Simulation of Strong Ground Motions for M9 Megathrust Earthquake using Modified Empirical Green's Functions as M7 Class earthquake records

H. J. Si[1], K. Irikura[2]

[1]Seismological Research Institute Inc., Tokyo, Japan

[2]Aichi Institute of Technology, Aichi, Japan

E-mail contact of main author: shj@seismo-r.com

Abstract. We proposed a modified empirical Green's function method to simulate ground motions from a target earthquake using the records of an empirical Green's function (eGf) event whose size is not small enough compared with the expected subfaults of the target earthquake. The target earthquake is a megathrust earthquake with Mw 9. To simulate broadband ground motions from such a great event, the records of an M_w 7 event is very useful because the records have high resolution at long-periods of 2 to 20 s as well as at short-periods of 0.02 to 2 s. The source area of the target event is divided into subfaults whose size is the same as the eGf event. The ground motions from those subfaults are summed coherently at periods longer than a certain period (Ts), i.e. a corner period, and incoherently summed at periods less than the T_s. There is one problem that the M_w 7 has too wide source-area to use its record as the eGf. Then, we modify the ground motions of the eGf event to have the spectral characteristics of a smaller event (e.g. M_w 5 event) with a corner period compatible with the T_s in the conventional empirical Green's function method. We call them the modified empirical Green's functions, noted as meGf. The proposed method is verified by simulating strong ground motions from the 2005 M_w 7.2 Miyagi-ken-oki earthquake. Finally, we applied the method to simulate the strong motion from the 2011 M_w 9.1 Tohoku earthquake. The results show that the synthetic ground motions match well the observed ones. We need to confirm the rupture process of the M_w 7.2 event by synthesizing its ground motions using the records of some smaller events (e.g. M_w 5 event) as the eGfs.

Key Words: Empirical Green's function method, eGf, meGf, Modified empirical Green's function method.

1. Introduction

The empirical Green's function method (eGFM) is one of the well-used methods for the simulation of strong ground motion from an earthquake [1], and has been improved and verified in the past studies since the method was proposed [2-4]. However, the eGFM have a critical limitation on its application. That is, the method can only be applied when some adequate earthquake records are available to be used as the empirical Green's functions (eGf). In fact, in many cases, the lack of such eGf leads to failure of using the empirical Green's function method. This is because of that the application of the traditional empirical Green's function method has been done as follows. The source fault of a scenario earthquake (large event) to be simulated is divided into subfaults, each of which is the fault area of the natural eGf event. Ground motions from the scenario earthquake are successfully simulated with delay and sum of the eGf, showing forward or backward rupture directivity. However, if the fault area of the natural eGf event is not small enough compared with the subfault of the scenario earthquake, the ground motions are not well simulated.

In this study, we proposed a method to make the application of eGFM possible when only the records from an earthquake with a fault area larger than the expected fault area of the subfaults (relatively large event) is available. In the proposed method, such records are modified to fit the expected fault area so that it can be used as an eGf.

2. Method

The eGf method has been developed for the simulation of ground motions from the source fault of a large event using observed records of small events. The source fault is divided into N x N subfaults, the areas of which are taken to be equal to the fault area of the small event. The ground motions from the large event are expressed as a superposition of the records of small events as follows:

$$U(t) = C\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{r}{r_{ij}}F(t - t_{ij}) * u(t) \qquad (1)$$

Where

$$t_{ij} = \frac{r_{ij} - r_0}{\beta} + \frac{\xi_{ij}}{V_R} \qquad (2)$$

$$F(t) = \delta(t) + \frac{1}{n'}\sum_{k=1}^{(N-1)n'} \delta\left[t - (k-1)\frac{\pi}{(N-1)n'}\right] \qquad (3)$$

and U(t) and u(t) are the ground motion for the large event and the observed record of the small event used as the eGf, respectively. The terms r, r_{ij}, and r0 are the respective distances from the site to the hypocenter of the small event, from the site to the (i , j) subfault, and from the site to the starting point of rupture on the fault plane of the large event. The term ξ_{ij} is the distance between the starting point and (i,j) subfault, β is the shear wave velocity, V_r is the rupture velocity, τ is the rise time or slip duration of the large event, and n' is an arbitrary integer number to shift the artificial periodicity to a frequency higher than that of interest. This eGf method was described by Kamae and Irikura (1998) in detail.

