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GENERATION OF SYNTHETIC EARTHQUAKE ACCELEROGRAMS USING SEISMOLOGICAL MODELING OF KOREAN PENINSULA

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Abstract

Earthquake design spectrum in current Korean Building Code (KBC2009) [1] is derived from the International Building Code 2000[2], and does not account for characteristics of the earthquakes in Korea known as a low-to-moderate seismicity region. To overcome this problem, a seismological model based on stochastic methods such as SMSIM [3] was used to determine the appropriate values of the seismological parameters in Korean Peninsula by benchmarking recorded ground accelerograms from recent 10-years Korean earthquakes whose magnitudes are M_w 3.5 to 5.0. The source acceleration spectra of Odaesan and Andong earthquake having magnitude of M_w 4.72 and 4.0 were developed by using Brune's [4] and 2-f_c [5] source spectrum models. To simulate accelerograms, geometrical spreading corresponding to attenuation relationship for Korea, the anelastic attenuation of spectral amplitudes, and the duration model for ENA in SMSIM were used. However the site condition are assumed to be generic rock. Then, synthetic accelerograms for future earthquakes having a magnitude of 6.5 and the stress drop of 100 bar with the hypocentral distance ranging from 14 km to 400 km in Korea are generated by this seismological model. Design response spectrum in KBC2009 is compared with spectra derived by using this seismological stochastic model: Response spectra of the simulated accelerograms with the earthquake, M_w 6.5, and the stress drop of 100 bar at the hypocentral distance of 14 km are in general similar to the design spectrum of KBC2009 with the seismic zone factor, 0.22g, and site class, S_B, but show lower spectral values for the period exceeding 0.5 sec than the design spectrum of KBC2009.

Keywords: Synthetic accelerogram, Stochastic model, Earthquake, Korea

1. Introduction

Earthquake design spectrum in current Korean Building Code [1] is derived from the International Building Code 2000[2], and does not account for characteristics of the earthquakes in Korea known as a low-to-moderate seismicity region. To overcome this problem, seismological parameters used in the stochastic method adopted in SMSIM [3] were calibrated for the earthquake in Korean Peninsula. The number of earthquakes whose magnitude (M_w) are larger than 3.5 in recent 10 years are four and shown in Table 1. Earthquake accelerogram data were downloaded from strong motion network of Korea Meteorological Administration (KMA) for the development of the stochastic model. Fig. 1 shows the locations of the stations of KMA in Korea and the epicenter of the four events. Fig. 2 shows the PGA distribution of Odaesan earthquake having the largest magnitude of M_w 4.72 among them.

Table 1 - Earthquakes with magnitude M_w 3.5 to 5.0 in the last ten years in Korea [6, 7]

No.	MM/DD/YY	HH:MM:SS	Latitude (ºN)	Longitude (ºW)	M_w	$\Delta\sigma$ (bar)	Note
1	01/20/07	20:56:53	37.68	128.59	4.72	137	Odaesan
2	05/02/09	07:58:28	36.56	128.71	4.0	65	Andong
3	02/05/13	21:25:36	35.77	127.97	3.5	54	Geochang
4	12/22/15	04:31:25	36.03	126.96	3.9	-	Iksan

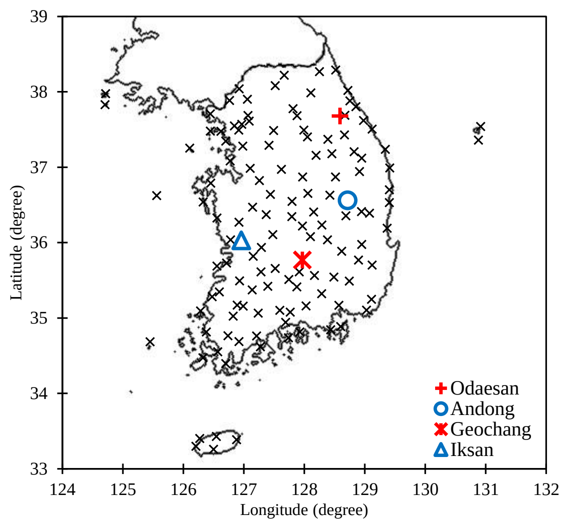


Fig. 1 - Locations of KMA stations

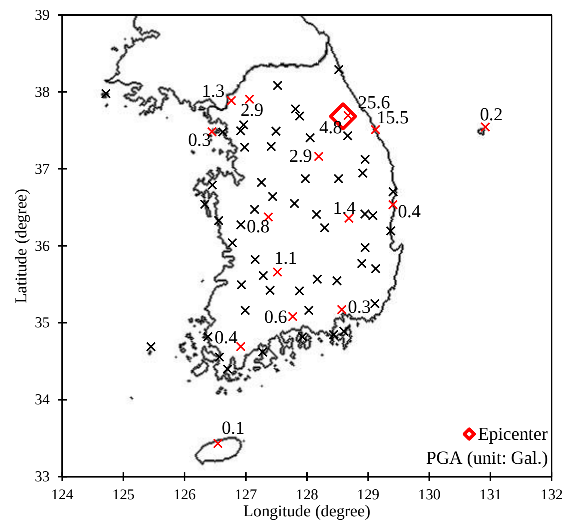


Fig. 2 - PGA distribution of Odaesan earthquake

Fig. 3 shows the horizontal (EW) and vertical components of the recorded accelerograms for the Odaesan earthquake. H/V ratios of PGA are about 2.

