한반도의 최대지진

Maximum Earthquakes in the Korean Peninsula

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요 지

한반도 주요 지체구조구에 대한 최대지진을 지진 및 지질자료를 이용하여 여러 가지 방법으로 결정하였다. 한반도에서 발생한 가장 큰 지진은 MMI IX - X의 범위에 걸치며 이는 M = 7.0 - 7.7 에 해당한다. Gumbel의 극대치 제3분포를 이용하면 지체구조구별 최대지진은 M = 7.1 - 7.9 의 범위에 놓이고, 응력방출 양상을 분석하면 M = 6.7 - 7.7 가 도출된다. 단층길이와 규모와의 상관관계에서 최대지진은 M = 7.4 - 7.6 에 놓인다. 한반도의 주요 지체구조구 사이에 최대지진의 현격한 차이를 나타내는 지진 및 지질학적 증거는 없다. 역사지진의 평가에서 강진들은 대략 1 계급 (M = 0.7) 과대 평가되는 경향이 있으므로, 한반도의 최대지진은 대략 M = 7.0으로 추정된다.

1. INTRODUCTION

Reasonable estimation of earthquake ground motions is very important in earthquake engineering and seismic hazard analysis. In this analysis, we attempt to estimate maximum earthquakes in major tectonic provinces of Korea. Maximum earthquake is one of the most important parameters in design earthquake in earthquake engineering.

Maximum earthquake can be estimated by analyzing earthquakes data and active faults (Yegulalp and Kuo, 1974; Matsuda, 1976; Reiter, 1990; Kijko and Sellevoll, 1992: Yeats *et al.*, 1997) Maximum earthquakes in Korea were estimated by Lee and Kim (2000) and Kim *et al.* (2000) by statistical analysis of Korean historical and instrumental earthquakes.

The Korean Peninsula lies in the Eurasian Plate and its seismicity shows the typical characteristics of the intraplate seismicity, a very irregular strain release in both space and time. The seismicity of the peninsula is poorly understood due to lack of reliable instrumental data; furthermore, its understanding depends heavily on the incomplete historical earthquake date.

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The present study will use the strain release pattern dominated by historical earthquakes and distributions of surface faults in major tectonic provinces of the peninsula in estimating maximum earthquakes therein.

2. DATA

2.1. Earthquake Data

Studies of Korean historical earthquakes have been made by Japanese seismologists during the Japanese rule of Korea (Wada. 1912; Musha, 1951) and Korean seismologists since the late 1970s. To date, the most complete and reliable historical earthquake catalogue is that of Lee (2000), comprising 1965 earthquake records from historical literatures such as Samgooksagi, Koryosa, and Choseonwanjosillog. He estimated the epicenters and intensities of these earthquakes. Lee's catalogue of Korean historical earthquakes was used in this study.

For instrumental earthquake data since 1905, we used the data of Bulletins of Meteorological Observatory of the Government General of Korea during 1905-1945 and those of Korean Meteorological Administration since 1945 until 2000. In addition to these instrumental data, those of Lee and Jung (1980) and Kim (1980) were also used in this study.

2.2. Geological Data

The Korean peninsula is located between seismically highly active Japanese Islands and China. The peninsula is connected geologically to China. Massifs of Precambrian basement and basins of Paleozoic and Mesozoic sediments constitute the peninsula (Reedman and Um, 1975). Some Cenozoic volcanic extrusives are found along the Chugaryeong Graben Zone and Cheju and Ulreung islands.

The Korean Peninsula may be broadly divided into about 16 tectonic units (KIGAM, 1995). Characteristics of faults in these tectonic units are not well understood. Especially, the relationship between the seismicity and faults is very poorly understood. In the peninsula, only the Yangsan fault is admitted to be seismically active (Lee and Na, 1983: Lee and Jin, 1991). At present, it is difficult to tell which faults on geological map of KIGAM (1995) are seismically active.

Since we are concerned about the maximum earthquakes in this study, we assume the largest faults in major tectonic provinces are active and attempt to estimate maximum earthquakes corresponding to the faults. Following Lee and Kim (2000), we estimated maximum earthquakes for only 5 major tectonic provinces, i.e., Pyongnam Basin, Kyonggi Massif, Okchon Folded Belt, Ryongnam Massif, and Kyongsang Basin, and for the whole peninsula since there are not sufficient earthquake data for other tectonic provinces. Figure 1 shows the 5 major tectonic provinces of this study. The largest faults manifested on geological map of KIGAM are the basic geologic data in estimating maximum earthquakes from the relationship between fault and magnitude.

