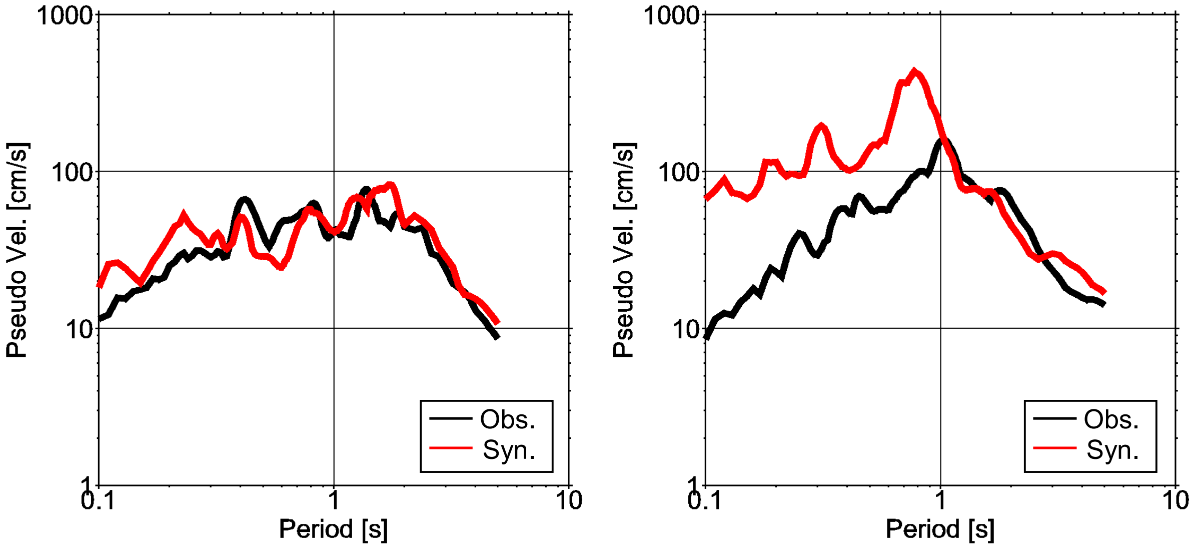
Table 2 Source parameters for each SMGA

	Seismic moment M_0 (Nm)	Area(km^2) (L (km) × W (km))	Stress drop $\Delta\sigma$ (MPa)	Rise time τ (s)
SMGA1	2.7×10^{18}	51.84 (7.2 × 7.2)	20.0	0.6
SMGA2	8.0×10^{17}	23.04 (4.8 × 4.8)	20.0	0.5
SMGA3	4.0×10^{17}	23.04 (4.8 × 4.8)	10.0	0.5



(a)ISK003 (b)ISK005

Figure 3. Comparison between the synthesized and observed motions at ISK003 and ISK005. Black line shows the observed waveform and red line shows the synthesized waveform.



(a)ISK003 (b)ISK005

Figure 4. Comparison of the pseudo velocity response spectra (PVRS) with damping factor of 0.05 of the synthesized motions and those of the observed motions at ISK003 and ISK005. Black line shows the PVRS of the observed motions and red line shows the PVRS of the synthesized motions.

THE 2005 WEST FUKUOKA PREFECTURE EARTHQUAKE (Mw6.5)

On 20th March 2005, West Fukuoka prefecture earthquake(Mw6.5) struck the Fukuoka prefecture in northern Kyushu district, Japan. In this earthquake, destructive strong ground motions showing the seismic intensity 6^{+} by the Japan Meteorological Agency have been recorded at strong motion observation stations in the near source area. Figure 5 shows location of the epicenter and CMT solution. The seismic fault plane is estimated left-lateral fault of the northwest-southeast direction. Table 3 shows parameters of mainshock.