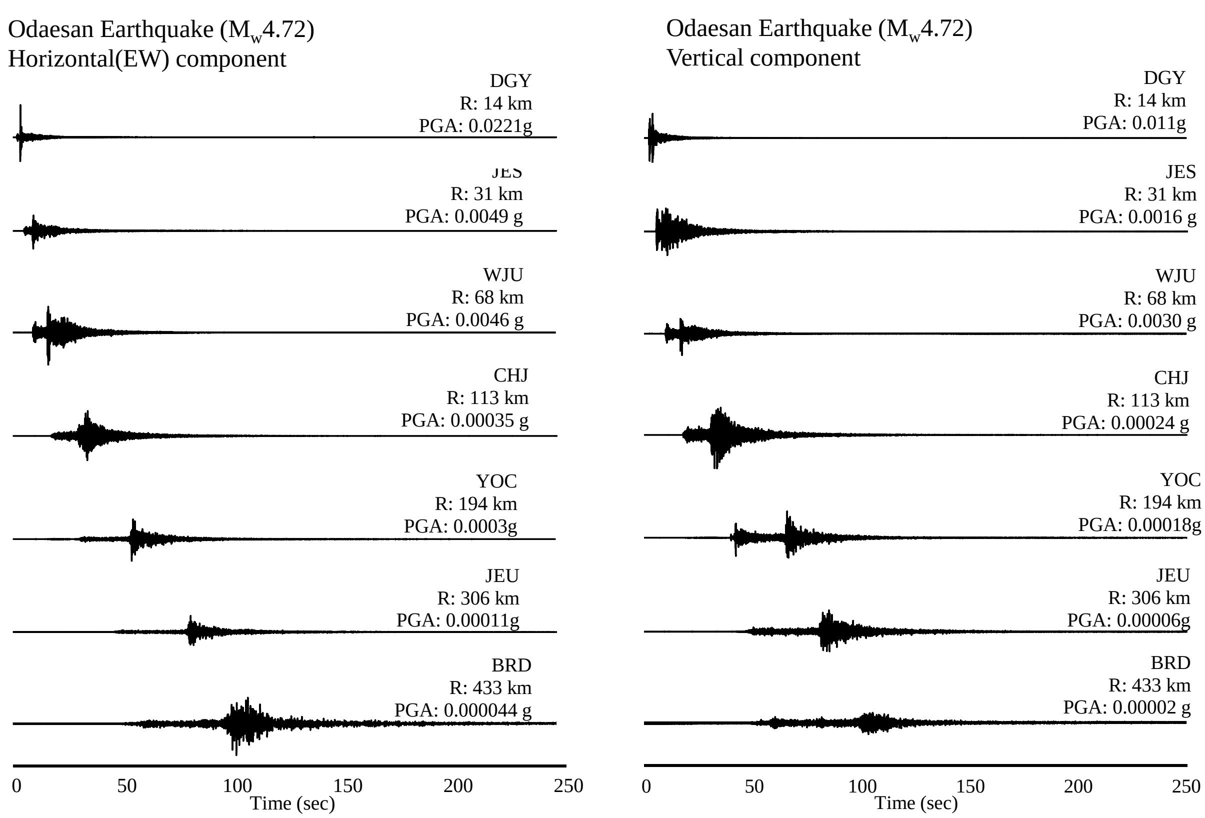


Fig. 3 - The horizontal (EW) and vertical components of the recorded accelerograms for the Odaesan earthquake. Station name, hypocentral distance (R), and peak ground acceleration are given to the right of each trace.

2. Simulation of Ground Motions Based on the Stochastic Method

2.1 Simulation Method

The essesntial ingredient for the stochastic method is the spectrum of the ground motion usually encapsulated and put into the form of simple equations.[8] Most of the effort in developing a model is in describing the spectrum of ground motion. The method begins with the specification of the Fourier amplitude spectrum of ground acceleration as a function of seismic moment and distance, Y(M_0, R, f), which can be represented by

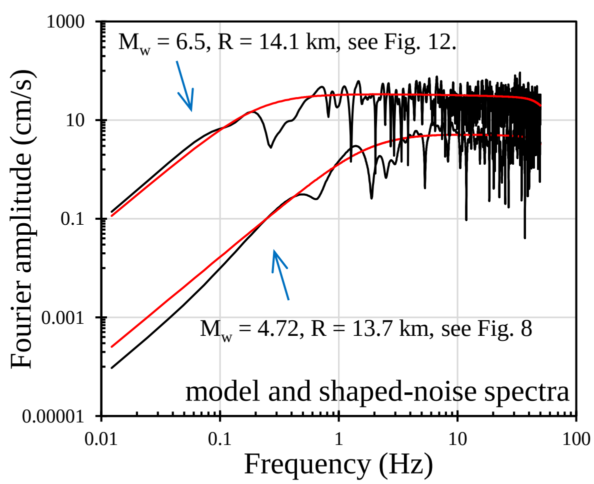
$$Y(M_0, R, f) = E(M_0, f)\,P(R, f)\,G(f)\,I(f) \tag{1}$$

The term $E(M_0, f)$ is the earthquake source spectrum for a specified seismic moment (i.e., Fourier spectrum of the ground acceleration at a distance of 1 km), and $P(R, f)$ is the path effect represented by simple funcions that account for geometrical spreading, attenuation, and the general increase of duration with distance due to wave porpagation and scattering. The term $G(f)$ is the local site effects, however, the local site effects were not considered in this study. The term $I(f)$ is a filter used to shape the spectrum to correspond to the particular ground-motion measure of interest. $I(f)$ is simply

