지구물리 Vol. 9, No. 3, Special Volume, pp. 171-179, 2006 J Korean Geophysical Soc

Predictive Equations of Ground Motions in Korea

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ABSTRACT Predictive equations of ground motions are one of the most important factors in the seismic hazard analysis. Unfortunately, studies on predictive equations of ground motions in Korea had been hampered due to the lack of seismic data. To overcome the lack of data, seismologists adopted the stochastic method based on the seismological model. Korean predictive equations developed by the stochastic method show large differences in their predictions. It was turned out through the analysis of the existing studies that the main sources of the differences are the uncertainties in the (Brune) stress drop $\Delta\sigma_B$ and spectral decay rate κ. Therefore, it is necessary to focus the future research on the reduction of the uncertainties in the two parameters.

Key words predictive equation of ground motions, stochastic method, stress drop, spectral decay rate

1. Introduction

Predictive equations of ground motions are often referred to as attenuation formulae because, for a given magnitude, they portray the attenuation of ground motion intensities according to the distance from the source. Though attenuation formulae had been derived from past earthquakes, they are used to predict ground motions from postulated future earthquakes. With more weight to the aspect of their usage, we will use the terminology of the predictive equation. In addition, ground motions in this article refer to seismic intensities, particle motions of the ground, or response spectra of oscillators of the single-degree-of-freedom.

Predictive equations of ground motions are one of the most important factors in the seismic hazard analysis. Unfortunately, studies on predictive equations of ground motions in Korea had been hampered due to the lack of seismic data. The lack of seismic data stems from no large earthquakes as well as meager seismic stations in the past. Since recent predictive equations in Korea were developed by using the limited seismic data, they show significant differences in their prediction. Therefore, it is worth reviewing overall predictive equations to cull the parameters on which we shall concentrate our efforts in the future research. In this context, this article reviews the existing predictive equations, analyzes the uncertainties of the model parameters, and provides suggestions for the future improvement. As we will see in the next section, there had been little material to review before the stochastic approach of Noh and Lee (1994, 1995), and all the researches thereafter adopted the stochastic approach. Hence, we will focus our discussion on the predictive equations developed by the stochastic method.

2. Review of predictive equations in Korea

2.1 History of predictive equations

Before 1990s, there were no reliable seismic stations in Korea. Therefore, intensity data were the only material to work with. For example, Lee (1984) proposed the predictive equation of seismic intensities based on the isoseismal maps of the 1936 Ssanggye-sa earthquake and the 1978 Hongseong earthquake. This equation was used up to early 1990s in the seismic hazard analysis (e.g., Lee and Noh, 1988; Lee and Jin 1989), but seldom used afterwards because, in the modern seismic hazard analysis, the quantities of primary interest are ground accelerations or response spectra rather than seismic intensities.

In early 1990s, several modern seismic stations were constructed in Korea. Then, earthquake stations drastically increased during 5 years from 1997 to 2001. As of 2004, there are more than one hundred digital stations including 3 borehole and 25 broadband stations. Moreover, they were connected to a single nation-wide seismic net-

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원고접수일 : 2006년 6월 29일 게재승인일 : 2006년 8월 24일

work called KISS (Korea Integrated Seismic System, see Chi *et al.* (2004) for details). KISS produces a considerable amount of seismic data from 30 to 40 Korean earthquakes a year. However, these earthquakes are not large enough to produce strong motion data. Their magnitudes are less than 5 except for three offshore earthquakes whose magnitudes are about 5 (KMA, 2005). This is the second type of 'lack of data' which means no strong motion data of engineering significance. Consequently, yet preferred were predictive equations developed in the other regions, for example, the eastern North America which was believed to have attenuation characteristics similar to those of the Korean Peninsula. However, as Aki (1983) pointed out, predictive equations of a region cannot be applied directly to other region even if those regions are geographically contiguous to each other because of possible differences of source mechanisms or medium properties, or both. Moreover, there had been no study carried out to demonstrate that the Korean Peninsula and the eastern North America are seismically similar to each other.

