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Source modeling of the mid-scale crustal earthquake by forward modeling using the empirical Green's function method

T. Ikeda
Nagaoka University of Technology, Nigata, Japan

Y. Kojima
National Institute of Technology, Nagaoka College, Niigata, Japan

ABSTRACT: Recently, structural damage caused by the middle-scale earthquake were reported. These damage were not so serious, but middle-scale earthquake is often generated. It is important that study of the source modeling the middle-scale earthquake. In this study, we attempted to make a source model of middle-scale earthquake by the empirical Green's function method. The target earthquake is inland crustal earthquake with Mj5.6 which occurred in southern Nagano prefecture in Japan on 25th June 2017. Resultantly, we proposed source model with single strong motion generation areas located in near hypocenter.

1 INTRODUCTION

Characteristic strong ground motion which include semi-large pulse with a duration of 1 to 3 second was generated in the 1995 Kobe earthquake. It caused serious damage to many civil structures and many building structures. The characteristic ground motion was caused by forward rupture directivity effect from directional characteristics of source rupturing. After this earthquake, research on strong ground motion prediction including source modeling was conducted by many researchers energetically. As a result, "Recipe for strong ground motion prediction" was constructing based on several research findings. Effectiveness of the recipe was verifying by strong ground motion simulation against a large-size earthquake. Recently, structure or lifeline system damages caused by the mid-scale earthquake were reported. Generally, damage scale by mid-scale earthquake was not so serious, but that earthquake is often generated. So it is important that study of the source modeling the mid-scale earthquake. In this study, we attempted to make a source model of mid-scale earthquake by the forward modeling (Kamae and Irikura, 1998) using empirical Green's function method (Irikura, 1986).

2 THE 2017 SOUTHERN NAGANO PREFECTURE EARTHQUAKE

The earthquake of $M_w5.2$ (Mj5.6) which occurred in southern Nagano prefecture in Japan on 25th June 2017 was selected for target earthquake. The fault plane of this earthquake was estimated a reverse fault type with the strike of NNE–SSW direction from CMT solution (NIED) and after-shocks distribution. Table 1. shows parameter of the southern Nagano prefecture earthquake. Figure 1 shows location of the epicenter of the main-shock and after-shocks. These after-shocks were occurred within

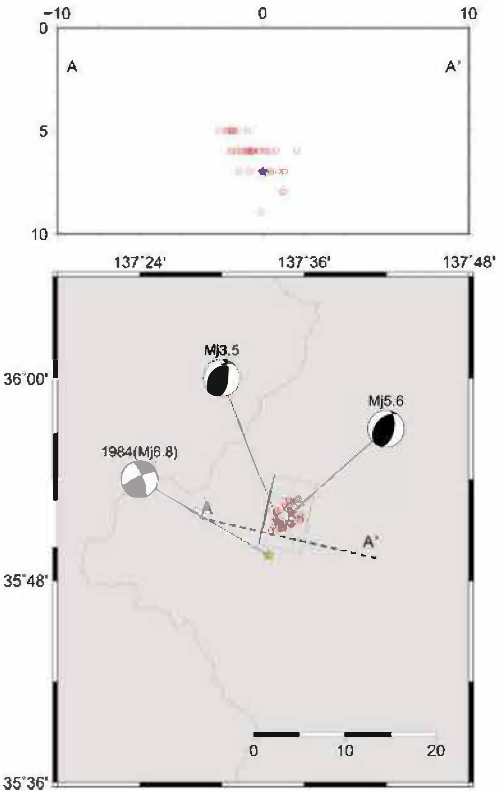

Figure 1. Epicenter of 2017 southern Nagano prefecture earthquake (Mw5.2) and after-shocks distribution which occurred within 24 hours and Mj ≥ 2. Mj6.8 is the earthquake occurred in 1984. Mj3.5 is the earthquake as used for empirical Green's function event.