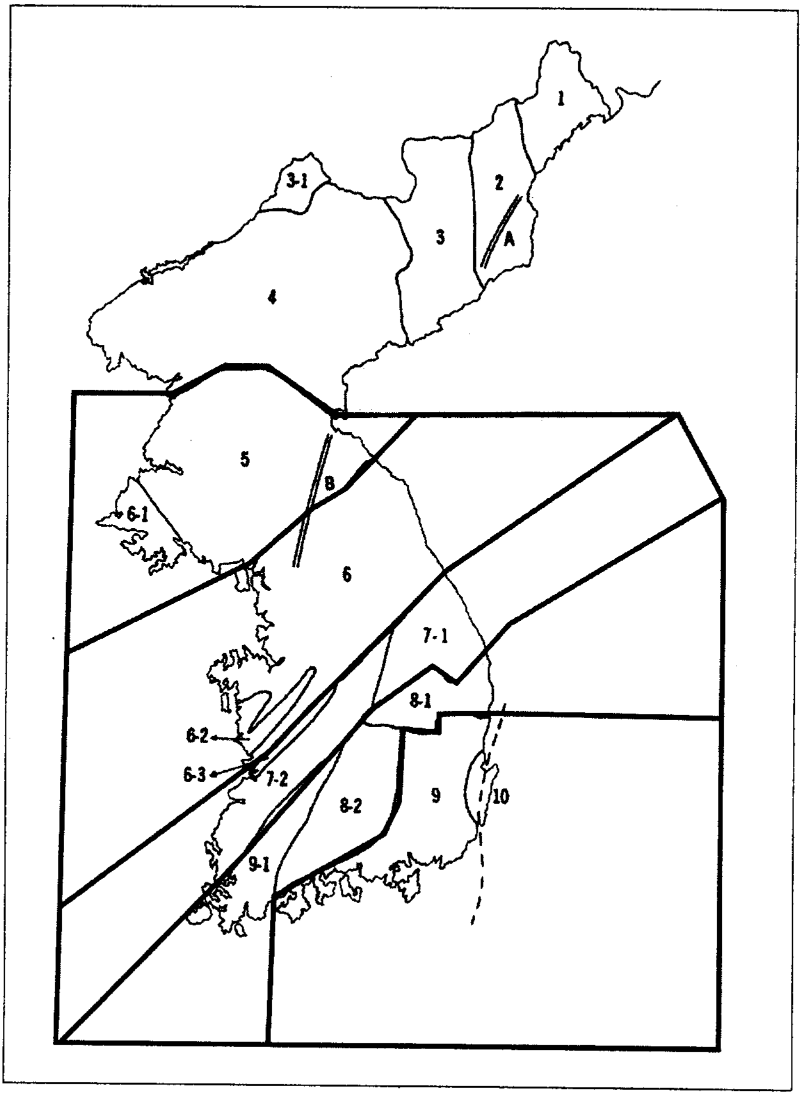

Figure. 1. Major tectonic provinces of Korea (5 : Pyongnam Basin, 6 : Kyonggi Massif, 7 : Okchon Folded Belt, 8 : Ryongnam Massif, 9 : Kyongsang Basin)

3. ANALYSIS OF DATA

3.1. Earthquake Data

There are several ways of estimating maximum earthquakes from analysis of earthquake data.. Lee and Kim (2000) estimated maximum earthquakes for 5 major tectonic provinces of the Korean peninsula as well as for the whole peninsula by the method of Kijko and Sellevoll (1992) which employs the extreme value statistics and maximum likelihood method to incomplete and complete earthquake data in the lump.

In this study, we will employ three methods, i.e., the largest earthquakes ever occurred, the Gumbel's (1960) extreme value statistics of third type, and analysis of strain release pattern (Makropoulos and Burton, 1983).