An alternative approach to overcome the meager seismic data was attempted by Noh and Lee (1994, 1995). They analyzed seismic data available at that time to estimate source and medium properties (Noh and Lee, 1994), and then applied the stochastic method of Boore (1983) to develop predictive equations (Noh and Lee, 1995). Considering the low seismicity of Korea, it is hardly expected that sufficient strong motion data will be accumulated within several tens of years. If this is the case, the approach of Noh and Lee (1994, 1995) would be the most promising one in Korea for the time being. Naturally, Noh and Lee's approach drew a considerable attention and was followed by many researchers (Park, J.U. *et al.*, 1999; Jo and Baag, 2001, 2003; Park, D.H. *et al.*, 2001; Junn *et al.*, 2002). The main focus of the subsequent researches was the re-estimation of source and medium properties by using seismic data available then.

2.2 Parameters in the source and propagation model

Fourier amplitude spectrum of shear waves at the free surface can be described as following (Boore and Atkinson, 1987).

$$A(f) = C \cdot S(f) \cdot D(f) \tag{1}$$

where C is the scaling factor, $S(f)$ is the source spectral function, and $D(f)$ is the diminution function. Each factor is again composed of several model parameters. In this section, we will review the values of model parameters used in the predictive equations in Korea, to find out which model parameters are governing sources of the differences among predictive equations.

2.2.1 Scaling factor

The scaling factor C at the hypocentral distance r is given by

$$C = \frac{< R_{\theta\varphi} > \cdot F \cdot V}{4\pi\rho\beta^3} \cdot \frac{1}{r} \tag{2}$$

In equation (2), $< R_{\theta\varphi} >$ is the average radiation pattern of which root-mean-square on the focal sphere is $\sqrt{2/5}$ (≒ 0.63). F accounts for the free surface effect and is equal to 2 under the assumption that the free surface is flat and the shear waves are composed of the SH waves. V is the partition of a vector into the horizontal component of which root-mean-square is $1/\sqrt{2}$. The product of these three parameters is equal to $\sqrt{4/5}$ which is near unit, so some authors neglect them (e.g., Street and Turcotte, 1977). In all studies in Korea, the value of $\sqrt{4/5}$ was used for $< R_{\theta\varphi} > \cdot F \cdot V$. The parameter ρ is the crustal density at the seismogenic depth. The crustal density of 2.7 g/cm^3 is generally accepted without any adverse criticism. Of course, other values are often used, for example 2.8 g/cm^3 (McGuire and Hanks, 1980; Atkinson, 1993). All studies in Korea used 2.7 g/cm^3.

The shear wave velocity β of 3.5 km/s was widely accepted in Korea, except for Park, D.H *et al.* (2001) who used 3.68 km/s. The shear wave velocity generally shows some variation within a limited range. For example, Boore (1983) used 3.2 km/s for western North America. Boore and Atkinson (1987) used 3.5 km/s for eastern North America while Atkinson and Boore (1995) used 3.8 km/s. In the Brune's source model (1970, 1971), the high-frequency ground acceleration A_{hf} (i.e., $f >> f_c$) scales as $A_{hf} \sim 1/\beta$. Therefore, the increment of β by 0.18 km/s results in the decrement of A_{hf} by just 5%.

The distance term $1/r$ accounts for the geometrical spreading factor of body waves radiated from a point source. The distance beyond which the dominant ground motions can be better described by the *Lg* phase rather than by *S* waves is approximately that of two crustal thickness (Herrmann and Kijko, 1983), or roughly 100 km. Boore and Atkinson (1987) modeled the transition from body-wave to surface-wave content by a change in the geometrical spreading factor at a cross-over distance of r_x, from $1/r$ to $1/\sqrt{rr_x}$. The factor r_x guarantees continuity of the motions at $r = r_x$. Although the motions are continuous, they show a kink at $r = r_x$ due to a sudden change of geometrical spreading rate. Since the kink is artificially introduced, it needs to be removed in proper ways (e.g., Boore and Atkinson, 1987).

2.2.2 Source spectral function

Assuming the ω-squared shape (Aki, 1967; Brune, 1970), the source spectral function of ground acceleration is defined by

$$S(f) = \frac{(2\pi f)^2 M_0}{1+(f/f_c)^2} \tag{3}$$

where f is the frequency in Hz, M_0 is the seismic moment, and f_c is the corner frequency.