Table 1. Source parameter of the 2017 southern Nagano prefecture earthquake

Origin time (JST)[a]	2017-6-25 7:02:15.3
Epicenter[a]	35°52.0' N 137°35.1' E
Depth (km)[a]	7
Magnitude	Mj5.6[a], Mw5.2[b]
Seismic moment[b]	6.89×10^{16} Nm
STR/DIP/RAK[b]	219;13/40;53/111;73

[a]JMA, [b]F-net

24 hours from main-shock and its magnitude more than 2.

Strong ground motions were generated near source area in this earthquake and suffered to many houses.

Fire and Disaster Management Agency, Ministry of Internal Affairs and Communications was reported that 27 houses suffered partial damage and many roads was closed by landslide and rock fall.

A large scale earthquake of Mj6.8 is generated at the near epicenter in 1984 and it caused heavy damages in near source area. The epicenter of this earthquake was shown in Figure 1. It is located in very near with epicenter of target earthquake but fault mechanism is deferent.

3 STRONG GROUND MOTION WHICH OBSERVED AROUND SOURCE AREA

Strong ground motions in the wide area including near source area were observed at K-NET, KiK-net and local government seismic observation network. K-NET and KiK-net are seismic observation network of NIED, it was called "Kyoshin network". Figure 2 shows epicenter of main-shock and seismic stations.

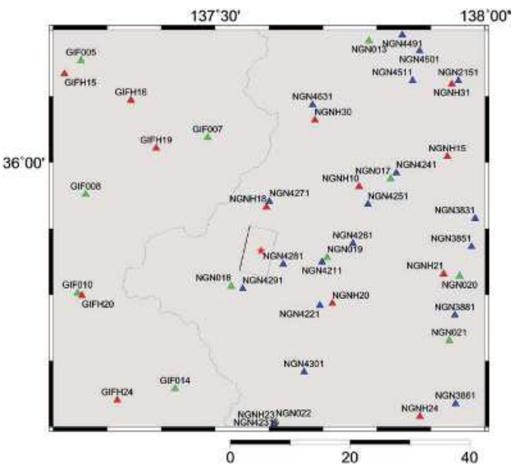

Figure 2. Location of the epicenter of the 2017 southern Nagano prefecture earthquake and seismic observation stations of NIED and local government.

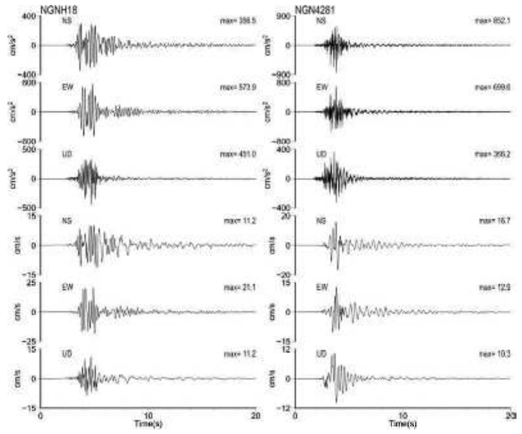

Figure 3. Acceleration and velocity waveform at NGNH18 and NGN4281.

Red triangle mark means KiK-net, green triangle mark means K-NET and blue triangle mark means local government station. Figure 3 shows acceleration waveform and velocity waveform which were observed at NGNH18 and NGN4281. Both records were observed on the ground surface. Velocity waveform was calculated from 0.1-10Hz band-pass acceleration waveform by Fourier integration procedure. NGNH18 was located in the strike direction of the fault plane. NGN4281 was located in the transverse direction of the fault plane.

Duration of principal motion at each waveform were not so long. NGN4281 of the nearest station is about 2 seconds. Pulse wave was included in waveform at NGN018 and NGN4281.

4 SOURCE MODELING

4.1 *Method*

We attempted making a source model of the 2017 Nagano prefecture earthquake by forward modeling (Kamae and Irikura, 1998) using empirical Green's function method (Irikura, 1986).

In this method, at first we make an initial source model which consist of single or multiple strong ground motion generation area (SMGA). Location and number of SMGA are referred from waveform inversion result. Secondary, parameters of SMGA such as location, size, stress drop and rise time were tuned based on agreement between observation and synthesis. The source model made by this procedure is called SMGA model.