3.2. Largest Historical Earthquakes

The largest earthquakes ever occurred in various tectonic provinces may be lower bounds of maximum earthquakes. The seismicity of the Korean peninsula during the 20th century is rather low compared to those of earlier times as evidenced in historical literatures.

For the historical earthquakes, we can estimate only their intensities, not magnitudes. The intensity I of the historical earthquake may be converted to magnitude M by the following relation.

$$M = 1 + \frac{2}{3} I \tag{1}$$

The largest historical earthquakes ever occurred in 5 major tectonic provinces of the peninsula based on the compilations of Lee (1998 , 1999) are given in Table 1.

It should be noted that the error usually involved in estimating intensity of historical earthquake is ± 1, which is about ±0.7 in magnitude. As a whole, historical seismicity data shows the maximum earthquake for the Kyongsang Basin is about M = 7.7 and those for other areas of the peninsula are about M = 7.0.

Table 1. The Largest Historical Earthquakes Occurred in Major Tectonic Provinces

Geological Unit	MMI	M
Pyongnam Basin	IX	7.0
Kyonggi Massif	IX	7.0
Okchon Folded Belt	IX	7.0
Ryongnam Massif	IX	7.0
Kyongsang Basin	X	7.7

3.3. Extreme Value Method

Let X be a random variable with a probabilistic function of *F(X)*

$$F(x) = P(X \leq x)$$

If the initial distribution function *F(x)* is known, it is easy to derive the exact distribution of the largest values. In most cases, however, the initial distribution function is not known. It is then necessary to deal with the asymptotic forms of distributions. There are only three asymptotic distributions of extremes, and each assumes a specific behavior for absolute large values of the variate (Gumbel, 1960).

In the first asymptotic distribution, the variate is unlimited in both directions. In the second asymptotic distribution, a lower limit for variable X exists. There exists an upper limit in the third asymptotic distribution of the largest values. For the occurrence of maximum earthquakes, the third asymptotic distribution naturally has a better physical meaning for a probabilistic model than either the first or the second distribution. Therefore, we consider only the third asymptotic distribution in this study.

The third asymptotic distribution of the largest value is defined by

$$\Phi_n^{(3)}(x) = \exp[-(\frac{\omega - x}{\omega - u_n})^{k_n}], \ k_n > 0, \ x \leq \omega, \ u_n < \omega \qquad (2)$$

where w is the upper limit of largest values, k_n is the shape parameter, u_n is the characteristic largest value, and $\Phi_n^{(3)}(u_n) = 1/e$ and $\Phi_n^{(3)}(\omega) = 1$.

Yegulalp and Kuo (1974) gave three methods of estimating parameters of the third asymptotic distribution. For the case that there are missing earthquake data for certain periods, he recommended to use the least square method. For Korean historical earthquake data, there are a number of time intervals of no earthquake records. Therefore, we adopted the least square method to estimate parameters of third asymptotic distribution.

We put together historical and instrumental earthquake data of the peninsula and picked up the largest earthquakes for the period of 50 years in 5 major tectonic provinces of the peninsula as well as the whole peninsula. The intensities of the historical earthquakes are converted into magnitudes by equation (1). When there are only records of small earthquakes whose intensities are difficult to estimate for certain time interval, we assumed the maximum earthquake during the period is MMI Ⅳ. The estimated parameters including maximum earthquake by this approach for major tectonic units are given in Table 2. For other time intervals such as 30 and 100 years, estimated maximum earthquakes for certain areas turned to be unacceptably large; for instance, M=12.9 for 30 years and M=34.4 for 100 years in the Okchon Folded Belt, probably due to incompleteness of historical data.

Table 2 shows the results for major tectonic provinces and the whole peninsula.
Maximum earthquakes estimated by Gumbel's third asymptotic distribution range from M=7.1 in the Kyonggi Massif to M=7.9 in the Ryongnam Massif.

3.4. Strain Release Pattern

The relationship between the magnitude and the frequency of earthquake occurrence in a region is given by the following Gutenberg - Richter formula.

Table 2. Estimated Parameters of the Third Asymptotic Distribution

Geological Unit	ω	u	$\lambda = 1/k$
Pyongnam Basin	7.17	4.75	1.00
Kyonggi Massif	7.06	4.37	1.05
Okchon Folded Belt	7.10	5.35	0.67
Ryongnam Massif	7.88	5.14	0.48
Kyongsang Basin	7.56	4.32	0.95
Whole Peninsula	7.53	5.93	1.59

$$\text{LogN} = a - bM \quad (3)$$

where N is the number of earthquakes with magnitudes equal to or above M, and a and b are constants characteristic of the region concerned.

