한반도 남부 지역의 지진동 감쇄식 개발

Development of Attenuation Equations of Ground Motions in the Southern Part of the Korean Peninsula

박 지 억* 노 명 현** 이 기 화***
Park, Ji Uk Noh, Myung Hyun Lee, Kie Hwa

국문요약

본 연구의 목적은 한반도 남부 지역에서의 지진동 감쇄식을 개발하는 것이다. 활용 가능한 계기 지진 자료로부터 지진원 및 지반 매질의 특성을 추정하고 그 값을 입력 요소로써 사용하였다. 확률진동이론에 의하여 최대 지반가속도 및 의사 속도 응답스펙트럼을 모사하여, 이로부터 최대 지반 가속도 및 의사 속도 응답스펙트럼에 대한 감쇄식을 지역규모(local magnitude) 및 진원거리의 함수로 개발하였다.

주요어 : 지진동 감쇄식, 최대 지반 가속도, 의사 속도 응답스펙트럼, 확률진동이론

ABSTRACT

The objective of the study is to develop attenuation equations of the ground motions in the southern part of the Korean peninsula. The earthquake source characteristics and the medium properties were estimated from available instrumental earthquake records and used as input parameters. The peak ground accelerations(PGA) and pseudo-velocity response spectra(PSV) were simulated by the random vibration theory. The attenuation equations for the PGA and PSV were constructed in terms of local magnitudes and hypocentral distances.

Key words : *attenuation equation of ground motion, peak ground acceleration, pseudo-velocity response spectrum, random vibration theory*

1. Introduction

Development of the attenuation equations of peak ground motions and response spectra in the Korean Peninsula were hampered by the lack of a strong-motion database from which a direct empirical relationship could be derived. For this reason, the attenuation equations developed in the other regions(usually northern part of the United States) were frequently referred to in the past seismic-hazard studies of the Korean Peninsula. It has been noted that the use of them was one of the most important source of uncertainties in the final result of the seismic hazard analysis.

Based on a few felt earthquakes in the Korean Peninsula during the 20th century, the attenuation equations of peak ground acceleration has been developed for the seismic hazard analysis, by converting intensities to peak accelerations. However, the attenuation equations developed in this way are no better than those in the other regions because the intensity-acceleration conversion formulae them-

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* Student member · Graduate Student, Dept. of Geological Sciences, Seoul National University
** Member · Senior Researcher, Korea Institute of Nuclear Safety
*** Member · Professor, Dept. of Geological Sciences, Seoul National University

본 논문에 대한 토의를 6월 30일까지 학회로 보내 주시면 그 결과를 게재하겠습니다.

selves were not only derived from the earthquakes in the other regions but also accompanied by uncertainties from the scatters of data used.

Considering the low seismic activity of the Korean Peninsula, it would take a long time to develop an empirical attenuation equation by using Korean earthquake data. An alternative to the empirical attenuation equation was proposed by Noh and Lee.(1),(2) Noh and Lee(1),(2) developed attenuation equations of ground motions by the random vibration theory. Parameters required to characterize earthquake sources and medium properties were estimated from small earthquakes in the southeastern part of the Korean Peninsula. From the methodological view point, the present study follows the same line as Noh and Lee(1),(2). However, the present study differs from Noh and Lee(1),(2) on two points. First, the local magnitudes (M_L) of earthquakes are employed in the attenuation equations. Although moment magnitude (M) is in worldwide use as an unified measure of an earthquake size, the local magnitude is more widely used in Korea. Second, the correction of attenuation equations is made by using observed ground motion values. In Noh and Lee(1),(2), the correction of the attenuation equations was not considered because the absolute ground motions of the analyzed earthquakes could not be recovered.

2. Determination of input parameters

Earthquake records analyzed in this study were acquisited from the seismic network operated by KIGAM(Korea Institute of Geology, Mining and Materials)(Chi et. al.(3)). Origin times, locations and local magnitudes of the selected earthquakes are listed in Table 1.