Several inverted source models have already been estimated from strong ground motion data (e.g. Asano and Iwata, 2006; Sekiguchi et al., 2006). These results have several features in common such as relatively large slip exists south-east side of the hypocenter. We constructed best fit source model with as a same procedure of the 2005 Noto earthquakes. Figure 6 shows best fit source model of 2005 West Fukuoka prefecture earthquake. Relatively large single SMGA is placed in the south-east side of the hypocenter.

We selected aftershock of Mw4.4 as small-event used as EGF. CMT solution of aftershock indicate in Figure 5. The CMT solution of the aftershock is similar to a mainshock. Table 3 shows parameters of aftershock to use as EGF. We assume an S-wave velocity of 3.5km/s along the wave propagetion path and a rupture velocity of 2.5km/s on the fault plane. Furthermore, we assumed that the rupture should start from the bottom of the north west side corner inside SMGA and propagate radially.

After several trials, we obtained the best fit source model shown in Figure 5 and Figure 6. The source parameters for SMGA is summarized in Table 4. The synthesized motions at FKOH03 and FKO006 are compared with the observed ones in Figure 7. Figure 8 shows the comparison between the synthetic and observed PVRS with damping factor of 0.05. From Figure7 and Figure 8, we can see that the synthetic at FKOH03 on the hard ground, is in good agreement with the observed one. But, we can point out easily that the synthetic acceleration and velocity ground motion at FKO006 on the soft soil layers, is extremely overestimated compared with the observed one.

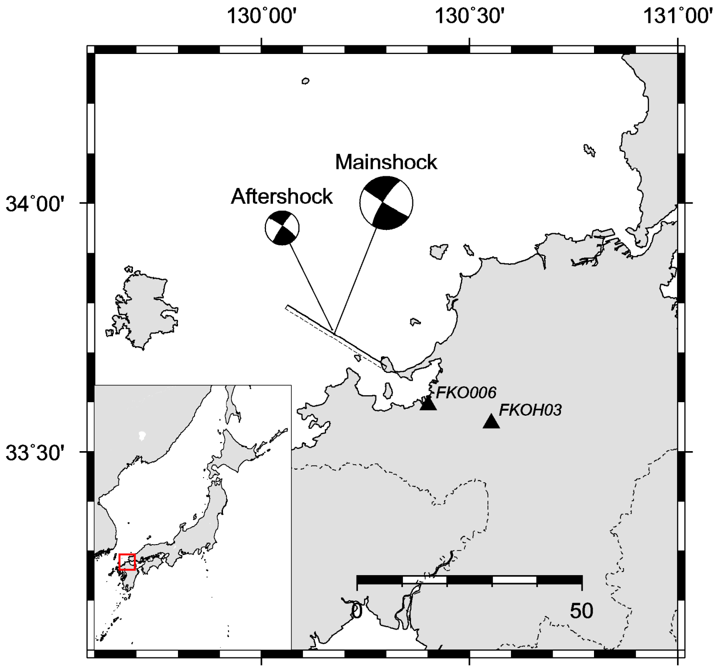


Figure 5. Location of the 2005 West Fukuoka prefecture earthquake (Mw6.5), Japan and target site of strong ground motion simulation.

Table 3 Source parameters of the 2005 West Fukuoka prefecture earthquake

		Main-Shock	Small-event
Origin time	(JST)	2005/03/20 10:53:40.3	2005/03/20 20:38:16.4
Latitude	(deg.)	37.7383N	37.7450N
Longitude	(deg.)	130.1750E	130.1700E
Depth	(km)	9.0	11.0
Mw		6.5	4.4
Seismic moment	(Nm)	7.8×10^{18}	5.6×10^{15}
Strike/Dip/Rake	(deg.)	122/87/-11	111/83/-5
Stress drop	(MPa)	-	1.66
Area	(km^2)	-	4.0

