INTERNATIONAL SYMPOSIUM ON DAMS FOR A CHANGING WORLD
-Need for Knowledge Transfer across the Generations & the World
Kyoto, Japan June 5, 2012

Reproduction of Seismic Waveforms of the 2011 Off the Pacific Coast of Tohoku Earthquake at a Dam Site Using the Empirical Green's Function Method

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ABSTRACT:
Dam sites located in the Tohoku area have seismic records associated with the 2011 off the Pacific coast of Tohoku Earthquake and its aftershocks. Seismic waveforms of the main shock recorded at the base of a dam site were reproduced using waveforms of a small event based on the empirical Green's function method. The rupture area of this earthquake covers several hundred of kilometres and characterised source models which have plural strong-motion-generation-areas (SMGAs) have been proposed. The comparison of the observed and synthetic waves made it clear that nearly simultaneous arrivals of waves from SMGAs at off-shore Fukushima prefecture and off-shore Ibaraki prefecture contributed to the maximum acceleration value at the target dam site.

Keywords: empirical Green's function method, the 2011 off the Pacific coast of Tohoku Earthquake, aftershock, dam site

1. INTRODUCTION

Dam sites located in Tohoku area have recorded many seismic waveforms of the 2011 off the Pacific coast of Tohoku Earthquake, Japan, which occurred on March 11, 2011 (main shock, M_w 9.0) and its aftershocks. Several kinds of rupture processes of the main shock have been proposed using teleseismic waveforms (e.g., Ide *et al.*, 2011, Ammon *et al.*, 2011) or strong motions (e.g., Furumura *et al*., 2011, Kurahashi and Irikura, 2011). It is common that every rupture model shows complex rupture propagation though the results vary from the focused frequencies or the analysis methods. In this study, the relationship between the recorded waveforms and the rupture processes was investigated, by reproducing the waveforms of the main shock. The empirical Green's function (EGF) method (Irikura, 1986) was used for reproduction.

The EGF method is a technique to synthesize seismic records of a large event using the recorded data at small events as Green's functions. After the second proposal of Japan Society of Civil Engineering (JSCE), following the Southern Hyogo prefecture earthquake in 1995, simulation of earthquake ground motions using the Green's function approach for a potential rupturing fault, has been included in one of the seismic resistant design codes (JSCE, 1996). Since the EGF method mainly depends on and uses small ground motion histories, small events selected as Green's functions are necessary to share the same path and radiation characteristics with the target event. Seismic waveforms recorded at the base of dam sites are suitable for this analysis, where seismic motion is less affected by sedimentary layers.

The authors reproduced the waveform of the main shock by the EGF method using a waveform of a small event as the Green's function. The influence rate of rupture processes to the waveforms was discussed, comparing the synthesized data and the recorded waveform.

2. WAVEFORM REPRODUCTION OF THE MAIN SHOCK

The target dam site is located in the Tohoku area, and the location is marked by a filled triangle in Fig. 1. This dam is a rock-fill dam. Seismographs are installed at the tops and the base of the dam. This site has recorded seismic waves of the main shock and its aftershocks. Seismic waveforms of horizontal upstream-downstream (orthogonal to the enclosing bund) component recorded at the base of the dam site were used in this study.

To simulate strong motions using EGF method, the characterized source model and the EGFs are needed. The characterized source model was constructed using Kurahashi and Irikura (2011) model, which consists of five strong-motion-generation-areas (SMGAs).

Table 1. The source parameters of the main shock and the small event.

	Origin time	Latitude (deg)	Longitude (deg)	Depth (km)	M_W	Strike (deg)	Dip (deg)	Rake (deg)	M_0 (N m)	Corner frequency (Hz)	Stress drop (MPa)	Area (km²)
Main shock	2011/03/11 14:46:18.12	38.103	142.861	23.7	9.0	24/193	81/10	92/79				
Small event	2010/03/14 17:08:04.18	37.724	141.818	39.8	6.5	20/199	69/21	91/89	6.83E+18	0.25	21.2	84.6