Here, generally the Fourier spectra of observed recording *O(f)* can be represented by the multiplication of source spectrum *S(f)*, path effect *P(f)*, and site effect *G(f)*, that is, *O(f)*= *S(f) P(f) G(f)*. Based on this equation, we can modify $O_L(f)$, a recording derived during an earthquake with relative larger source area (refer to as eGf event) to be that for an earthquake with an appropriate source area so it can be used as a Green's function (refer to as the modified Green's function, meGf, noted as $O_G(f)$), by substituting the source spectrum of the eGf event $S_L(f)$ by that of the meGf earthquake $S_G(f)$, as shown in Eq. (4). Here, we assume that the path effects and site effects are similar for both the meGf earthquake and the eGf event, and both the eGf event and meGf event follow the omega square model. Then the equation (1) can be modified to Eq. (5). Eq. (4) and (5) are the basic equations for the modified empirical Green's function method.

$$O_G(f) = O_L(f) S_G(f) / S_L(f) \qquad (4)$$

$$U(t) = C\sum_{i=1}^{N}\sum_{j=1}^{N}\frac{r}{r_{ij}}F(t - t_{ij}) * O_G(t) \qquad (5)$$

The method can be implemented in the following procedures.

(1) We model the source spectra for the eGf event ($S_L(f)$), and the meGf event fits the subfaults of the scenario earthquake to be simulated ($S_G(f)$), and calculate the ratio of $R_{G/L}(f)$= $S_G(f)$/ $S_L(f)$. Both the source spectra are estimated based on the omega square model (Boore, 1983).

(2) We calculate the Fourier spectra of the recordings of the eGf event, that is, the earthquake with larger source area. The Fourier spectra is multiplied by the ratio of $R_{G/L}(f)$ to derive the Fourier spectra for meGf following Eq.(4). The derived Fourier spectra is transferred to time domain to derive meGf, that is, the waveform of the target earthquake. The meGf means the modified empirical Green's function.

(3) We use the meGf to simulate ground motion from the scenario earthquake based on the procedure of the traditional eGf method [e.g., 2-3] but with following changes. That is, in order to cancel the influence due to the longer rise time of the eGf event, the rise times are shorten to some extent in the simulation based on the numerical experiments.

The proposed method is illustrated in Fig.1.

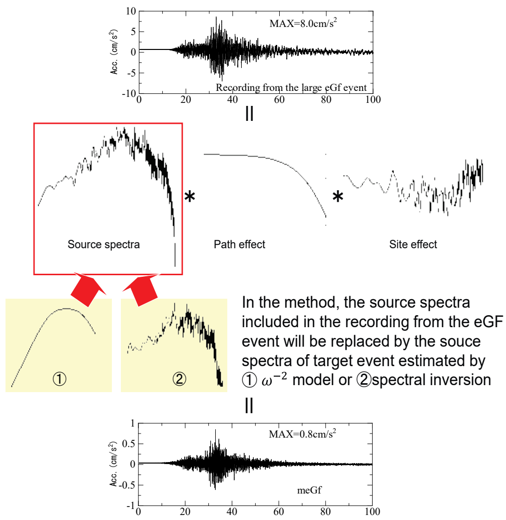

FIG. 1. Illustration of the concept of the modified empirical Green's function. There are two methods to replace the source spectra included in the recordings. In this study, we only suggest the method of using ω^{-2} *models since it's easy to implement the method.*

3. Validation of the proposed method

In this Chapter, we applied the meGf method to reproduce the seismic records observed during the 2005 Miyagi-ken oki earthquake. Here, we use the 2005 Miyagi-ken oki earthquake itself as the eGf event.