On the other hand, the energy of earthquake is related to its magnitude as

$$\text{LogE} = A + BM \quad (4)$$

Båth (1975) gave 12.24 and 1.44 for values of A and B, respectively.

Earthquake energies of historical earthquakes can be estimated by equations (1) and (9).

Makropoulos and Burton (1983) proposed a method of estimating maximum earthquakes by examining the strain release pattern in a certain region using the relationships (8) and (9) analytically and graphically. In this study, we adopted the graphical method of estimating maximum earthquake since the historical earthquake data are incomplete.

If we draw the cumulative seismic energy release against time from earthquake data in a certain area, the line connecting the initial and final points gives the mean annual seismic strain release which is the vertical difference divided by data period. We can draw two lines enveloping the cumulative energy release diagram parallel to the straight line representing the mean annual strain release. The vertical difference between these two parallel lines gives the maximum earthquake. Figure 2 to 7 show cumulative strain energy diagrams for 5 major tectonic provinces as well as the whole peninsula. Table 3 shows maximum earthquakes estimated by analysis of strain release pattern.

For the whole Korean peninsula, the maximum earthquake turns out to be M=7.7. Maximum earthquakes for major tectonic provinces of the peninsula range from M=6.7 for the Okchon Folded Belt to M=7.7 for the Kyeongsang Basin.

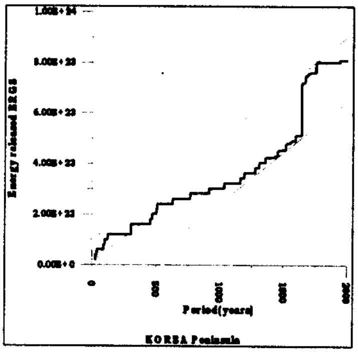

Fig. 2. Strain energy release in Korea

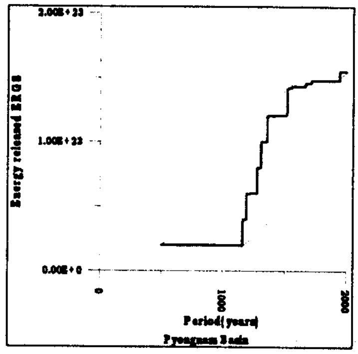

Fig. 3. Strain energy release in Pyongnam Basin

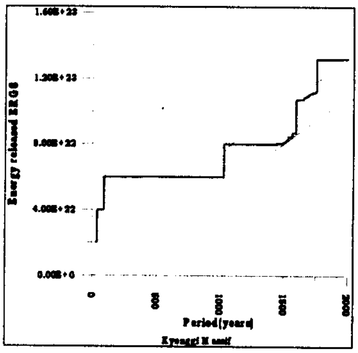

Fig. 4. Strain energy release in Kyonggi Massif

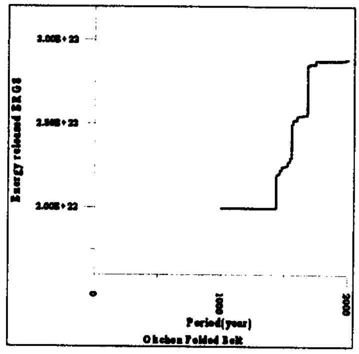

Fig. 5. Strain energy release in Okchon Folded Belt

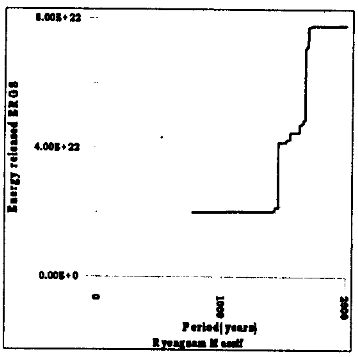

Fig. 6. Strain energy release in Ryongnam Massif

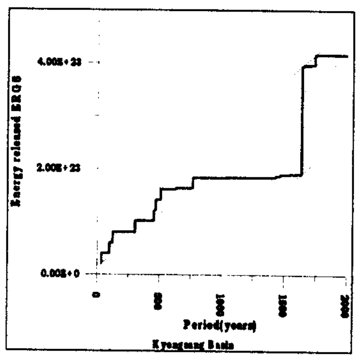

Fig. 7. Strain energy release in Kyongsang Basin

3.5. Geological Data

There exist empirical relations relating earthquake magnitude to associated surface faulting and deformation. Matsuda (1976) made an extensive compilation of these relationships. Among these relationships, we will use that of between magnitude and surface fault length.