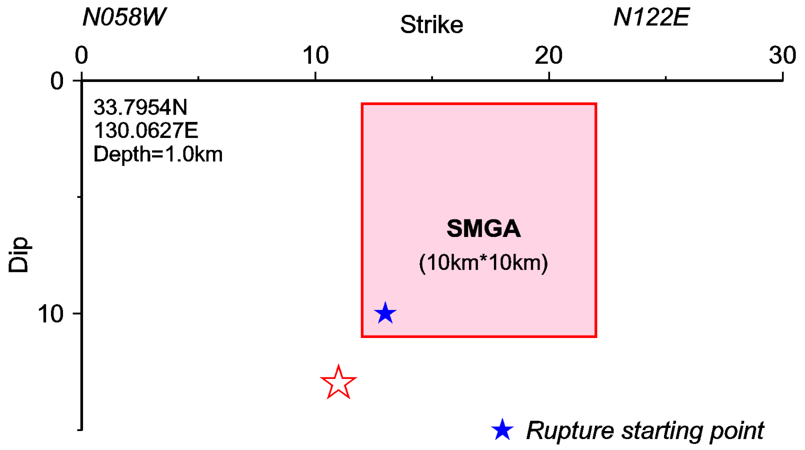
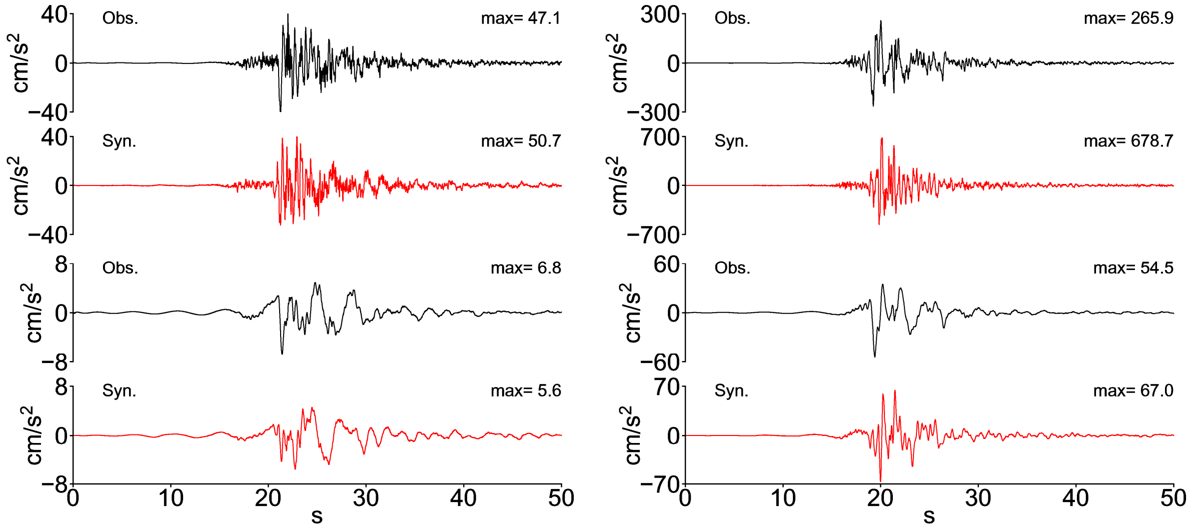


Figure 6. Source model of 2005 West Fukuoka prefecture earthquake (Mw6.5), which consist of 1 relatively large strong motion generation area (SMGA)