Table 1 Origin times, epicentral locations and local magnitudes of the selected earthquakes

Origin time (year/month/day, hour:minute:second)	Latitude of Epicenter(° N)	Longitude of Epicenter(° E)	Local Magnitude
95/12/06, 17:47:22.60	36.4119	128.1366	3.1
95/12/21, 08:25:26.91	36.4100	128.1400	3.1
95/12/22, 05:24:48.33	34.1311	130.2294	3.3
96/02/27, 04:39:33.98	35.5700	129.2955	3.0
96/03/02, 21:42:06.70	36.1965	127.5430	3.3
96/03/20, 04:54:12.45	36.4327	128.1665	3.0
96/04/14, 02:20:47.64	35.5069	127.5638	3.1
96/04/14, 05:22:11.05	35.5190	127.5358	3.9
96/05/06, 07:46:40.15	33.4548	128.4000	3.3
96/05/06, 21:02:58.12	35.5033	127.5847	3.0
96/05/07, 00:12:59.17	34.4519	127.2356	3.8
96/05/13, 00:49:27.12	35.5000	130.2190	3.9
96/05/13, 08:08:55.73	35.4943	130.2006	3.1
96/05/16, 11:05:43.27	35.1850	129.0691	3.0
96/06/21, 01:04:07.77	36.0212	126.5400	3.2
96/08/03, 00:06:58.96	37.2332	129.4525	3.2
96/08/14, 18:10:03.06	36.4100	128.0175	3.5
96/09/27, 19:32:23.89	35.3583	129.4857	3.1
96/10/16, 04:45:30.40	36.1243	128.1883	3.8
96/10/25, 00:39:23.04	35.5187	127.5308	3.3

Table 2 lists the parameters necessary for the application of the random vibration theory. The detailed description of the parameters can be found in Noh and Lee(1),(2). The same values of the parameters presented by Noh and Lee(2) except $\Delta\sigma$ were adopted in this study. The upper six parameters in Table 2 are region-dependent. Among the six parameters, our main concern is the analyses of the apparent stress drop $\Delta\sigma$ and the spectral decay parameters κ (or $f_{\max}$) and Q.

2.1 Diminution of Fourier amplitude spectrum of ground acceleration at high-frequencies

The diminution of the Fourier spectrum shape of ground acceleration at high frequencies can generally be modeled by high-cut filter. The filters can be classified into two types. One is described by Q and $f_{\max}$ and the other by κ. As in Noh and Lee(1),(2), the exponential filter in terms of κ was also used in the present study. Because the distribution of epicentral distances is inadequate for the analysis of κ, the present study did not perform an independent analysis of κ, but adopted κ proposed by Noh and Lee(1),(2), which is rewritten as

$$\kappa = 1.4\times10^{-2}(\pm3.8\times10^{-3}) + 1.6\times10^{-4}(\pm3.9\times10^{-5})r \qquad (1)$$

2.2 Estimation of apparent stress drop

As mentioned before, there are two distinctive features of the present study: (i) The local magnitudes are employed in the attenuation equations, (ii) The attenuation equations are fitted into observations. These two goals are accomplished together in a single process of estimating apparent stress drop, $\Delta\sigma$. Fixing all the parameters in Table 2 except $\Delta\sigma$, the ground motion values are repeatedly computed with various $\Delta\sigma$ values and compared with observed ground motion values. Then, we select a value of estimated apparent stress drop that minimizes the differences between computed and observed ground motions. Therefore, there is all the difference between the $\Delta\sigma$ of the present study and the conventional stress drop. It should be noted that the $\Delta\sigma$ in the present study is simply a variable to be adjusted for fitting the computed ground motion values to the observed ones.