Fig. 2 shows the location of the SMGAs for the 2005 M_w7.2 Miyagi-ken oki earthquakes proposed by Suzuki and Iwata (2007)[5], and the epicentres of the meGf event used in this study. The eGf event used in this study is the latter part of the recordings of the 2005 M_w7.2 Miyagi-ken oki earthquake shown in Fig.3, which are generated from the second SMGA. The main parameters of the 2005 Miyagi-ken oki earthquake and the numbers of summations are shown in Table 1-2. The stress drops of the meGf event (M_w4.0 with focal depth of about 45 km) is estimated to be 6.2 MPa. The simulation is carried out for the KiK-net station of MYGH11 and MYGH12, as shown in Table 2.

The source spectra for the second SMGA of eGf event and the meGf event are estimated based on the omega square model [6]. The waveforms of the recording from the eGf event and the derived meGf are also shown in Fig.3.

The comparison of the results of the simulation with the observation at MYGH11 and MYGH12 are shown in Fig.3. The figures show that the response spectra of simulation fits the observation data well, implying that the method proposed in this study is valid.

Table 1. Parameters for SMGAs of the 2005 Off Miyagi-ken earthquake (after Suzuki and Iwata, 2007)

	S (km^2)	M_0 (N m)	$\Delta\sigma$ (MPa)	τ (s)	T_0 (s)
SMGA1	9.6×9.6	6.39×10^{18}	17.6	0.33	4.3
SMGA2	7.2×7.2	5.23×10^{18}	34.1	0.27	11.3

Table 2. Number of summations

	M_0(Nm)	σ (MPa)	NL	NW	NT	NL × NW × NT
SMGA1	6.39E+18	17.6	12	12	11	1584
SMGA2	5.23E+18	34.1	9	9	8	648

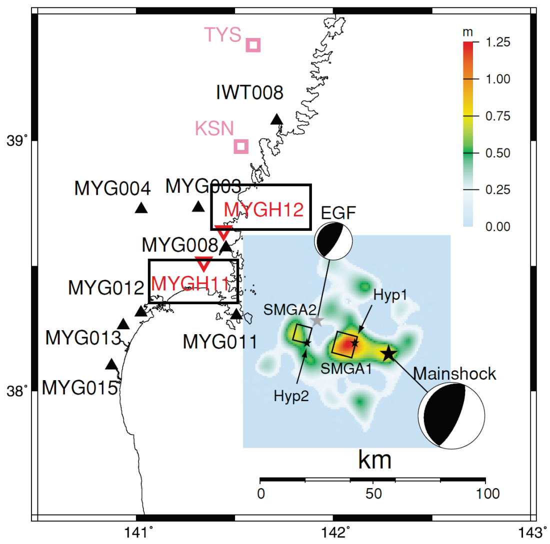

FIG. 2. Location of SMGAs for the 2005 M_w7.2 Miyagi-ken oki earthquake proposed by Suzuki and Iwata. (2007), shown as black rectangular. Grey star shows the epicenters of the meGf event (Mw4.0) used in this study. Black stars show the epicenter, and rupture starting point for SMGAs of the 2005 Mw7.2 Miyagi-ken oki earthquake. Red rectangular show the observation station used in the simulation. (after Suzuki and Iwata, 2007)

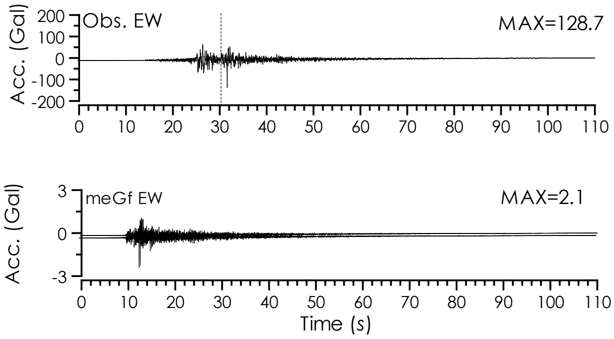

FIG. 3. Upper: the waveform recorded at MYGH12. The last part of the waveform are adopted to estimate meGf (from the broken line). Lower: waveform of meGf at MYGH12 (M_w4.0).