Though the ω-square model is assumed in the above, there is another candidate scaling model, the ω-cube model. In spite of long-time study after the Aki (1967) where he concluded the ω-square model to be more consistent with observations, seismologists have not found concrete evidences to support the Aki's conclusion yet. Hanks (1979) also demonstrated that, though one cannot assert the ω-cube model is wrong, one can better explain observed data with the ω-square model. Boore (1983) illustrated by stochastic simulation that the ω-cube model cannot fit the peak acceleration and peak velocity data simultaneously. In Korea, the ω-square model was adopted by all researchers.

Following Brune (1970, 1971), the relations among corner frequency f_c, seismic moment M_0, and stress drop $\Delta\sigma_B$ are expressed as

$$\Delta\sigma_B = 7M_0/16a^3 \text{ and} \tag{4a}$$

$$a = 2.34\beta/2\pi f_c \tag{4b}$$

where a is the radius of the equivalent circular source. By removing a, equations (4a) and (4b) reduce to

$$f_c = 4.9\times10^6 \beta(\Delta\sigma_B/M_0)^{1/3} \tag{5}$$

where f_c is in Hz, β is in km/s, $\Delta\sigma_B$ is in bars, and M_0 is in dyne-cm. Given a seismic moment for which ground motions to be predicted, the only parameter to be specified in equation (3) is the stress drop.

There are two important points to be noted regarding the stress drop being discussed here. First, it is not equivalent to the original definition of stress drop. The original concept of stress drop was introduced as a static measure of final fault slip relative to fault dimension and was estimated from measurements or inferences of these geologically-based parameters (e.g., Kanamori and Anderson, 1975). Second, equation (5) gives stress drops that are surprisingly close to a constant for earthquakes of wide range of magnitude, typically about 100 bars. Moreover, the stress drops estimated by equation (5) generally show large discrepancies from those estimated by the other methods (McGuire and Hanks, 1980; Hanks and McGuire, 1981; Atkinson and Beresnev, 1997). For these reasons, the stress drop estimated by equation (5) is often called the Brune stress drop. In this article, the Brune stress drop is denoted by $\Delta\sigma_B$, in distinction from stress drops estimated by the other methods. Atkinson and Beresnev (1997) argued that the large discrepancy stems from the point source approximation which is not valid for large earthquakes due to the finite-fault effect. Therefore, as suggested by Boore (1983), the Brune stress drop here should be considered as simply a measure of the strength of high-frequency ground motion rather as a stress drop *per se*. It is interesting that Park, J.U. *et al.* (1999) treated the stress drop as an unknown parameter to be adjusted to fit the predictions to the observations.

The first estimation of the Brune stress drop in Korea was reported by Jun and Kulhánek (1991). Their estimates distribute over 8 to 56 bars. They fitted the data to a straight line, which implies increasing stress drop as increasing magnitude. However, their data do not clearly support the increasing stress drop. Rather, if the single highest estimate is removed, their data seem to exhibit the constant stress drop which is now widely accepted, at least for the stochastic prediction of ground motions.

Table 1 summarizes stress drops ($\Delta\sigma_B$), together with spectral decay parameters (κ) and shear wave velocities (β) which were estimated by independent data analyses

Table 1 Shear wave velocities (β), stress drops ($\Delta\sigma_B$), and spectral decay rates (κ) estimated from earthquakes in Korea.

References	Estimates of parameters		
	β	$\Delta\sigma_B$	κ
Noh and Lee (1995)	3.5 km/s	50 bars	1.397E-2 + 1.634E-4 R^*
Jo and Baag (2001)	3.5 km/s	100 bars	1.12E-3 + 2.24E-4 $r^\dagger$
Park, D.H. *et al.* (2001)	3.68 km/s	105 bars	1.31E-3 + 1.37E-4 r
Junn *et al.* (2002)	3.5 km/s	65 bars	5.16E-3 + 1.47E-4 r
Jo and Baag (2003)	3.5 km/s	92 bars	1.6E-2 + 1.57E-4 r

* Epicentral distance in km
† Hypocentral distance in km

for the stochastic prediction of ground motions in Korea. Table 1 shows that the stress drops in Korea distribute over a factor of 2. From equations (3) and (5), the ground acceleration A_{hf} at high frequencies scales as $A_{hf} \sim \Delta\sigma_B{}^{2/3}$. Therefore, the increment of $\Delta\sigma_B$ by 100% results in the increment of A_{hf} by about 60%.