We chose the peak ground acceleration as a comparison parameter of observations and simulations. The instrument-corrected PGA

Table 2 Input parameters used for the development of attenuation equations

Parameter	Description of parameter	Value of parameter
$\Delta\sigma$	Apparent stress drop	10 bars
β	Shear wave velocity near the source	3.5 km/s
ρ	Density of the medium near the source	2.7 g/cm^3
κ	Fourier spectrum decay parameter	$1.4\times10^{-2}+1.6\times10^{-4}r$
Q	Effect of wave path	-
f_{max}	High-frequency Fourier spectrum decay parameter	-
F	Free surface effect(SH wave)	2
$\langle R_{\theta\phi} \rangle$	Average radiation pattern(S wave)	0.63
V	Partition of a vector into horizontal component	$1/\sqrt{2}$

were used as the observed PGA. To obtain the value of the observed PGA from the available earthquake data of velocity type we followed the procedure for the instrument correction suggested by KIGAM.(4) These observed PGA are compared with the PGA computed by applying the random vibration theory.

For the purpose of computation of simulated PGA, the observed earthquakes in Table 1 were grouped into four magnitude groups, i. e., M_L=3.0, 3.1 as M_L=3.05, M_L=3.2, 3.3 as M_L=3.25, M_L=3.5 as M_L=3.5, and M_L=3.8, 3.9 as M_L=3.85. For each magnitude group, PGA were computed at every corresponding epicentral distance of the observations.

The result turned out that the minimum RMS differences between the observed PGA and the computed ones are achieved at the range of $\Delta\sigma$ from 3 to 12 bars. For each magnitude group of M_L=3.05, M_L=3.25, M_L=3.5, and M_L=3.85, we obtained $\Delta\sigma$'s of 3, 6, 10, and 12 bars, respectively. This result shows an interesting tendency that $\Delta\sigma$ increases as the magnitude increases.

In the case of larger earthquakes of $M_L \geq 5.0$, we cannot deny the possibility that we may adopt the value of $\Delta\sigma$ larger than 12 bars. However, the lack of strong earthquakes data in the Korean Peninsula gives no guarantee that the increasing trend of $\Delta\sigma$ will be continued in the range of larger magnitude.

Based on the comparison result fitted into observations and focused on the earthquake motions for larger magnitudes, $\Delta\sigma$ of 10 bars is adopted and then applied to the computation of the peak ground accelerations and the pseudo-velocity response spectra which are used in the development of attenuation equations.

The $\Delta\sigma$'s estimated in this study are much lower than the value of 50 bars adopted by Noh and Lee.(2) We used the local magnitudes of the observed earthquakes determined by Chi et. al.(3) without correction for the estimation of the apparent stress drop. However, it is pointed out that the local magnitudes determined by Chi et. al.(3) may overestimate the Richter's local magnitudes.(4) The lower estimated $\Delta\sigma$'s can be partly resulted from the highly determined local magnitudes by Chi et. al.(3)

3. Results and comparison

Attenuation equations for peak ground accelerations(PGA) and pseudo-velocity response spectra(PSV) were constructed based on the computed values by random vibration theory. In this study, the data consisted of the computations at 11 epicentral distances, distributed at equal logarithmic intervals between 10 and 100 km, and for 11 local magnitudes at equal intervals between 5.0 and 7.5. The predicted PGA and PSV(5% damping) are fitted to the following equations by the least squares method.

$$\log_{10} y = c_0 + c_1 R - \log_{10} R \tag{2}$$

and

$$c_i = \xi_0^i + \xi_1^i (M_L - 6) + \xi_2^i (M_L - 6)^2 + \xi_3^i (M_L - 6)^3, \quad i = 0, 1, \tag{3}$$

where y, R and M_L are predicted PGA (cm/s^2) or PSV (cm/s^2), hypocentral distance (km) with a uniform focal depth of 10 km and local magnitude, respectively. The coefficients, ξ are given in Table 3.