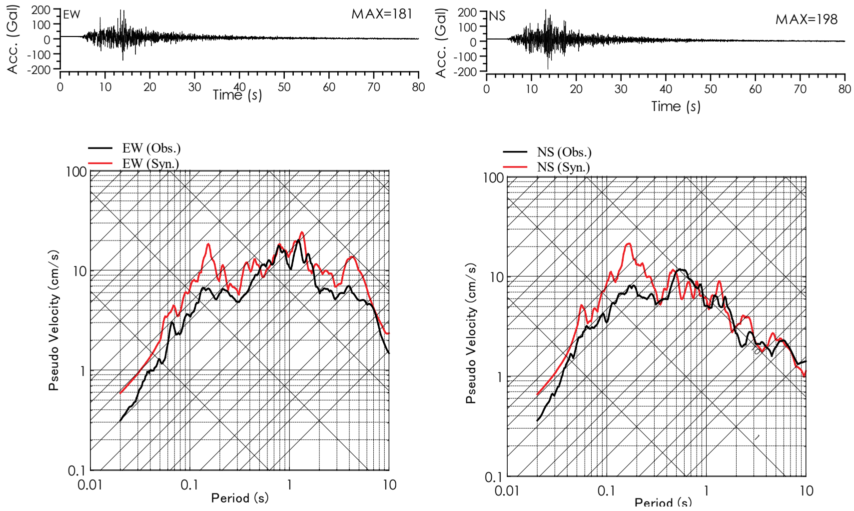

FIG. 4. Synthetic waveforms (upper panels) and Pseudo velocity response spectra (red lines in lower panels) at MYGH11. The black lines show the Pseudo velocity response spectra observed at MYGH11.

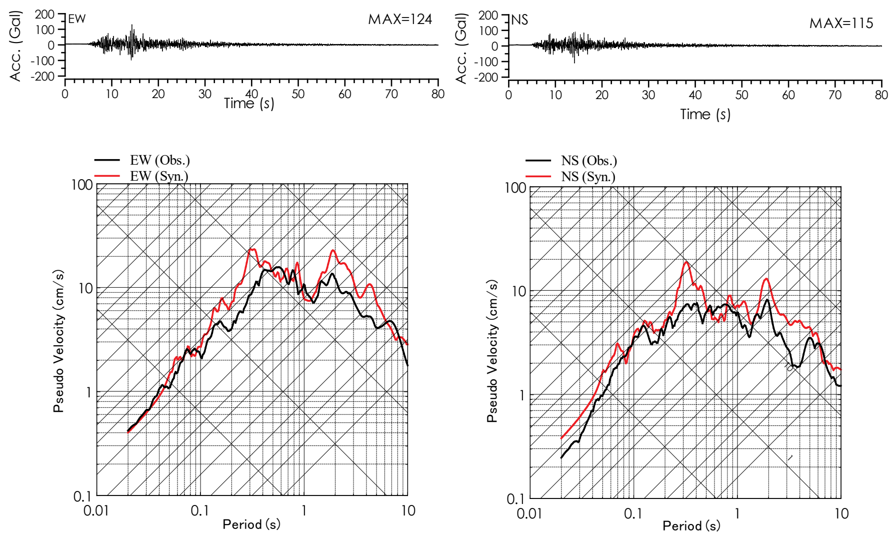

FIG. 5. Synthetic waveforms (upper panels) and Pseudo velocity response spectra (red lines in lower panels) at MYGH12. The black lines show the Pseudo velocity response spectra observed at MYGH12.

4. Simulation of strong ground motion from the Mw9.1 Tohoku earthquake

In this Chapter, we applied the method to simulate the strong motion records recorded during the 2011M_w 9.1 Tohoku earthquakes using the SMGA models by Kawabe and Kamae (2013)[7]. Location of SGMAs and observation stations used in the simulation of strong ground motion are shown in Fig. 6. The eGf event is the same in Chapter 3, that is, the 2005 M_w7.2 Miyagi-ken oki earthquake (See Fig.2 for details). The main parameters of the Mw6.3 meGf earthquake are shown in Table 4.

The method for the estimation of meGf is the same in Chapter 3. The waveforms of the recording from the eGf event and the derived meGf are also shown in Fig.7.