2.2.3 Diminution function

Diminution function $D(f)$ models the spectral decay of ground motions and is represented by

$$D(f) = \exp[-\pi f r / Q(f)\beta]P(f) \qquad (6)$$

where $Q(f)$ is the quality factor and $P(f)$ is a kind of high-cut filter to make the source spectrum band-limited.

Two forms of $P(f)$ can be used (Boore, 1986). One is the Butterworth filter given by $P(f) = [1 + (f/f_m)^{2s}]^{-1/2}$ where f_m is the same as $f_{\max}$ (Hanks, 1982) and s is an integer that usually takes 4 (e.g., Boore, 1983; Boore and Atkinson, 1987). The other is the exponential filter advocated by Anderson and Hough (1984) expressed as $P(f) = \exp(-\pi\kappa_0 f)$, where κ_0 is the spectral decay rate. The subscript 0 indicates that the distance dependency is not taken into consideration. Boore and Atkinson (1987) discussed relations between f_m and κ_0. However, these relations do not mean the equivalency of $P(f)$ in the two forms. They should be understood in the context of overall feature of predicted ground motions (Boore and Atkinson, 1987; Noh and Lee, 1995).

On the other hand, Noh and Lee (1994, 1995) modeled the spectral decay rate by $\kappa = \kappa_s + \kappa_q R$. They related κ_q and κ_s to Q and κ_0, respectively to get

$$D(f) = \exp(-\pi\kappa_q f R) \cdot \exp(-\pi\kappa_s f) \qquad (7)$$

where R is the epicentral distance. Noh and Lee (1995) used equation (7) as a replacement of equation (6) because there were no reliable estimates of $Q(f)$ and f_m in Korea at that time. It should be noted that one of equations (6) and (7) is not superior to the other, as long as any of them can simulate ground motions within the scatter of observed data.

In Table 1, all but one (Noh and Lee, 1995) modeled κ as a function of hypocentral distance r. Different type of distance has different physical implication on κ_s and κ_q. If κ is modeled in terms of the hypocentral distance r, κ_s should be attributed solely to the source effect. This is analogous to the interpretation of $f_{\max}$ by Papageorgiou and Aki (1983a, b) where the high frequency energy is not generated in the earthquake source. In the other case, κ_s is attributed to both the source and recording-site effects. And κ_q is not directly related to Q.

In Table 1, the variation of κ_s is much larger than that of κ_q because corrections for the site effects of stations were not carried out. From equation (7), the effect of κ is significant at high frequencies, which implies that ground accelerations are more sensitive to the variation of κ than ground velocities or displacements.

2.2.4 Duration of ground motions

The last parameter to be specified is the duration (T_d) of ground motions, which is not explicitly expressed in the equations above. The duration controls length of the time window over which the spectral energy given by equation (1) distributes. Ground motions in the time domain decrease as increasing duration because the same amount of the spectral energy distributes over a longer time interval, and vice versa. The duration (T_d) is the sum of the source duration (T_s) and path duration (T_p). The source duration is the faulting duration, which can be estimated as $T_s \sim 1/f_c$ (Hanks, 1979; Hanks and McGuire, 1981). Herrmann (1985) attributed the path duration of *Lg* waves to the dispersion effect and approximated it to $T_p = 0.05r$. Combining these two, the duration is expressed as

$$T_d = 1/f_c + 0.05r \tag{8}$$

There are more complicated duration models on the empirical basis (e.g., Atkinson, 1995; Atkinson and Boore, 1995). Complicated duration models were studied also in Korea, but they have not been used.