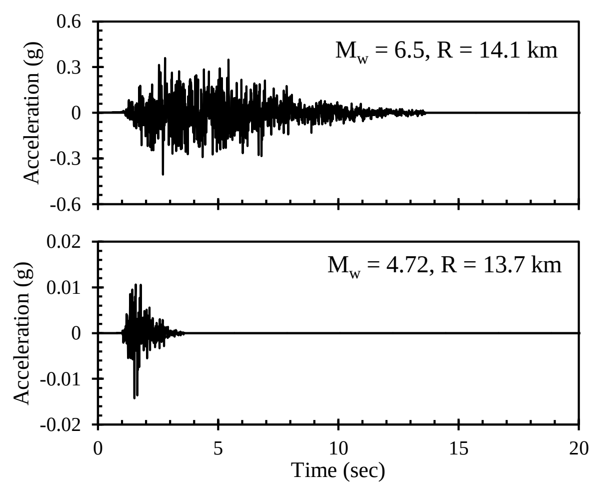
$$I(f) = 1/(2\pi f)^p \tag{2}$$

where p = 0 for acceleration, 1 for velocity, or 2 for displacement.

The time-domain implementation of the stochastic method used in this study begins with the generation of a windowed acceleration time series comprised of random Gaussian noise with zero mean amplitude; the variance is chosen such that the spectral amplitude is unity on average. The duration of the window is specified as a function of magnitude and distance. The spectrum of the windowed time series is multiplied by the desired amplitude spectrum [$Y(M_0, R, f)$]. The filtered spectrum is then transformed back into the time domain to yield a simulated earthquake seismogram for that magnitude and distance. Fig. 4 shows an actual application of time-domain simulation using Brune [4] model. White noise (Gaussian) is generated for a dur ation given by the duration of the motion; this noise is then windowed; the windowed noise is transformed into the frequency domain; the spectrum is normalized by the square-root of the mean square amplitude spectrum; the normalized spectrum is multiplied by the ground motion spectrum Y (Fig. 4(a)); the resulting spectrum is transformed back to the time domain (Fig. 4(b)).



(a) Model and shaped-noise spectra



(b) acceleration

Fig. 4 – Simulation of ground motions using the stochastic method for Korean peninsula

The exponential window is given by:

$$w(t; t_n) = a(t/t_n)^b \exp(-c(t/t_n)) \tag{3}$$

Where the parameter a, b, and c are determined such that w(t) has a peak with value of unity when $t = \varepsilon \times t_n$ and $w(t) = \eta$ when $t = t_n$. The equation for a, b, and c follow:

$$b = -(\varepsilon \ln \eta)/[1 + \varepsilon(\ln \eta - 1)] \tag{4}$$

$$c = b/\varepsilon \tag{5}$$

$$a = (\exp(1)/\epsilon)^b \tag{6}$$

In this study, ε and η are use 0.2 and 0.05. The time t_n is given by

$$t_n = f_{T_{gm}} \times T_{gm} \tag{7}$$

Where T_{gm} is the duration of ground motion and f_{Tgm} is factor to convert the box duration to the exponential duration given value by 2.0.[3]

2.2 Development of the Source Fourier Spectrum in Korea

The source spectrum was estimated from the horizontal component of the S wave, using the following relation between the source spectrum ($S_a(f)$) and the observed acceleration spectrum ($A_{obs}(f)$) [9]

$$S_a(f) = \left[4\pi\rho_0{\beta_0}^3 R\right]\left[\exp\left(\frac{\pi f R}{Q\beta_0}\right)\right] A_{obs} \tag{8}$$

Where ρ_0 and is density near the source, R is the hypocentral distance, and Q is the frequency-dependent attenuation parameter. Eq. (8) was derived with the assumption that the product of the free-surface factor, the radiation pattern, and the factor partitioning the motion into the horizontal components is unity.

Theoretical source spectra is compared with the estimated source spectra from the recorded accelerograms at the hypocentral distance 13 to 73 km for Odaesan (M_w 4.72) and Andong (M_w 4.0) earthquakes in Fig. 5. The source spectrum estimated by actual record of the closest station from epicenter is plotted with blue line in Fig. 5 (a) - (d). The curve shows the theoretical spectra, single-corner-frequency and two-corner-frequency model. The 1-f_c source acceleration spectrum $S_a(f)$ is

$$S_a(f) = \omega^2 S(f) \tag{9}$$

Where $\omega=2\pi f$ and the moment-rate function $S(f)$ approaches the seismic moment M_0 for low frequencies. For the Brune [4] model, $S(f)$ is given by

$$S(f) = M_0/[1 + (f/f_0)^2] \tag{10}$$

The source corner frequency f_0 is related to the seismic moment (M_0) and the stress parameter ($\Delta\sigma$) by

$$f_0 = 4.9 \times 10^6 \beta_0 (\Delta\sigma/M_0)^{1/3} \tag{11}$$

Where the shear velocity near the source (β_0) has units of km/sec, and the units of M_0 and $\Delta\sigma$ are dyne-cm and bars, respectively. M_0 has relation to moment magnitude, M_w as Eq. (12) [10]