The comparison of the results of the simulation with the observation at MYGH04 and MYGH12 are shown in Fig.8 and 9, respectively. For the results for MYGH04, components longer than 3.3s are eliminated to avoid the influence by noise. The figures show that the response spectra of simulation fits the observation data well.

Table 4. Parameters for the meGf event, the 2002 M_w6.3 earthquake

Mo (N・m)	Stress Drop (MPa)	Density (g/cm^3)	V_s (km/s)	f_{max} (Hz)	Focal Depth (km)
3.87E+18	12.0	2.8	3.8	8.3	44

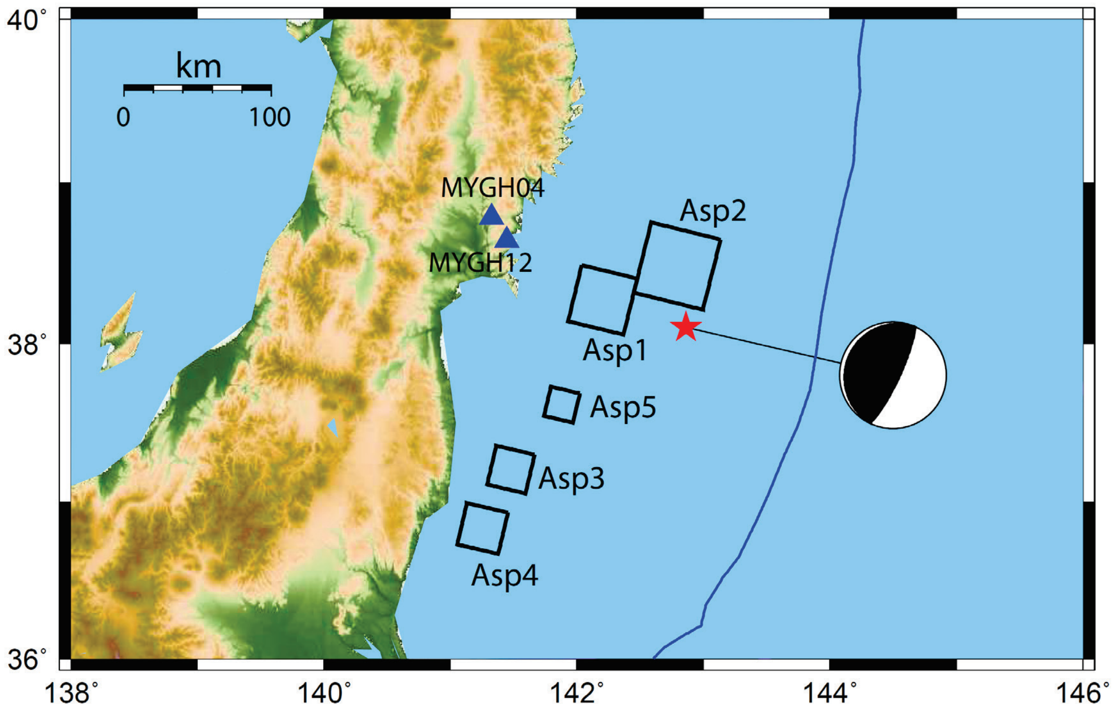

FIG. 6. Location of SMGAs for the Tohoku earthquake proposed by Kawabe and Kamae (2013) is shown as black rectangular. Red star shows the epicenter of the mainshock. Blue triangles show the observation station used in the simulation.

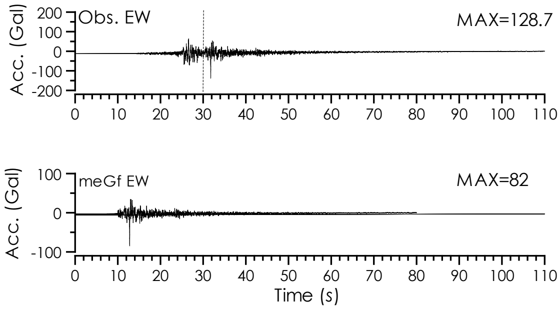

FIG. 7. Upper: the waveform recorded at MYGH12. The last part of the waveform is adopted to estimate meGf (from the broken line). Lower: modified waveform as meGf at MYGH12(M_w6.3).