3. Comparison of the predictive equations in Korea

3.1 Fourier amplitude spectra

Fig. 1 shows Fourier amplitude spectra (FASs) for moment magnitude $M = 6$ at hypocentral distance $r = 50$ km, predicted by five studies: N&L95 (Noh and Lee, 1995), P&LBK01 (Park, D.H. *et al.*, 2001), J&B01(Jo and Baag, 2001), J&JB02 (Junn *et al.*, 2002), and J&B03 (Jo and Baag, 2003). Shear wave velocities, stress drops, and spectral decay rates used are listed in Table 1. The rest parameters take same values in the five studies; $< R_{\theta\varphi} > \cdot F \cdot V = \sqrt{4/5}$, $\rho = 2.7\ \mathrm{g/cm^3}$, and $T_d = 1/f_c + 0.05r$.

P&LBK01 is smallest below 0.2 Hz due to the largest shear wave velocity. If all the spectral decay rates are comparable, FAS levels at high-frequencies ($f >> f_c$) are governed by stress drops. An exception is observed between J&JB02 and J&B03. J&B03 has a higher stress drop than J&JB02, but J&B03 becomes smaller than J&JB02 as passing over the frequency of about 8 Hz. This is because the spectral decay rate κ of J&B03 is much larger than that of J&JB02.

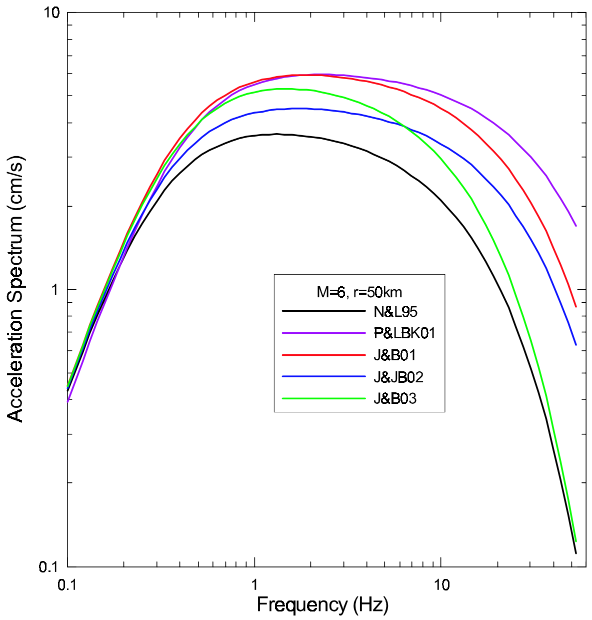


Fig. 1 Fourier amplitude spectra of ground accelerations predicted by five studies: N&L95 (Noh and Lee, 1995), P&LBK01 (Park, D.H. *et al.*, 2001), J&B01(Jo and Baag, 2001), J&JB02 (Junn *et al.*, 2002), and J&B03 (Jo and Baag, 2003).

3.2 Predictive equations

Time-domain ground motions corresponding to the FASs given by equation (1) can be calculated by applying the random vibration theory or by simulating time series (Boore, 1983). The random vibration theory saves much time for calculating ground motions, but requires additional corrections for response spectra (Boore and Joyner, 1984). Simulation of time series starts with the windowing of a time sequence of band-limited random white Gaussian noise with zero expected mean and the variance to give unit FAS on the average. The FAS of the windowed time series is multiplied by the specified FAS, and transformation back to the time domain yields the final time series (see Boore (1983) for details). Researchers except Noh and Lee (1995) took the latter: simulation of time series.

Two regression models were used to depict attenuation patterns of ground motions in the time domain:

$$\log y = c_0 + c_1 r - \log r \tag{9a}$$

$$\ln y = c_0 + c_1 r - c_2 \ln r - \ln[\min(r,100)] - \frac{1}{2}\ln[\max(r,100)] \tag{9b}$$

where y is the ground motion of interest and coefficients c_i are polynomials of magnitude as follows.

$$c_i = \xi_0^i + \xi_1^i (M-6) + \xi_2^i (M-6)^2 + \xi_3^i (M-6)^3,$$
$$i = 0,\ 1,\ \text{or}\ 2 \tag{10}$$

The last two terms in the right hand side of equation (9b) were introduced for the geometrical spreading of Lg waves. Equation (9a) was adopted by Noh and Lee (1995), Park, J.U. *et al.* (1999), and Park, D.H. *et al.* (2001) while equation (9b) by Jo and Baag (2001), Junn *et al.* (2002), and Jo and Baag (2003).