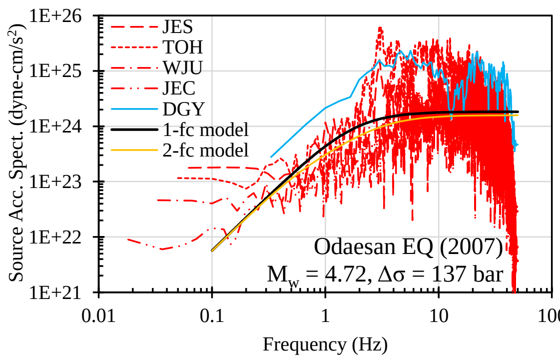
$$\log M_0 = 1.5 M_w + 16.05 \tag{12}$$

The calculated material properties are β_0 = 3.7 km/sec, and ρ_0 = 2.8 gm/cm^3, and moment are $M_0 = 1.41 \times 10^{23}$ dyne-cm and 1.2×10^{22} dyne-cm for Odaesan and Andong earthquakes. The values for the material properties β_0 and ρ_0 were taken form Yun and Park's velocity model [6] for the region. The 2-f_c source acceleration spectrum [5] $S_a(f)$ is

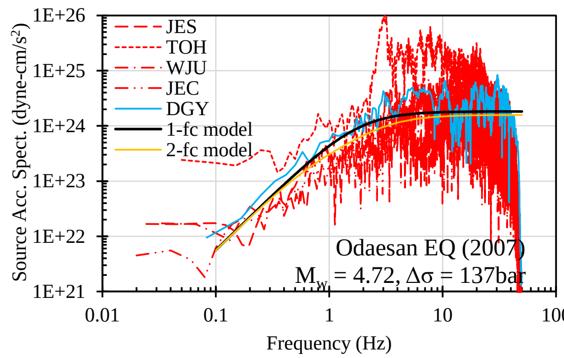
$$S_a(f) = (2\pi f)^2 M_0 \left(\frac{1-\varepsilon}{\left[1+\left(\frac{f}{f_A}\right)^2\right]} + \frac{\varepsilon}{\left[1+\left(\frac{f}{f_B}\right)^2\right]} \right) \tag{13}$$

where ε represents some fraction of the total moment, and f_A and f_B are the under and upper corner frequencies. The values of f_A, f_B and ε for the Korean peninsula are

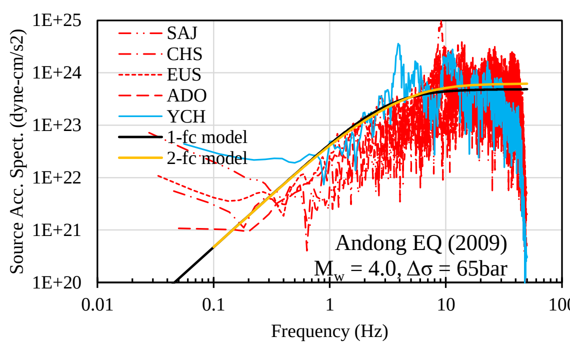
$$\begin{pmatrix} log f_A = 2.41 - 0.533 M_W \\ log f_B = 2.14 - 0.36 M_W \\ log\varepsilon = 0.53 - 0.22 M_W \end{pmatrix} \tag{14}$$



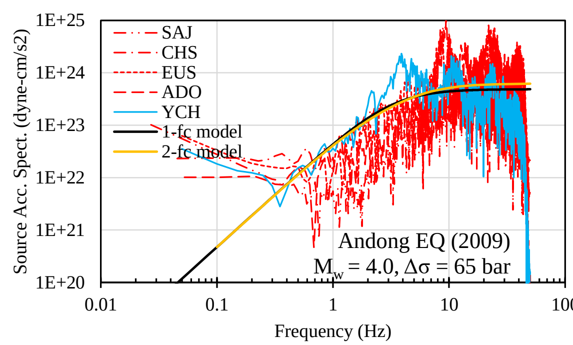
(a) Odaesan EQ, EW



(b) Odaesan EQ, NS



(c) Andong EQ, EW



(d) Andong EQ, NS

Fig. 5 – Source Fourier acceleration model compared with those computed from the recorded horizontal components in Korea

2.3 The Path effect - Attenuation and Duration

The simplified path effect [8] is given by the multiplication of the geometrical spreading and Q functions

$$\mathrm{P[R,f]} = Z(R)\exp[-\pi \mathrm{fR}/\mathrm{Q(f)}c_Q] \tag{15}$$

where c_Q is the seismic velocity used in the determination of $Q(f)$, and the geometrical spreading function $Z(R)$ is given by a piecewise continuous series of straight lines:

$$Z[\mathrm{R}] = \begin{cases} \dfrac{R_0}{R} & R \le R_1 \\ Z(R_1)(\dfrac{R_1}{R})^{p1} & R_1 \le R \le R_2 \\ \vdots & \vdots \\ Z(R_n)(\dfrac{R_n}{R})^{p_n} & R_n \le R \end{cases} \tag{16}$$

In applications, R is usually taken as the closest distance to the rupture surface, rather than the hypocentral distance. As an example of $Z(R)$, the three-segment geometrical spreading operator used in Atkinson and Boore's [11] predictions of ground motions in eastern North America. For this example, R_0 = 1, R_1 = 70, p_1 = 0, R_2 = 130, and p_2 = 0.5. However, the atteunation relationship in Korea [12] has differences between the three-segment geometrical speading for ENA which is given in Eq. (17).

$$\ln\mathrm{PGA} = C_0 + C_1 R + C_2 ln\mathrm{R} - \ln[\min(\mathrm{R}, 100)] - 1/2\ln[\max(\mathrm{R}, 100)] \tag{17}$$