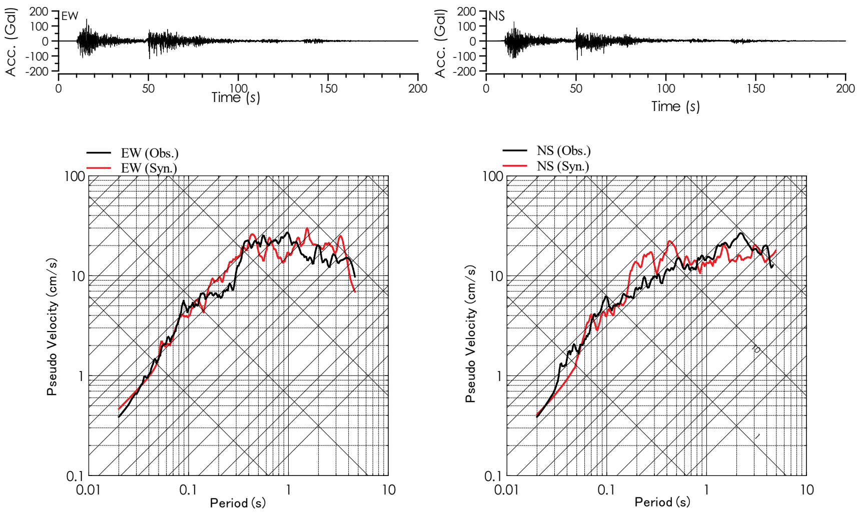

FIG. 8. Synthetic waveforms (upper panels) and Pseudo velocity response spectra (red lines in lower panels) for the M9.1 mainshock at MYGH04. The black lines show the Pseudo velocity response spectra observed at MYGH04.

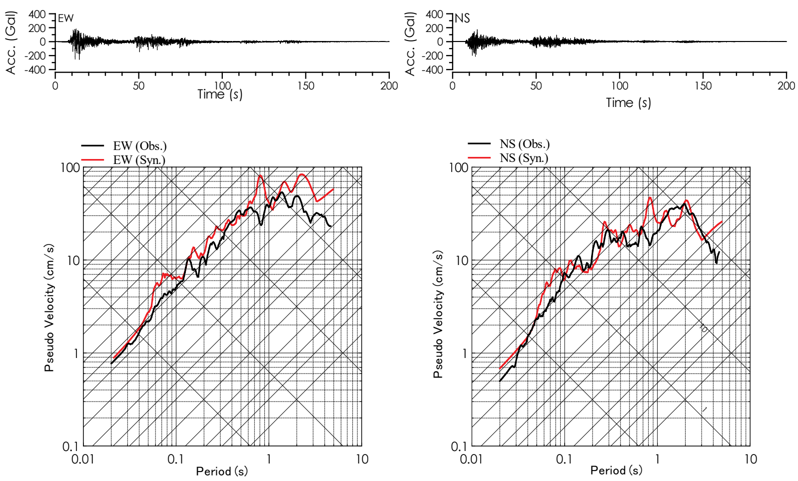

FIG. 9. Synthetic waveforms (upper panels) and Pseudo velocity response spectra (red lines in lower panels) for the M9.1 mainshock at MYGH12. The black lines show the Pseudo velocity response spectra observed at MYGH12.

5. Conclusions

We proposed a modified empirical Green's function method to simulate ground motions from a scenario earthquake using the records of an empirical Green's function (eGf) event whose size is not small enough compared with the expected subfaults of the target earthquake. In the method, the spectral characteristics of the records of the eGf event is modified to have the corner period T_s which coincides with an appropriate subfault size for simulating the ground motions of the target earthquake. We call them the modified empirical Green's functions, noted as meGf. The proposed method is applied to simulate strong ground motions from the 2005 M_w 7.2 Miyagi-ken-oki earthquake and the 2011 M_w 9.1 Tohoku earthquake. The results show that the synthetic ground motions match well the observed ones. However, we still need to confirm the rupture process of the M_w 7.2 event by synthesizing its ground motions using the records of some smaller events (e.g. M_w 5 event) as the eGfs.

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7. References

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