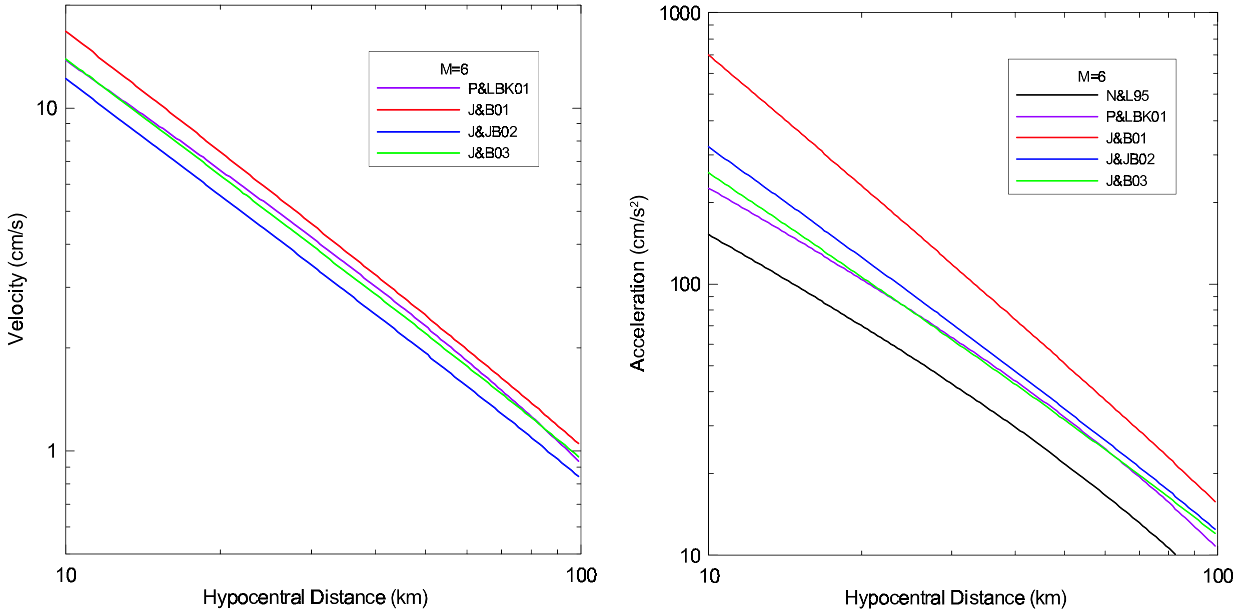
Fig. 2a and 2b show peak ground velocities (PGVs) and accelerations (PGAs) for an earthquake of $M = 6$ predicted by the same studies as in Fig. 1. The PGV prediction curve by Noh and Lee (1995) is not shown because they provided only the PGA prediction. To make the comparison simple, attenuation curves are shown up to $r = 100$ km at which geometric spreading rate changes (see equation (9)). Except for P&LBK01, the distribution patterns of predicted PGV and PGA curves are in accordance with the expectation from FASs in Fig. 1. From FASs, PGVs and PGAs of P&LBK01 are expected to be comparable to or larger than that of J&B01. But in Fig. 2, they are much smaller than those of J&B01. It is suspected that there were some errors in the calculation of FAS of J&LBK01 (Park, D.H., 2005, personal communication). For this reason, P&LBK01 will be excluded in the subsequent discussion.

J&B01 predicts the highest PGVs and PGAs, as expected from FASs. The largest difference of PGAs is observed between N&L95 and J&B01. It is mainly attributed to the difference in stress drops. [Although Noh and Lee (1995) applied the stress drop of 50 bars, they recognized that this value was uncertain due to the lack of reliable data.] It is worth noting that PGVs of J&B03 are higher than those of J&JB02 (Fig. 2a) while the converse is observed in PGAs (Fig. 2b). This feature is caused by the crossover of the two FASs at the frequency of about 8 Hz (Fig. 1).