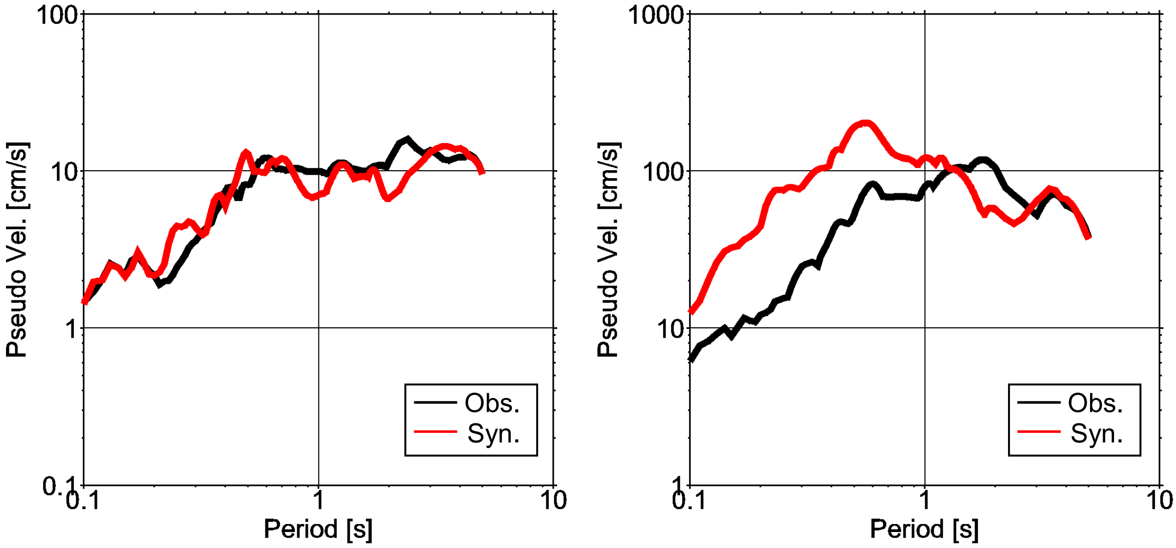
Table 4 Source parameters for SMGA

	Seismic moment M_0 (Nm)	Area(km^2) (L (km) × W (km))	Stress drop $\Delta\sigma$ (MPa)	Rise time τ (s)
SMGA	2.17×10^{18}	100.0 (10.0 × 10.0)	13.3	0.6



(a)FKOH03 (b)FKO006

Figure 7. Comparison between the synthesized and observed motions at FKOH03 and FKO006. Black line shows the observed waveform and red line shows the synthesized waveform.



(a)FKOH03 (b)FKO006

Figure 8. Comparison of the pseudo velocity response spectra (PVRS) with damping factor of 0.05 of the synthesized motions and those of the observed motions at FKOH03 and FKO006. Black line shows the PVRS of the observed motions and red line shows the PVRS of the synthesized motions.

STRONG GROUND MOTION PREDICTION REFLECTING NONLINEAR SITE EFFECT

The reflection of the nonlinearity of the ground is carried out in the following procedures again. First of all, we construct the ground model for the surface layer that is shallower than engineering base based on soil investigation results. Next, we calculated motion on the engineering base from small ground motion observed on the surface using as EGF by deconvolution analysis. We synthesised strong motion on the engineering base by EGFM. Finally we obtained strong ground motion of the surface reflecting non-linear site effect by non-linear total stress dynamic response analysis. Modified RO model (Tatsuoka and Fukushima, 1978) was applied to the non-linear relationship between the shear stress and shear strain of the non-linear total stress dynamic response analysis.