Effectiveness of SMGA model was verified by previous researches (Ikeda et al., 2011) even though SMGA has a rectangular shape and homogenized physical property. In this study, we do not consider backward of source area because the strong ground motion was comprised of only elastic wave generated from SMGA. NGNH18, NGNH20, GIFH24, GIFH19, GIFH20 and NGNH30 were used as target site that compared synthetics result with observed one. Because to remove the influence of the soil characteristics nonlinearity, we used underground records. Figure 2. shows location of each stations.

4.2 *Assuming the fault plane*

A fault plane that includes the JMA hypocenter with a length of 7.8 km and width of 7.8 km was assumed by after-shock distribution. The strike and dip angles were set to 13° and 54°, respectively, referring to the F-net moment tensor solution (NIED). Latitude and longitude of reference point of fault plain were 35.836N and 137.545E. Figure 2. shows fault plain.

4.3 *Select of the element earthquake to use as empirical Green's function event*

The empirical Green's function method (EGFM) synthesize strong ground motion of large earthquake using similarity law between large earthquake and small earthquake. So we have to very carefully select an element earthquake as use empirical Green's function event.

In this study, we selected element earthquake from 14 earthquakes which satisfied following condition.

1. Epicenter: 35.8N - 35.9N, 137.5E - 137.65E
2. Magnitude: Mj3.5 – Mj4.5
3. Focal mechanism of F-net: Evaluated

As a result, earthquake with Mj3.5 were selected as an empirical Green's function event. Figure 1 shows epicenter of element earthquake and focal mechanism of F-net. Table 2 shows source parameter of element earthquake.

Area and stress drop were evaluated by Brune method (Brune, 1970 and Brune, 1971) and circular crack method (Eshelby, 1957). Equation (1) and equation (2) shows Brune method and circular crack method. Corner frequency of element earthquake (f_{ca}) to use Brune method was evaluated by source spectral ratio fitting method (SSRM) by Miyake et al. (1999). SSRM method fit a source spectral function based on ω^{-2} source spectral theory into an observed source spectral ratio and calculate f_{ca}, N and C. Here, N is number of synthesis and C is ratio of stress drop between large earthquake and element earthquake. Equation (3) shows source spectral function (SSRF(f)).

$$r_e = \frac{2.34\beta}{2\pi f_{ca}} \tag{1}$$

$$\Delta\sigma_e = \frac{7}{16}\frac{m_0}{r_e^{\,3}} \tag{2}$$

Table 2.Source parameter of the element earthquake to use as empirical Green's function event

Origin time (JST)[a]	2017-6-25 9:48:42.7
Epicenter[a]	35°51.5' N 137°34.1' E
Depth (km)[a]	6
Magnitude	Mj3.5[a], Mw3.6[b]
Seismic moment[b]	3.04×10^{14} Nm
STR/DIP/RAK[b]	227;7/37;60/124;67
Corner frequency	2.37Hz
Stress drop	0.8MPa
Area	0.95km^2

[a]JMA, [b] F-net

$$SSRF(f) = \frac{M_0}{m_0}\frac{1+\left(\dfrac{f}{f_{ca}}\right)^2}{1+\left(\dfrac{f}{f_{cm}}\right)^2} \tag{3}$$

Here, f is frequency, r_e is equivalent radius (km), β is shear wave velocity of rock basement (km/s), $\Delta\sigma_e$ is stress drop of element earthquake (MPa), M_0 and m_0 are seismic moment of large earthquake and element earthquake respectively (Nm). f_{cm} and f_{ca} are corner frequency of large earthquake and element earthquake respectively.

In this study, we use main-shock to use as large earthquake. Observed source function ratio was calculated by broadband velocity records which observed at KNM, NAA, FUJI, TTO and SRN. Figure 4 shows location of broadband seismic observation stations.