Table 3. Maximum Earthquakes by Strain Energy Release Analysis.

Geological Unit	E/year	E_{max}	M_2	M_3
Pyongnam Basin	9.02E+19	6.9E+22	5.44	7.36
Kyonggi Massif	5.68E+19	5.91E+22	5.30	7.31
Okchon Folded Belt	8.91E+18	6.12E+21	4.77	6.66
Ryongnam Massif	4.7E+19	3.68E+22	5.25	7.18
Kyongsang Basin	2.02E+20	2.03E+23	5.67	7.67
Whole Peninsula	4.01E+20	2.49E+23	5.87	7.73

3.6. Surface Fault Length

The magnitude of earthquake may be related to the associated surface fault by

$$\text{Log } L = \alpha M - \beta \text{ (L in km)} \tag{5}$$

where α and β are constants characteristic of the area concerned.

Matsuda's compilations are listed in Table 4.

Table 4. α and β in Eq. (5) for various regions

Region	α	β
USA	1.02	5.76
World-wide	1.32	7.99
Anatolia	1.14	6.38
Japan	0.6	2.9

We measured the largest surface fault lengths for 5 major tectonic provinces from Geological map of Korea (KIGAM, 1995) and obtained maximum magnitudes from equations (11) to (14). The results are listed in Table 4. The maximum earthquakes obtained from the relation for Japan which lie between M=8.6 and M=8.3 is particularly greater than the values obtained from relations for other regions which range from M=7.4 to M=7.8. In the light of the generally low intraplate seismicity of the Korean peninsula, the values obtained from the relation for Japan seems unacceptably large; the values obtained from the relation for Anatolia, ranging from M=7.4 in the Okchon Folded Belt to M =7.6 in the Kyongsang Basin, seems rather reasonable.

Table 4. Maximum Earthquakes by Fault Length.

Geological Unit	USA	World - Wide	Anatolia	Japan
Pyongnam Basin(146km)	7.77	7.69	7.50	8.44
Kyonggi Massif(138km)	7.74	7.67	7.47	8.40
Okchon Folded Belt(123km)	7.70	7.64	7.43	8.32
Ryongnam Massif(130km)	7.72	7.65	7.45	8.36
Kyongsang Basin(170km)	7.83	7.74	7.55	8.55

4. DISCUSSIONS AND CONCLUSIONS

Intensities of historical earthquakes generally tend to be overestimated due to scarce seismic informations which are, furthermore, seriously affected by local site effects. The estimated intensities of Korean historical earthquakes may err by about one unit; it is likely that the intensities of maximum historical earthquakes of Lee's (1999) catalogue are smaller than actual values by about one unit.

The largest historical earthquakes ever occurred in the peninsula range from MMI IX to X which correspond to M=7.0 and M=7.7, respectively. If these intensities are overestimated by one unit, maximum earthquakes will range from M= 6.3 and 7.0; these lower values seem more reasonable taking into account the general low intraplate seismicity of the peninsula.

Method of Gumbel's (1960) third asymptotic distribution reveals the maximum earthquake in the peninsula lie between M=7.0 and M=7.9, while analysis of strain release indicates they lie between from M=6.7 and M=7.8. Maximum earthquakes estimated by lengths of the largest faults range from M=7.4 to M=7.6.

Previous study of Lee and Kim (2000) showed that there exist no significant seismic distinctions among major tectonic provinces of the peninsula. The generally low intraplate seismicity of the Korean peninsula as well as the likelihood of overestimation of sizes of strong historical earthquakes taken into account, various methods of this study indicate M=7.0 may be recommended as the maximum earthquake in the peninsula, irrespective of different tectonic provinces, for the time.

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