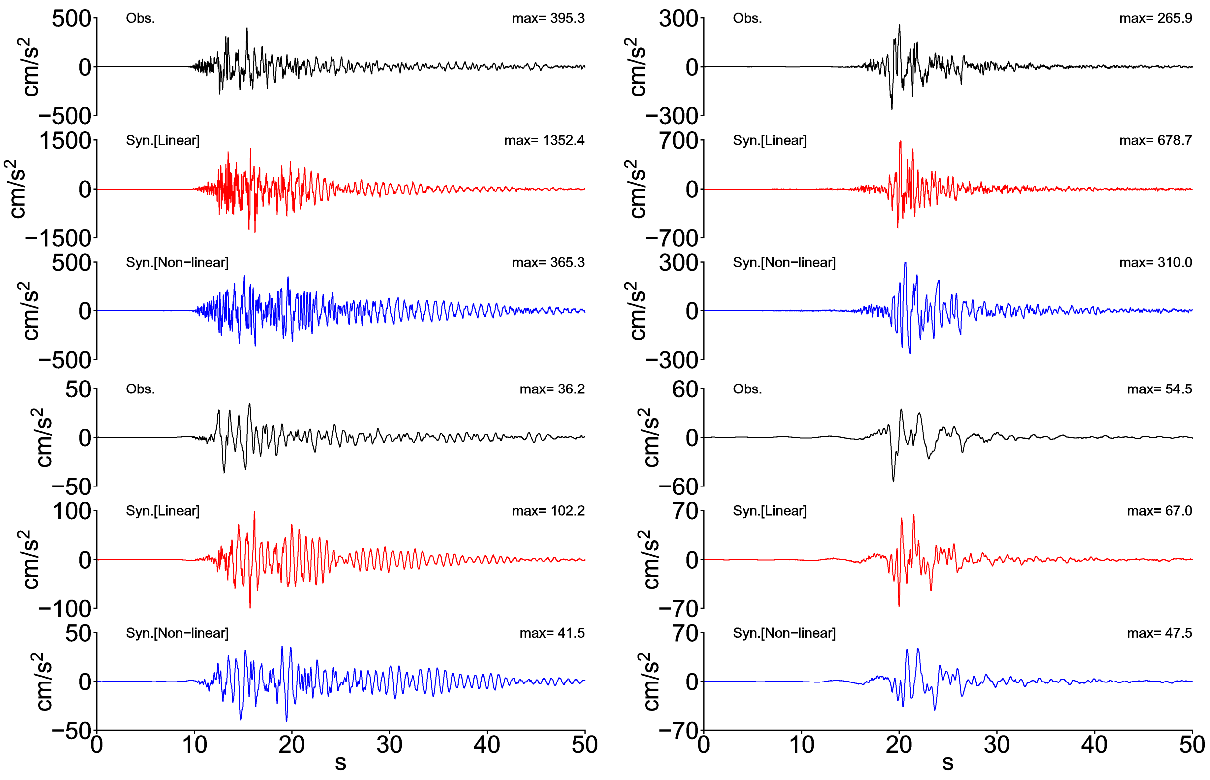
We performed non-linear simulation of ISK005 and FKO006 by proposed method. Table 5(a) and Table 5(b) shows soil parameters needed in non-linear simulations of ISK005 and FKO006. Figure 9(a) and Figure 9(b) shows the results of the nonlinear simulation are composed with the observed acceleration and velocity motions at ISK005 and FKO006 respectively. Acceleration waveform and velocity waveform of both ISK005 and FKO006 are greatly improved by considering the nonlinearity of the sedimentary soils. The overestimated amplitude of simulated ground motions became at the same level as an observed ones. Figure 10(a) and Figure 10(b) shows PVRS of analysis results. You can see that the discrepancy between the synthetic pseudo velocity response spectra and the observed ones are improved by considering the nonlinearity of the sedimentary soils.

Table 5(a) Soil parameters for nonlinear dynamic response analysis of ISK005

No.	Soil type	Thickness (m)	Density (t/m^3)	Vs (m/s)	Modified RO model	
					$\gamma_{0.5}$	h_{max}
1	Cohesive soil	2.0	1.45	120	1.00×10^{-3}	0.20
2	Highly organic soil	7.0	1.50	60	4.59×10^{-3}	0.21
3	Silt	3.0	1.50	130	4.59×10^{-3}	0.21
4	Sandy soil	4.0	1.75	130	1.00×10^{-3}	0.20
5	Rock	3.0	1.90	290	1.00×10^{-3}	0.20
Base	Rock	-	2.10	400	-	-