Where the PGA and hypocentral distance, R have unit of cm/sec^2 and km. C is the constant value relative to moment magnitude and can be calculated by the Eq. (18).

$$C_k = \xi_0^k + \xi_1^k(M_W - 6) + \xi_2^k(M_W - 6)^2 + \xi_3^k(M_W - 6)^3, \quad k = 0, 1, 2 \tag{18}$$

Where $\xi_i^k(\mathrm{k} = 0, 1, 2; \mathrm{i} = 0, 1, 2, 3)$ are regression coefficients dependence of PGA, PGV, and PSA at frequency of 0.2 to 100 Hz. Fig. 6 (a) shows PGA distributions depending on hypocentral distance for M_W = 5, 5.5, 6, and 6.5. Using Eq. (17) and (18) simplied as shown in Fig. 6 (b) for the application to SMSIM.

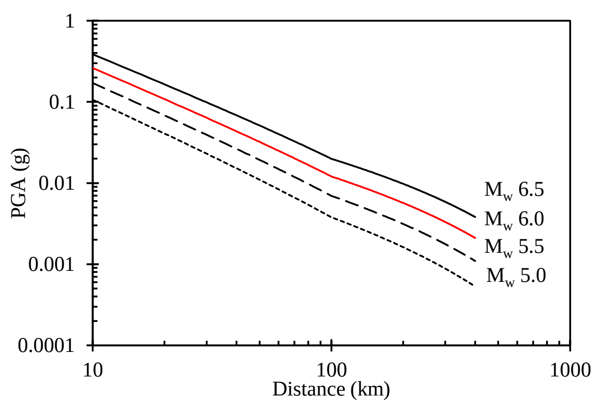
The additional input element of the stochastic predictions is the duration model. The duration model [11] generally has two terms,

$$T = T_0 + bR \tag{19}$$

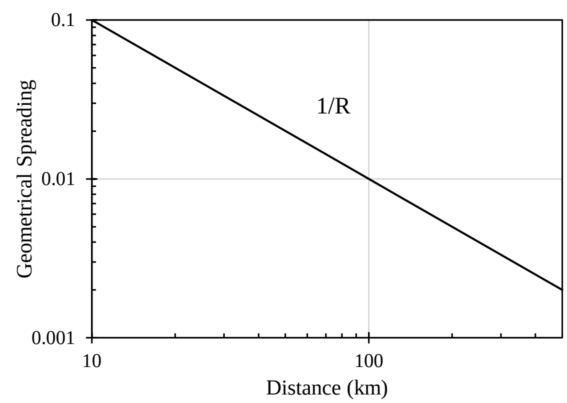
where, T_0 is the source duration and bR represents a distance-dependent terms. The source duration is assumed to be Eq. (20).

$$T_0 = 1/f_0 \tag{20}$$

The distance-dependent duration terms are derived from Boore [11] shown in Fig. 7. The distance dependence of duration is modeled as trilinear, using the transition distances 70 and 130km for consistency with the attenuation model; the slope b is zero for R < 10 km, 0.16 for 10 ≤ R < 70 km, -0.03 for 70 ≤ R < 130 km, 0.04 for 130 ≤ R < 1000 km.



(a) PGA depended on hypocentral distance for M_W = 5, 5.5, 6, and 6.5. [12]



(b) SMSIM input

Fig. 6 - Geometrical spreading corresponding to attenuation relationship of Korea

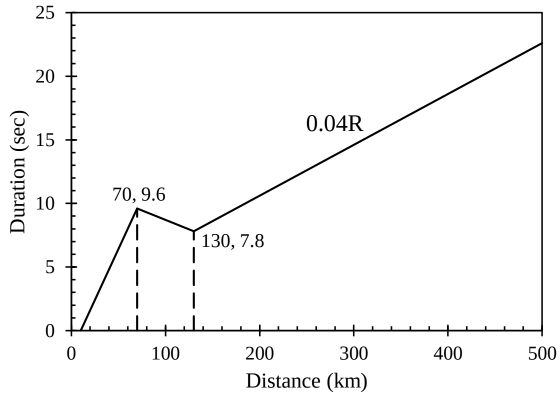


Fig. 7 - Mean of the rms duration minus the source duration

2.4 Comparison of Recorded and Synthetic Accelerograms

Ten artificial ground accelerograms with the same earthquake magnitude as Odaesan earthquake were simulated and generated for each of KMA stations recorded the Odaesan earthquakes (M_w 4.72). One sample of ten simulated accelerograms is compared to the corresponding actual records in Fig. 8.