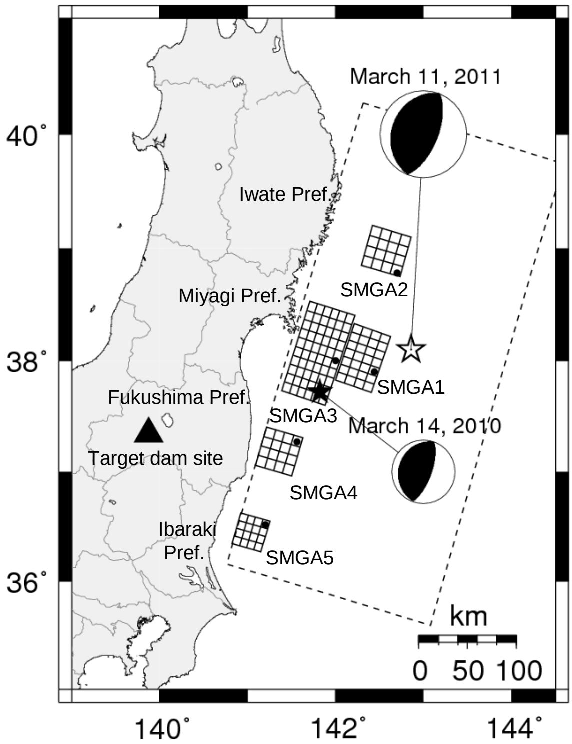

Figure 1. The location of the target dam site (filled triangle), the fault zone (large dashed rectangle) and characterized source model consisting of five SMGAs in the falult zone (small solid rectangles). The open star and the closed star show the epicentres of the main shock and the small event which was selected as the Green's function, respectively. The small rectangles and the closed circles inside them show the SMGAs and their initiation points.

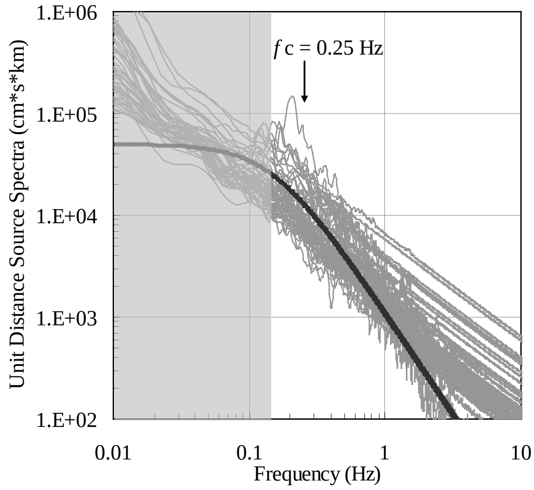

Figure 2. Displacement spectra estimated from bore-hole motion records at KiK-net stations on rock from the small event used as the EGF. The shadow area at low frequencies lower than 0.15 Hz shows unreliable frequency range that was not used for the simulation.

2.1. Selection of the EGF

The small events' records used as EGFs have to share the propagation path and site effects as well as the radiation characteristic from the source. The small event record on March 14, 2010 (M_W 6.5) was commonly selected as the EGF for each SMGA. The source parameters of the main shock and the small event reported by the Japan Meteorological Agency (JMA) and the CMT solutions reported by F-net (Okada *et al*., 2004) are shown in Table 1. The corner frequency of the small event was estimated using bore-hole motion records of KiK-net (Aoi *et al*., 2000) as shown in Fig. 2. The stress drop of the small event was calculated from the corner frequency and seismic moment relation (Boore, 1983). The fault area of the small event was obtained by the circular crack model by Brune (1970, 1971). In this study, the observed records used as the EGFs were band-pass-filtered from 0.15 Hz to 10 Hz, considering the reliable frequency range of the observed records.

2.2. Characterized Source Model and Ground Motion Simulation

The characterized source model was constructed using Kurahashi and Irikura (2011) model, slightly modifying the source parameters for our EGF. The source parameters of each SMGA, such as the length, width, seismic moment, stress drop and delay time from the origin time of each SMGA are listed in Table 2. To calculate ground motions from each SMGA, the area of the SMGA was divided into equally-sized square sub faults, the area of which was set to be the same as the small event area as shown in Fig. 1. SMGA 1 and SMGA 3 are located off-shore Miyagi prefecture. SMGA 2, SMGA 4 and SMGA 5 are located off-shore Iwate prefecture, Fukushima prefecture and Ibaraki prefecture, respectively.