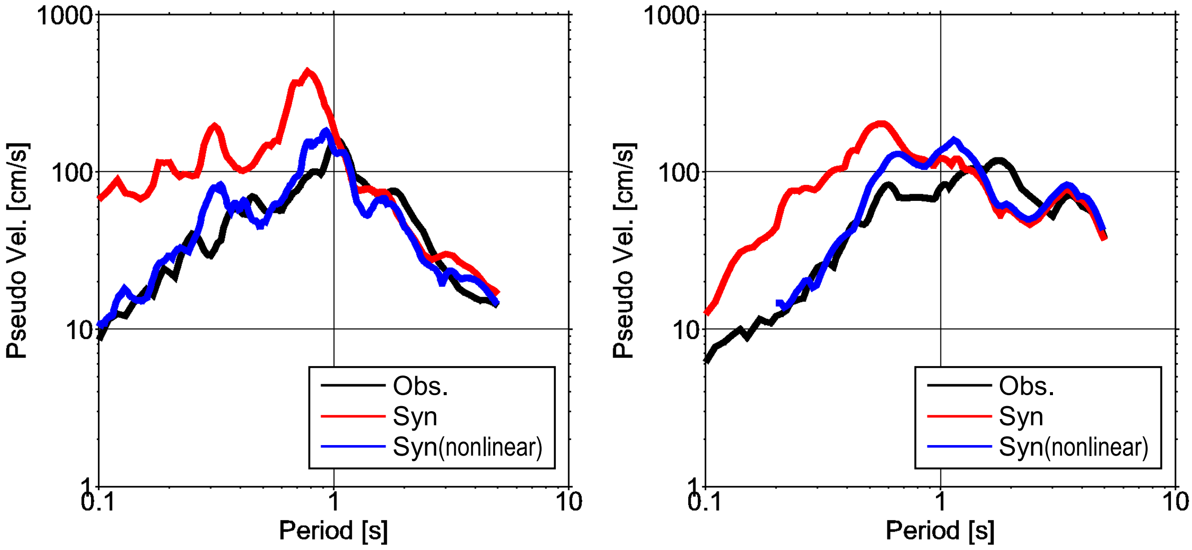
Table 5(b) Soil parameters for nonlinear dynamic response analysis of FKO006

No.	Soil type	Thickness (m)	Density (t/m^3)	Vs (m/s)	Modified RO model	
					$\gamma_{0.5}$	h_{max}
1	Cohesive soil	2.0	1.75	110	4.34×10^{-4}	0.28
2	Cohesive soil	1.2	1.75	130	4.34×10^{-4}	0.28
3	Silt	1.0	1.70	130	1.06×10^{-3}	0.25
4	Sandy soil	2.3	1.85	130	4.34×10^{-4}	0.28
5	Sandy soil	2.0	1.80	130	4.34×10^{-4}	0.28
6	Silt	3.0	1.70	150	1.06×10^{-3}	0.25
7	Sandy soil	3.5	1.95	180	4.34×10^{-4}	0.28
8	Gravel	10.0	1.95	320	4.34×10^{-4}	0.28
Base	Rock	-	2.20	1,000	-	-



(a)ISK005 (b)FKO006

Figure 9. Comparison between the synthesized and observed motions at ISK5 and FKO006. Black line shows the observed waveform and red line shows the synthesized waveform. And blue line shows the synthesized waveform by nonlinear simulation.



(a)ISK005 (b)FKO006

Figure 10. Comparison of the pseudo velocity response spectra (PVRS) with damping factor of 0.05 of the synthesized motions and those of the observed motions at ISK005 and FKO006. Black line shows the PVRS of the observed motions and red line shows the PVRS of the synthesized motions. And blue line shows the PVRS of the synthesized motion by nonlinear simulation.

CONCLUSIONS

EGFM is one of the most appropriate method for predicting the strong ground motion at near source area. But this method overestimates strong ground motions on the soft soil layers sites because it could not consider a nonlinearity of the surface layer. So we attempted expansion of EGFM to be applicable to the soft soil layers sites. Specifically, we have proposed a procedure of combining the EGFM and nonlinear dynamic response analysis. We applied proposed method to the past earthquakes and verified applicability. As a result, the effectiveness of the proposed method was confirmed. It will be necessary to increase verification examples, and to validate the effectiveness of the proposed method in future.

ACKNOWLEDGMENTS

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