Table 3 Coefficients of the attenuation equations for the peak ground accelerations ($a_{\max}$) and pseudo-velocity response spectra

Natural frequency		ξ_0	ξ_1	ξ_2	ξ_3
0.2 Hz	c_0	1.58615	0.909788	-0.168759	-0.102104E-01
	c_1	-0.105381E-02	-0.189277E-03	-0.572244E-03	0.377726E-03
0.5 Hz	c_0	1.79335	0.588258	-0.157304	0.401338E-01
	c_1	-0.159951E-02	-0.178094E-03	0.190465E-03	-0.278482E-04
1.0 Hz	c_0	1.79000	0.452038	-0.835927E-01	0.212819E-01
	c_1	-0.202176E-02	0.145665E-03	0.141858E-03	-0.584578E-04
2.0 Hz	c_0	1.71655	0.382792	-0.457077E-01	0.102689E-01
	c_1	-0.246042E-02	0.420174E-03	0.409379E-04	-0.529374E-04
5.0 Hz	c_0	1.54405	0.337127	-0.259730E-01	0.570779E-02
	c_1	-0.326803E-02	0.669057E-03	-0.760881E-04	-0.364332E-04
10.0 Hz	c_0	1.34720	0.319073	-0.196885E-01	0.460846E-02
	c_1	-0.431921E-02	0.788030E-03	-0.137650E-03	-0.247856E-04
20.0 Hz	c_0	1.05448	0.308252	-0.163720E-01	0.410355E-02
	c_1	-0.587387E-02	0.889311E-03	-0.190653E-03	-0.128754E-04
30.0 Hz	c_0	0.808280	0.304216	-0.153219E-01	0.394024E-02
	c_1	-0.648644E-02	0.966801E-03	-0.227023E-03	-0.385421E-05
$a_{\max}$	c_0	2.76736	0.310489	-0.180915E-01	0.497951E-02
	c_1	-0.434029E-02	0.978632E-03	-0.228263E-03	-0.538469E-05

In Fig. 1, the peak motion parameters computed from equations (2) and (3) are compared with those by Noh and Lee.(2) Results by Noh and Lee(2) were selected for comparison because their results were obtained by using the same method as that employed in the present study. On the whole, the peak motion values from equations (2) and (3) are smaller than those predicted by Noh and Lee.(2) Such smaller values can be explained by the lower apparent stress drop(10 bars) than that adopted by Noh and Lee.(2) Note that the predicted peak motions in Fig. 1 are expressed with different magnitude scales. However, there is no regional relation between two magnitude scales developed for the earthquakes in the Korean Peninsula. The close examination of the variation in predictions according to different magnitude scales couldn't be made. A rough comparison of predictions could be made based on the viewpoint that moment magnitude (M) generally agrees with M_L between $3 < M_L < 7$ for the earthquakes in other regions.(5)