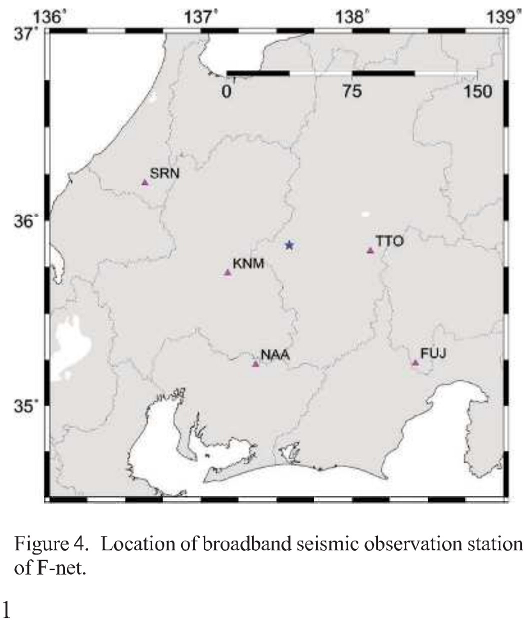

Figure 4. Location of broadband seismic observation station of F-net.

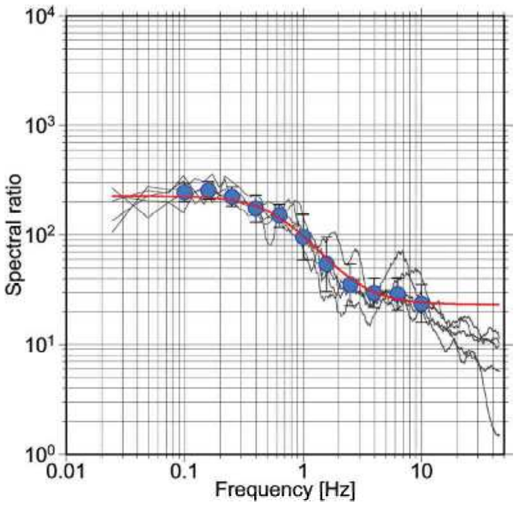

Figure 5. Curve fitting result between observed source spectral ratio and source spectral function.

Figure 5. shows result of curve fitting. Range of curve fitting is 0.1 – 10 Hz. Read curve is SSRF and blue circle are target. We evaluated corner frequency (f_{ca}) to be 2.37 Hz from curve fitting.

4.4 *Source modeling*

We set single SMGA because observation waveform does not see multi event. As a result of forward modeling, we make a source model with single SMGA which located in near hypocenter. Figure 6 shows source model of the 2007 Nagano prefecture earthquake. Table 3 shows parameters of the source model.

Figure 7 shows the synthesized acceleration waveforms, velocity waveforms and displacement waveform of EW component at each target stations compared with the observed ones. Figure 8 shows the pseudo velocity response spectrum with damping factor 0.05 (response spectrum) and acceleration Fourier spectrum (Fourier spectrum). Effective frequency range is 0.2–10.0 Hz.

Synthesized acceleration waveform and velocity waveform at NGNH18 which is the nearest station were good agreement with observed ones. Especially, synthetic waveform can reproduce pulse waveform. Also response spectrum and Fourier spectrum were good agreement with observed ones.

Table 3.Parameter of the source model

Area	8.56 km^2 (2.925 km × 2.925 km)
Synthesis number	3 × 3 × 3
depth (upper)	2.925 km
Stress drop	6.4 MPa
Rupture velocity	2.7 km/s
Rise time	0.2 s