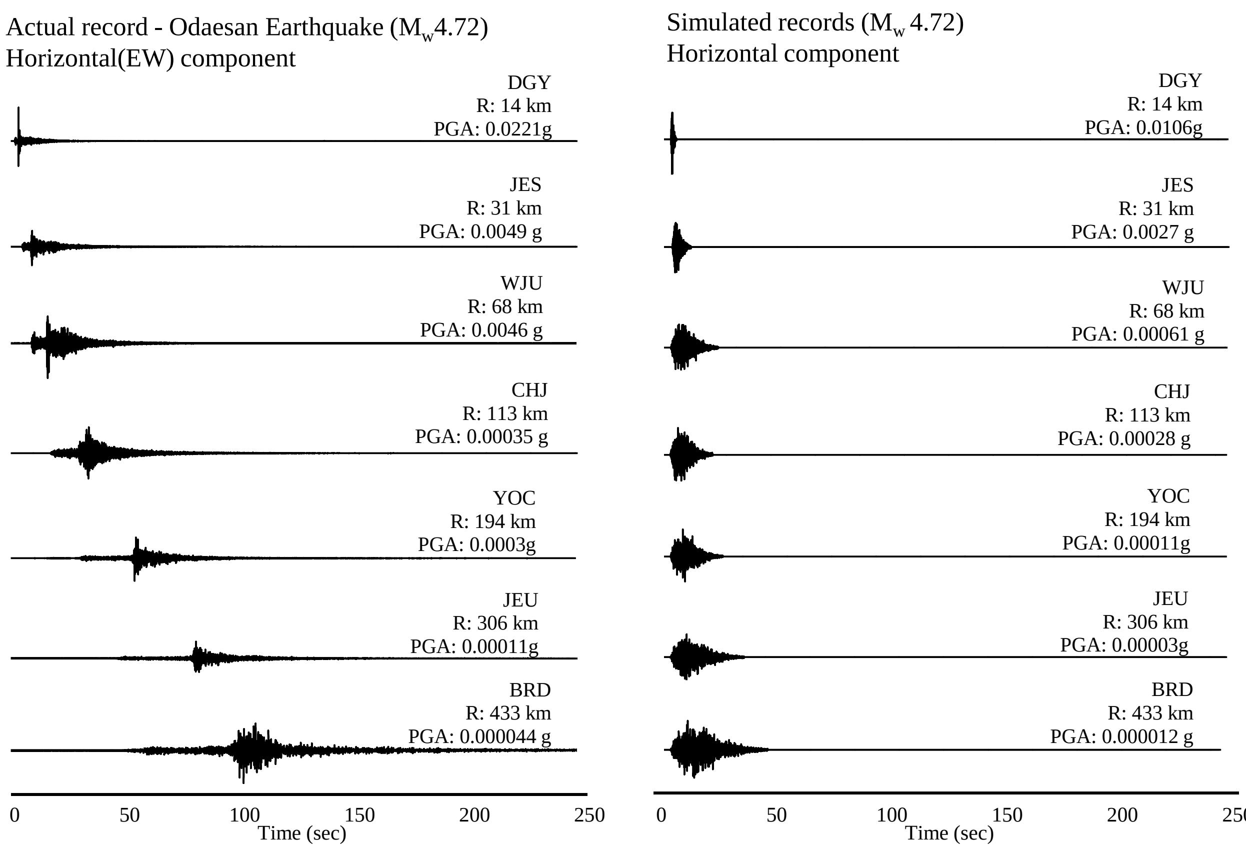


Fig. 8 - Horizontal component of recorded and simulated accelerograms

Fig. 9 shows spectral acceleration values at 1, 3, and 10 Hz of actual records and simulated seismograms and spectrum model of SMSIM [3]. The simulated seismograms data with $\Delta\sigma = 137$ bar are similar with actual data at 1, 3 and 10 Hz. PGAs of the simulated seismograms are lower than the actual records. Fig. 10 shows the response accleration spectra of actural records and simulated seismograms with $\Delta\sigma = 137$ bar. Simulated seismograms are generally lower than actual data. Especially, simulated seismograms were quite different than actual records in the period region which is 0.2 to 0.5 sec.

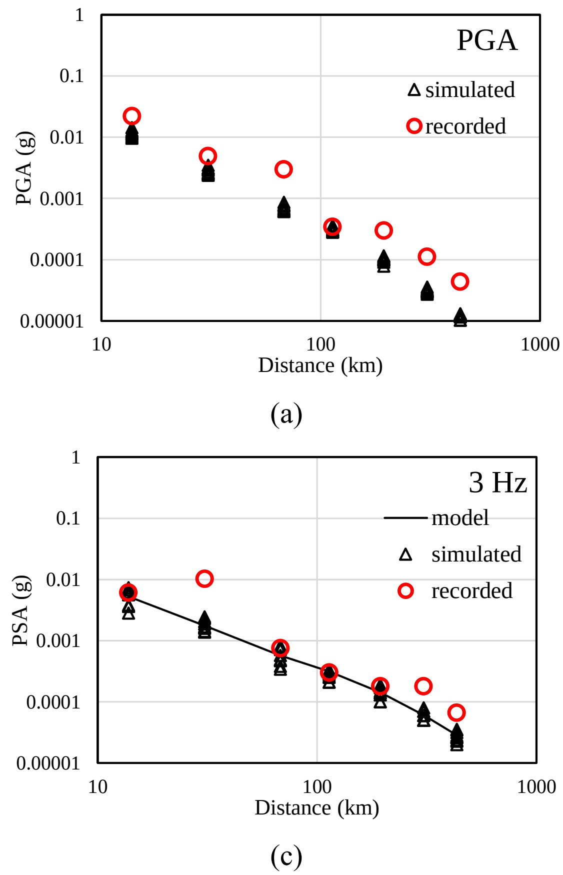


Fig. 9 - Predicted PGA (a) and response spectral values for 0.5 Hz (b), 1 Hz (c), 10 Hz (d) and comparison with recorded data (Odaesan EQ) with stress drop 137 bar