The rise times inside each SMGA were given by the empirical relations by Kataoka *et al*. (2003). The average S wave velocity and the rupture velocity were given to be 3.5 km/s and 2.8 km/s, respectively. The Q_S value for plate boundary earthquakes in Eastern Japan area, which

Table 2. The source parameters of each SMGA. These parameters were constructed using Kurahashi and Irikura (2011) model, modifying for our EGF.

	SMGA 1	SMGA 2	SMGA 3	SMGA 4	SMGA 5
L (km)	64.4	36.8	92.0	36.8	36.8
W (km)	36.8	36.8	55.2	36.8	36.8
$N_L \times N_W \times N_D$	7×4×12	4×4×7	10×6×11	4×4×4	4×4×3
M_0 (N m)	2.29E+21	7.65E+20	4.51E+21	4.37E+20	3.28E+20
Stress drop (MPa)	40.3	23.3	29.7	16.3	25.4
Delay time from origin time (sec)	15.64	66.42	68.41	109.71	118.17
Rise time (sec)	3.3	3.3	4.9	3.3	3.3

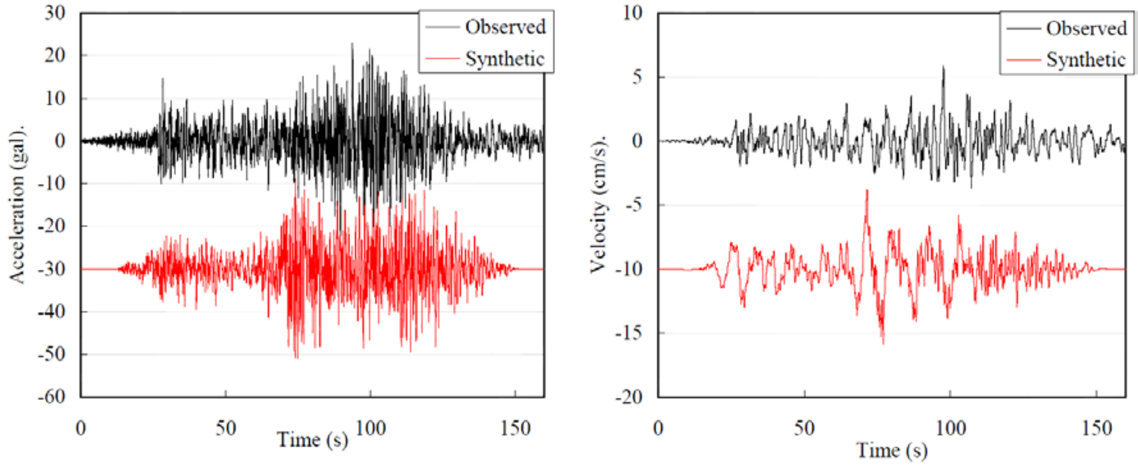

Figure 3. Comparison of the observed (upper black traces) and synthetic (lower red traces) seismographs by the EGF method at the dam site. The acceleration (left) and velocity (right) are composed.

was proposed by Kawase and Matsuo (2004), was used as the propagation property at this area; $Q_S = 93 f^{0.89}$. Here f is frequency (Hz).

3. DISCUSSION

The observed and synthetic waveforms at the dam site are shown in Fig. 3 and their Fourier spectra are shown in Fig. 4. Comparing the synthetic waveform with the observed, the shape of the recorded waveform was roughly explained by the synthetic using five SMGAs. The synthetic Fourier spectrum recreated the observed spectrum except for the peak of around 0.35 Hz. The synthetic spectrum was well consistent with the observed especially in the range of frequency higher than 1 Hz. The synthetic has smaller amplitude for lower frequencies compared to the observed. One EGF was commonly used for every SMGA in our calculation. A single EGF may not be a representative function for the whole fault zone, because the fault size of the main shock was large. Preparing individual EGFs for each SMGAs could recreate the amplitude at low frequencies.

The waveforms synthesized from individual SMGAs were shown in Fig. 5. The waveform until 50 sec. depended on SMGA 1, and SMGA 2 had a limited impact on the waveform. The influences from SMGA 3 to 5 overlapped on around 100 sec. The acceleration at the target site was mostly influenced by these three SMGAs. Though the fracture start times of these SMGAs were not the same, the arrival times at the target dam site were nearly simultaneous. The nearly simultaneous arrivals made the peak acceleration around 100 sec.