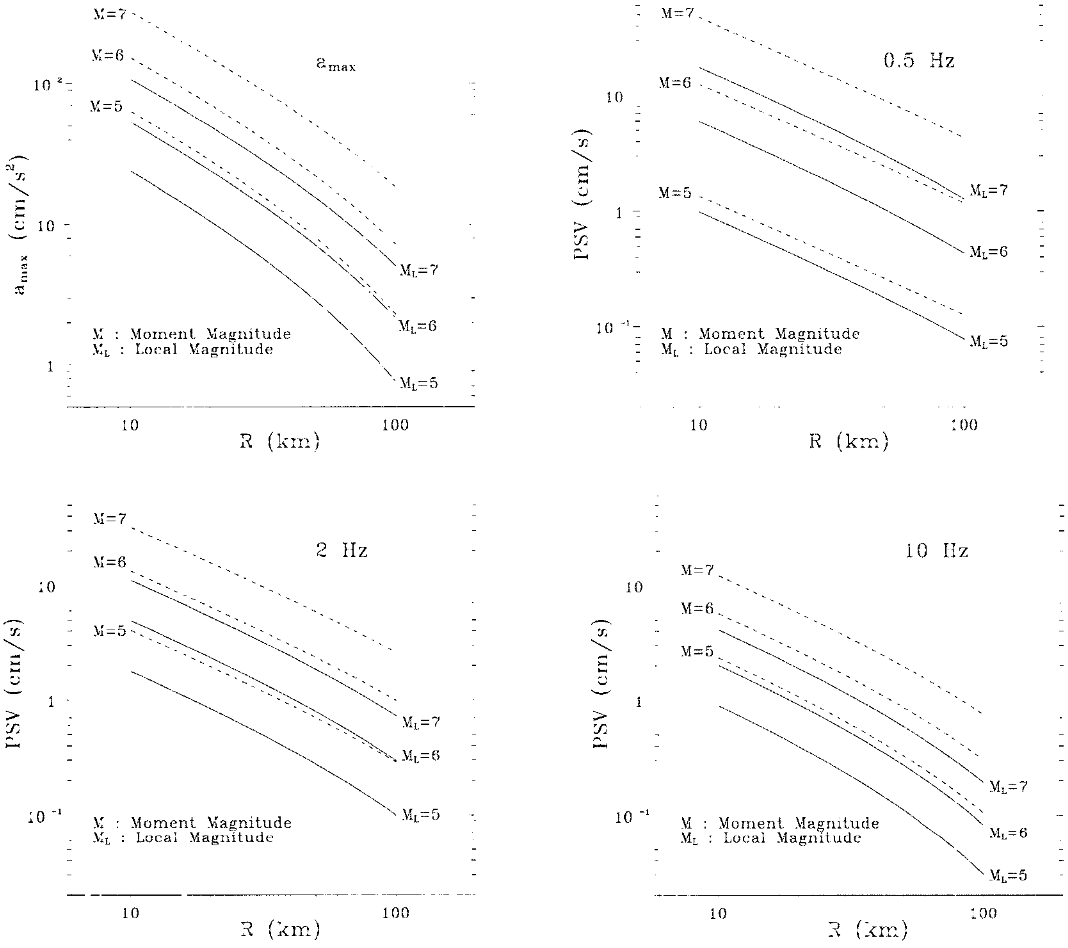

Fig. 1 Comparison of peak ground accelerations(a_{max}) and 5% damped pseudo-velocity response spectra(PSV) at natural frequencies of 0.5, 2 and 10 Hz for magnitudes of 5, 6 and 7. Solid lines and dotted ones represent the predictions by the present study and those by Noh and Lee(2), respectively. R(km) is hypocentral distance.

4. Conclusion and discussion

The attenuation equations for the peak ground accelerations and the pseudo-velocity response spectra(5% damping) at 8 natural frequencies were newly presented. These equations are represented in terms of local magnitude and hypocentral distance. They can be applied directly to the estimation of motion parameters in the Korean Peninsula without any magnitude conversion because all the magnitudes of Korean earthquake are presented in local magnitude scales.

The attenuation equations were constructed from the instrumental records from earthquake occurred in the southern part of the Korean Peninsula. The local magnitudes of these earthquakes range from 3.0 to 3.9. Therefore, the attenuation equations of the present study extrapolate the ground motions for the larger earthquakes($M_L > 3.9$). Whatever method may be used for the development of attenuation equations, the problem of the extrapolation would not be settled unless large earthquakes occur in the Korean Peninsula and are recorded by the appropriate seismic systems. High quality earthquake records through the accelerograph could reduce the errors which may be generated in the process of instrumental correction or transformation into different seismic systems. Accordingly, more precise estimation of ground motion parameters would be accomplished through the accelerogram of high quality.

Finally, we emphasize once again that the apparent stress drop(3-12 bars) estimated in this study is just a variable minimizing the difference between the predictions and the observations. Therefore, the stress drop of this study is quite different from that conventionally used.

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