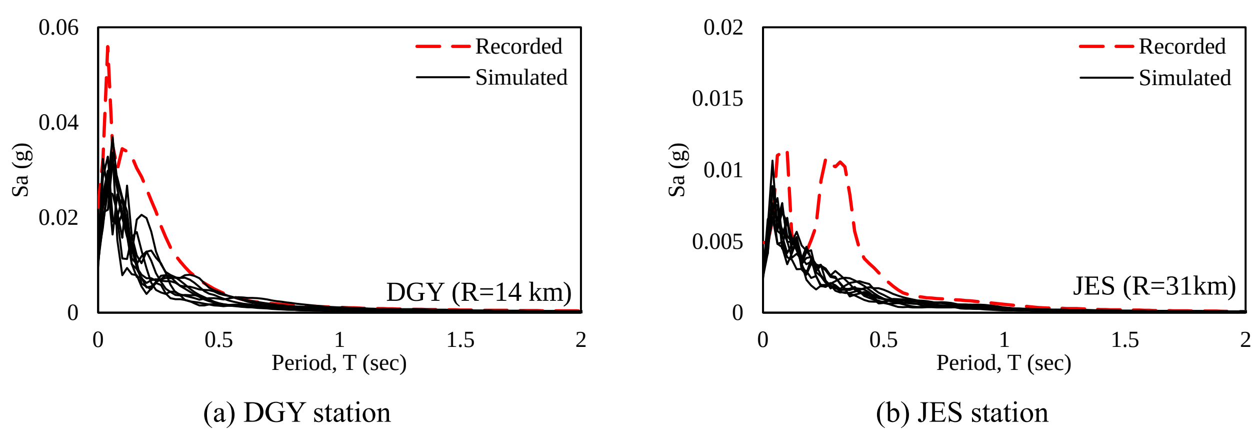


Fig. 10 - Response acceleration spectra of simulated seismograms with $\Delta\sigma$ = 137 bar and actual record at the hypocentral distances of 14 and 31 km

2.5 Simulation of Strong Ground Motion for Earthquake Magnitude 6.5 in Korea

Strong earthquake ground motions whose magnitude is M_w 6.5, though the probability of occurrance of that earthquake is low in Korea, are simulated by using the seismological model calibrated in previous sections. The stress drops of recorded earthquake in inland of Korea was about 50~200 bar.[6] For the stress drops of 50, 100, and 200 bars in the earthquakes with the magnitudes of M_w 4.72 and 6.5, the source specta are plotted in Fig. 11, and the corresponding corner frequency and source duration are shown in Table 2.

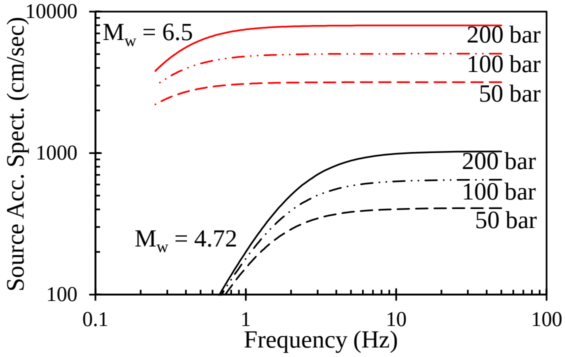
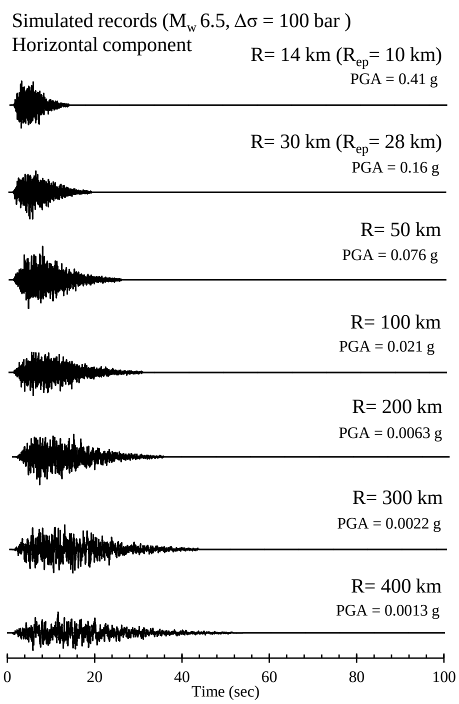


Fig. 11 - Source acceleration spectra of earthquakes with Δσ = 50, 100, 200 bars for the magnitudes 4.72 and 6.5

Table 2 - Corner freuency and source duration of earthquakes with Δσ = 50, 100, 200 bars for the magnitudes 4.72 and 6.5

Magnitude	**Stress drop, Δσ (bar)**	Corner frequency, f_0 (Hz)	Source duration, T_d (sec)
4.72	**50**	1.28	0.78
	100	1.62	0.62
	200	2.04	0.49
6.5	**50**	0.17	6.05
	100	0.21	4.80
	200	0.26	3.81

Considering the value of the stress drop being 137 and 65 bars to simulate Odaesan and Andong earthquakes ground motion, respectively, the stress drop of 100 bars in Korea appears to be reasonable, and strong ground motions with the earthquake magnitude, M_w 6.5, are simulated by using the relation (Eq. (12)). Fig. 12 shows the strong ground motions simulated by the stochastic model at the hypocentral distance ranging from 14 km to 400 km and Fig. 13 shows the corresponding reponse acceleration spectra. Here, the focal depth is assumed to be 10 km. The median of PGAs is 0.42g at the hypocentral distance of 14.1 km.