4. Further consideration of source spectral function

Equation (3) represents the far-field shear waves radiated from a point source. Though the point source approximation makes the source spectral function extremely handy, it does not convey, in return, some important characteristics of the finite fault source such as the breakdown of similarity, the directivity effect, and the near-field effect.

The breakdown of similarity occurs when the rupture front extends beyond the nearest fault plane boundary because fault planes are neither circular nor do ruptures initiate at the centers of fault planes. As discussed by



(a) (b)

Fig. 2 Attenuation curves predicted by the studies in Fig. 1: (a) attenuation curves for peak ground velocities (Noh and Lee (1995) is not available for PGV), (b) attenuation curves for peak ground accelerations.

Atkinson (1993), it is also expected based on rupture models that account for fault roughness such as the Brune (1970) partial stress drop model, the asperity model (Hartzell and Brune, 1979; McGarr, 1981), the specific barrier model (Papageorgiou and Aki, 1983a, b), and multiple-event models (Joyner and Boore, 1986; Boatwright, 1988). As a remedy for the breakdown of similarity, Joyner (1984) introduced the modified source spectral function with a pair of corner frequencies which takes the different values below and above a certain critical seismic moment. Joyner's approach was further studied by several researchers (e.g., Boore and Joyner, 1991; Atkinson, 1993; Atkinson and Silva, 2000). However, the two-corner frequency source model cannot still accommodate the near-field effect and directivity.

Beresnev and Atkinson (1997) proposed a synthetic source model to accommodate the effect of finite-fault rupture. In their model, the rupture plane is divided into sub-planes each of which is small enough to be approximated to the point source. The rupture initiates at the hypocenter and propagates to neighboring sub-planes with a specified rupture velocity. They applied it to the modeling of ground motions from the 1994 Northridge, California, earthquake (Beresnov and Atkinson, 1998a, b). Junn *et al.* (2002) also applied it to the development of predictive equations in the Korean Peninsula. [Junn *et al.* (2002) also provided the comparison of ground motions predicted by the point-source method and the finite-fault method.] Compared to the point source model, the source model of Beresnev and Atkinson (1997) is certainly an improved one. But it requires additional faulting information such as the rupture length and width which are unique to the fault of interest but are rarely available, especially for future events. Therefore, the source model should be selected by taking into account of available information.

5. Discussion and Conclusion

It is clear from the preceding discussion that the (Brune) stress drop $\Delta\sigma_B$ and spectral decay rate κ are the most uncertain parameters and they are the main sources of differences of the predictive equations in Korea. Therefore, it is necessary to focus the future research on the reduction of the uncertainties in the two parameters. Fortunately, KISS produces a large amount of high-quality seismic data recorded. This must encourage Korean seismologists. However, they still have a problem that strong motion data from large earthquakes greater than magnitude 5 are rare. Therefore, seismologists should carefully check if the stress drop estimated from small earthquakes is valid also for large earthquakes, even if the constant stress drop is assumed.

When dealing with the seismic data from small earthquakes, we face the low signal-to-noise (S/N) ratio problem. In this case, low-frequency levels of displacement FASs (i.e., seismic moments), corner frequencies, and spectral decay rate can be seriously distorted. Misestimate of the former two parameters leads to erroneous stress drops. Basically, the S/N ratio can be improved by installing seismographs at a quiet site or down in the borehole. This requires much money as well as time. As a trick to improve the S/N ratio, Noh *et al.* (2003) proposed the composite Fourier spectrum which is the vector norm of three component FASs. This simple processing enhances the coherent seismic signals and suppresses non-coherent noises in the three components. The composite Fourier spectrum method was successfully applied by Choi *et al.* (2004) in the estimation of seismic moments and corner frequencies of Korean earthquakes. The method of Noh *et al.* (2003) is useful in that it can be applied to all multi-channel seismic data.

Acknowledgement

I thank Mr. N.-D. Jo at Seoul National University and Ms. D.H. Park at KEPRI for their thoughtful review of the draft manuscript.

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