The observed waveform converges sooner than the synthetic as shown in Fig. 3. The synthetic one continues large acceleration until 130 sec. According to Furumura *et al.*, (2011), strong ground motions were originated from three large slips; the first two slips occurred over the plate interface of off-shore Miyagi prefecture near the hypocenter, and the third one just beneath the northern end of Ibaraki prefecture in the crust at about 130 sec. after the origin time. The third slip in the crust was inferred as an induced earthquake triggered by the large ground motion. The third slip was considered to apply to SMGA 4 and 5 at this calculation, considering the location and the fracture time. If a SMGA is placed at the

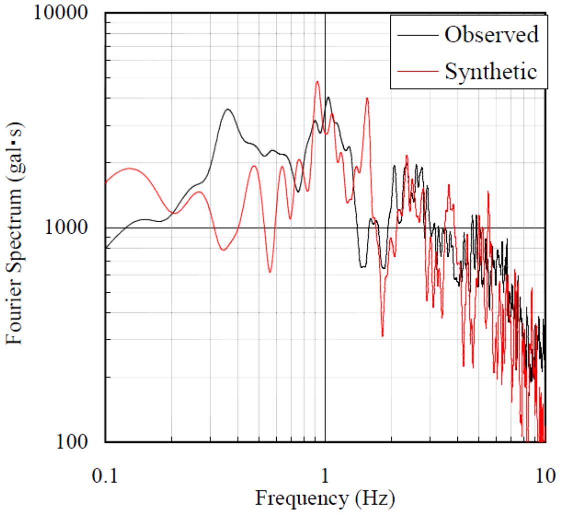

Figure 4. Fourier spectra of observed (black trace) and synthetic (red trace) accelerations shown in Fig. 3.

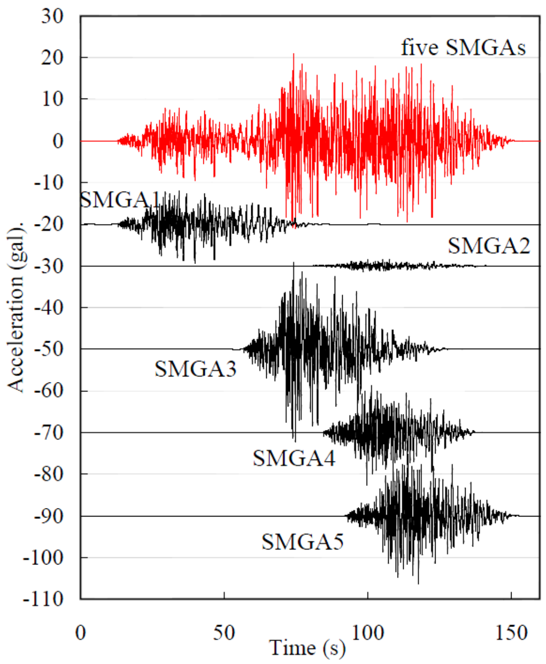

Figure 5. Comparison of synthetic waveforms from five SMGAs (upper red trace) and from individual SMGAs (lower black traces) from SMGA 1 to SMGA 5.

shallow crust of the northern end of Ibaraki prefecture instead of SMGA 4 and 5, more closely waveforms to the observed may be recreated. The wave packet of the shallow SMGA may appear approximately 10 sec. earlier than SMGA 4. This may move the peak acceleration time from about 110 sec. to 100 sec.

4. SUMMARY

The seismic waveform of the 2011 off the Pacific coast of Tohoku Earthquake recorded at the target dam site was reproduced using the empirical Green's function method. The comparison of the observed and synthetic waves made it clear that nearly simultaneous arrivals of wave packets from SMGAs at off-shore Fukushima and off-shore Ibaraki contributed to the maximum acceleration value at the site. The triggered earthquake model by Furumura *et al.*, (2011) can also explain the observed waveform.

ACKNOWLEDGEMENT

The authors are grateful to the National Institute for Earth Science and Disaster Prevention (NIED), Japan for providing strong motion data of the KiK-NET and the CMT solutions by the F-net.

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