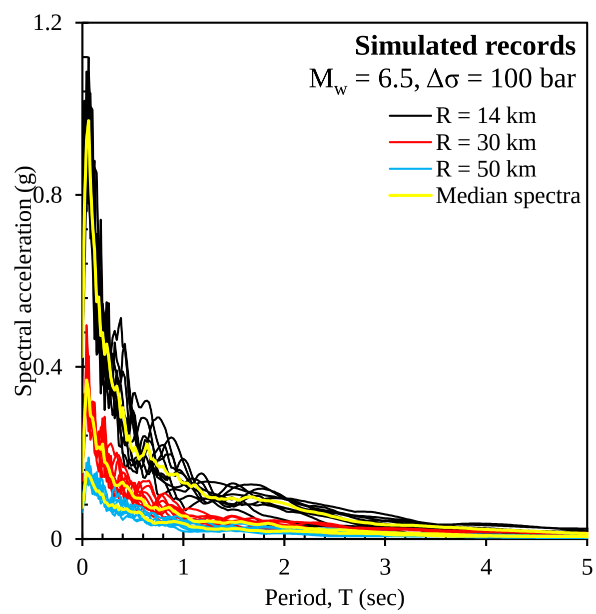


Fig. 12 - Estimated ground accelerograms with the earthquake, M_w 6.5, and Δσ = 100 bar at the hypocentral distance ranging from 14 km to 400 km

Fig. 13 - Response spectra of estimated strong ground motions with the earthquake, M_w 6.5, and Δσ = 100 bar

3. Comparison of Response Spectra from Simulated and Design Earthquake of KBC2009

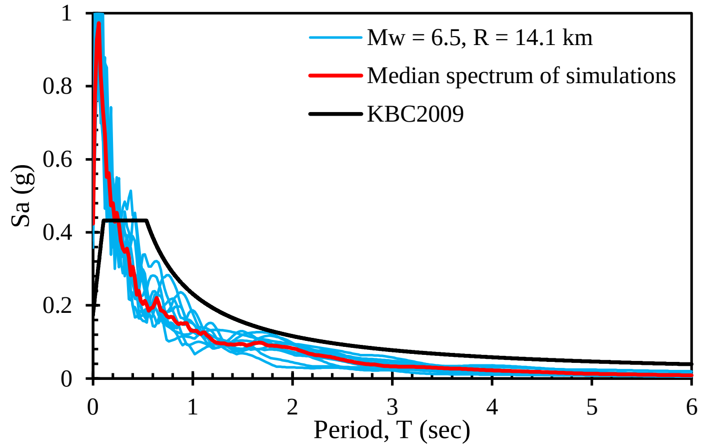


Fig. 14 - Comparison of acceleration response spectra of KBC2009 and simulated seismogram

The simulated ground motions by the stochastic model with earthquake magnitude, M_w 6.5, stress drop of 100 bars, and the focal depth of 10 km are compared with the design spectrum of KBC2009 [1] in Fig. 14. The design spectrum of KBC for rock site (site class S_B) in Seoul (seismic zone factor S = 0.22g) is used for comparison. The spectral accelerations of the design earthquake in KBC2009 are in general similar to the spectral accelerations of the simulated earthquake accelerograms, but significantly higher than those of the simulated seismograms in the period larger than 0.5 sec.

4. Conclusion

In this study, the earthquakes with the magnitude (M_w) larger than 3.5 which occurred in Korea in the last decade were used to calibrate seismological parameters in the stochastic model given by Boore [11], and the ground motions were generated by using this calibrated stochastic model to simulate the ground motions for Odaesan earthquake (M_w 4.72). The strong motion acclerograms for the earthquake magnitude, M_w 6.5, which is the expected largest earthquake in Korea, are simulated with these seismological parameters in Korea. The results of this study are as follow:

1) The source spectra of Odaesan and Andong earthquakes were obtained by using the source Fourier spectrum according to the Boore and Atkinson's approach [9]. And these spectra are fitted to the source models of Brune [4] and Atkinson [5] by adjusting the source parameters such as stress drop. The stress drops of Odaesan and Andong appear to be 137 and 65 bars, respectively. To simulate strong ground motions with the earthquake magnitude of M_w 6.5 in Korea, the magnitude-independent stress drop [13] of 100 bars is considered to be reasonable.

2) The path effects, the duration function and the anelastic attenuation of spectral amplitudes developed for eastern North America (ENA) are adopted for Korean peninsula due to the nonexistence of strong-motion earthquake data in Korea. However, the geometrical spreading model developed by Korean seismologists [12] is used in this stochastic model.

3) The simulated seismograms with the earthquake, M_w 4.72, are compared with the actural records of Odaesan earthquake (M_w 4.72) at the hypocentral distance ranging from 14 km to 433 km. Spectral accelerations of the simulated seismograms for 1, 3, and 10 Hz are similar to those of the recorded accelerations. PGA's of the simulated seismograms are generally lower than those of the actual records.

4) The extrapolation of the stochastic model to the earthquake, M_w 6.5, by the Eq. (12) to Korean Peninsula was performed to simulate the strong ground motions with the stress drop of 100 bars at the hypocentral distance ranging from 14 km to 400 km. Design response spectrum in KBC2009 is compared with the spectra derived

by using this seismological stochastic model: Response spectra of the simulated earthquake accelerograms at the hypocentral distance of 14 km are in general similar to the design spectrum of KBC2009 with the seismic zone factor, 0.22g, and site class, S_B, but show lower spectral values for the period exceeding 0.5 sec than the design spectrum of KBC2009.

5. Acknowledgements

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