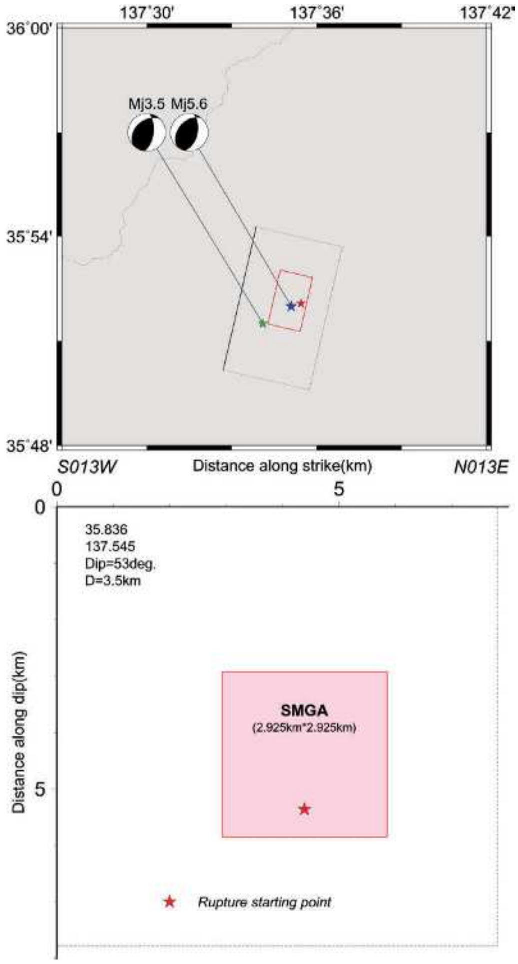

Figure 6. The source model of the 2007 Nagano prefecture earthquake.

Synthesized response spectrum and Fourier spectrum at GIFH24 is underestimated in more than 1Hz range.

Figure 9 shows relationship between seismic moment and short period source spectrum. Short period source spectrum was calculated by equation (4). Scaling law of Dan et al. (2001) was written in this figure. Equation (5) shows scaling law.

$$A = 2.46 \times 10^{10} \times \left(M_0 \times 10^7 \right)^{1/3} \tag{4}$$

$$A = 4\pi r \Delta\sigma_a \beta^2 \tag{5}$$

Here, A is short period source spectrum (Nm/s^2), r is radius of SMGA (km) and $\Delta\sigma_a$ is stress drop of SMGA. Shear wave velocity assumed 3.5km/s.

Relation between seismic moment and short period source spectrum can be express scaling law.

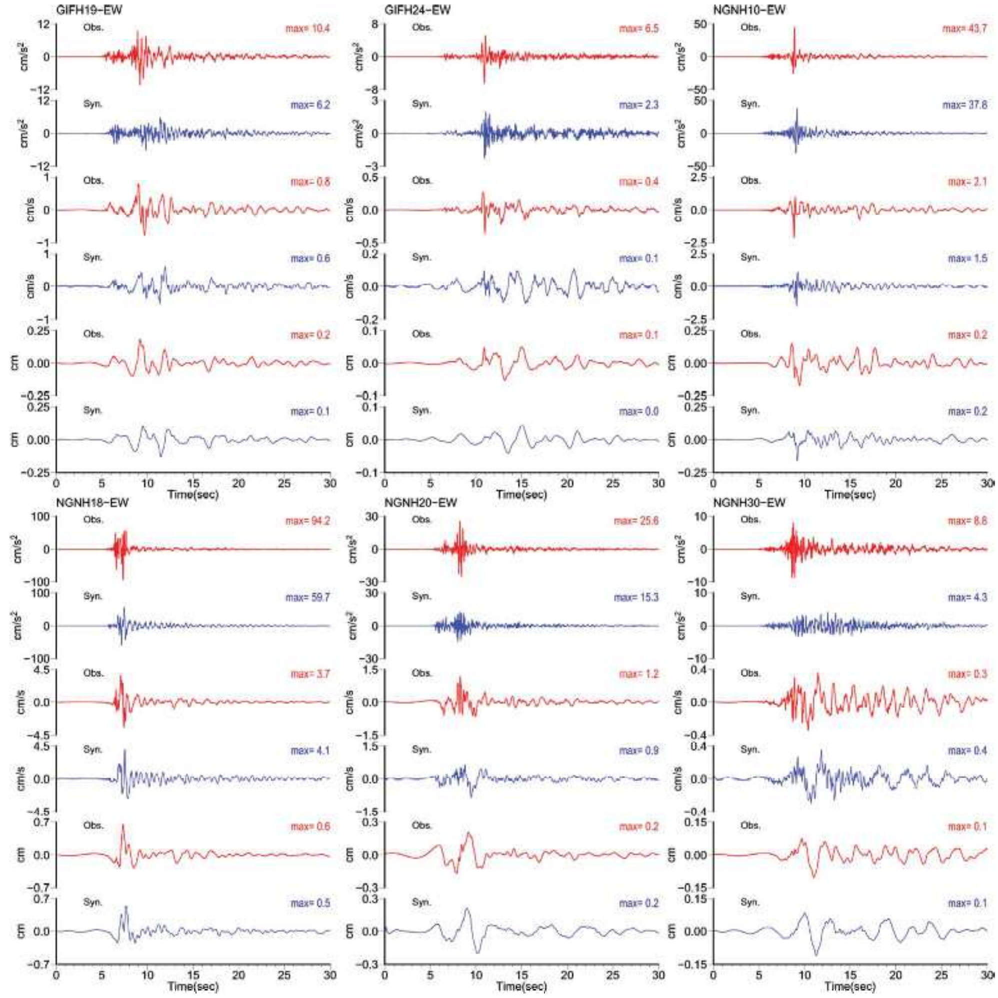

Figure 7.Comparison of the observed and synthetic waveforms of EW component at target station. The red color lines are the observed waveforms.

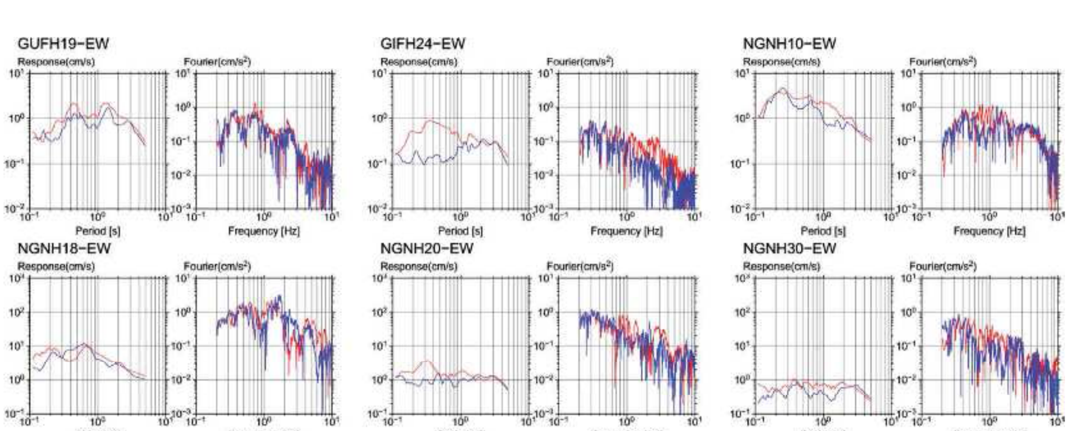

Figure 8.Comparison of the observed and synthetic pseudo velocity response spectrum and acceleration Fourier spectrum of EW component at target station. The red color lines are the observed waveforms.

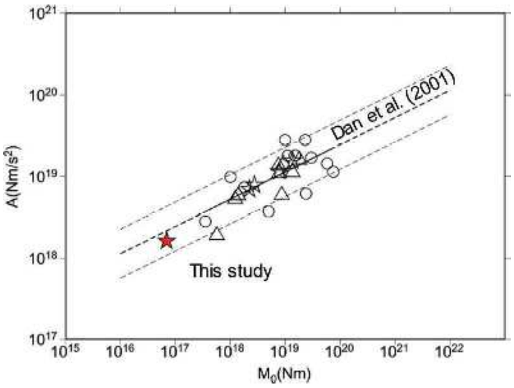

Figure 9. Relation between seismic moment and short period source spectrum.

5 CONCLUSION

We constructed the source model of the 2007 Nagano prefecture earthquake with Mj5.6 by the forward modeling using empirical Green's function method. The source model has a single SMGA. Relation between seismic moment and short period source spectrum can be express scaling law.

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