남 · 북한 지진 목록을 이용한 한국 지진 위험도

Seismic Risk Map of Korea Obtained by Using South and North Korea Earthquake Catalogues

김 소 구* 　　　이 승 규**

Kim, So Gu 　　Lee, Seoung Kyu

국문요약

본 연구에서는 서기 2년부터 1977년까지 남 · 북한의 역사 지진(A.D. 2-1904)과 초기 계기 지진(1905-1977) 목록을 이용하여 남한 지진 규모로 재조정된 지진 목록을 작성하였다. 역사 지진은 과거의 협소한 인구 분포로 인해 지진 기록의 누락이 많았다. 지진 위험도를 작성하기 위해 지진 발생 분포와 지체 구조의 특성을 고려하여 4개의 지진구(seismic province)를 설정하였다.

각 지진구에서 최대 잠재 지진 결정은 Gumbel의 최대치 이론을 이용하였다. 제 1 수정 점근 함수 분포에서 유한 상한 값(finite upper boundary)의 존재는 각 지진구에서 발생할 최대 잠재 지진의 진원(source)이 유한하다는 사실과 잘 일치한다. 따라서 이를 근거로 각 지진구에서 10년, 30년, 50년 이내에 2%, 5%, 10% 초과 확률을 갖는 최대 규모 지진을 추정하였다. 또한 각 지진구에서 유한 지진원은 과거에 발생했던 큰 규모의 특정 지진과 지진 지체 구조 정보에 근거하여 결정하였다.

연구 결과 조선 시대(1392-1904)의 지진 위험도에서는 경주, 울산 지역과 서울과 평양 지역을 따라 높은 지반 가속도 값을 보이며 경주 지역에서 0.24g의 최대 지반 가속도 값으로 나타났다. 계기 지진 목록(1905-1998)을 이용한 한반도의 지진 위험도에서는 경주, 울산, 대구 지역에서 0.10-0.12g의 최대 지반 가속도 값을 보였다. 그리고 계기 지진 목록(1905-1998) 만을 이용하여 작성한 서울 · 경기 지역의 지진 위험도에서는 김포, 잠실, 성남 지역의 한강을 따라 분포하는 충적층과 강남 지역의 지반 운동이 한강 이북의 대보 화강암 지역에 비해 비교적 높은 0.09-0.10g의 지반 가속도를 보이는 것이 특징이다.

주요어 : 지진목록, 최대치 이론, 지진위험도, 최대지반가속도

ABSTRACT

In this study, the readjusted earthquake catalogue is reconstructed using North and South Korea earthquake catalogues during A.D. 2 to 1977. Some earthquakes are often missed due to sparse population distribution in the ancient times. In order to make seismic risk map in Korea, we construct four seismic provinces based on earthquake distributions and tectonic characteristics in the Korean Peninsula.

Maximum potential earthquakes can be estimated using extreme value theory of Gumbel. The existence of the finite upper boundary for the modified first type asymptotic distribution is consistent with the fact that in each earthquake province the maximum potential earthquake is finite. Therefore we can estimate the maximum earthquakes that are expected to occur with 2%, 5%, and 10% exceeding probability within 10, 30, and 50 years. The finite seismic sources are determined taking into account the area occurred big earthquakes and the tectonic informations.

From the results, the seismic risk map using Chosun Dynasty(1392-1904) catalogue shows higher values along the line from Kyongju and Ulsan to Seoul and Pyongyang. The maximum value of ground motion in the Korea is 0.24g in the area of Kyongju city. The result using instrumental earthquake catalogue(1905-1998) shows that the maximum value of ground motion is about 0.10-0.12g in the areas of Kyongju, Ulsan, and Taegu cities. The seismic risk map of Seoul and Kyonggi areas is constructed using instrumental earthquake catalogue(1905-1998). The PGA values at Kimpo, Jamshil, and Songnam cities along the Han River and Kangnam area covered with Alluvium are relatively high with 0.09-0.10g compared with hard rock sites covered with Daebo granite of Kangbuk city center.

Key words *: earthquake catalogue, extreme value theory, seismic risk map, peak ground acceleration*

1. Introduction

Several Korean seismic risk maps have been constructed to provide the basic information on earthquake engineering and evaluation of seismic hazard. The previous studies were carried out by Kim(1), Kim and Kim(2), Kim(3), KIGAM(Korea Institute of Geology, Mining and Materials)(4)-(5), Lee et al.(6), Kim and Song(7),

* 정회원 · 한양대학교 한국지진연구소 · 교수

** 한양대학교 한국지진연구소 · 연구원

본 논문에 대한 토의를 2000년 6월 30일까지 학회로 보내 주시면 그 결과를 게재하겠습니다.

Kim et al.[8], and Baag et al.[9].

The seismic data and earthquake information of the Korean Peninsula are presumed to be incomplete and unstable until 1978. Furthermore, there are large differences in earthquake magnitudes determined by North and South Korea because there are systematic differences to convert historical earthquake intensity into magnitude scale.[10] Therefore, we try to redetermine the readjusted magnitude of Korean earthquake catalogue on the basis of North and South Korea earthquake catalogues for the period from 2 A.D. to 1977, and then we construct an upgraded seismic risk map of the Korea using the readjusted magnitude earthquake catalogue for the periods of Samguk Era(A.D. 2-1391), Chosun Dynasty (1392-1904), and Instrumental earthquake data (1905-1977) and KMA earthquake catalogue (1978-1998). Especially, we construct the seismic risk map of Seoul and Kyonggi area using instrumental earthquake data (1905-1998) taking into account the local site conditions of soil and rock type, and fault systems as basic input data for earthquake engineering. The maximum potential earthquakes within a seismic province can be determined by using the asymptotic distribution functions based on the extreme value theory. The maximum earthquakes expected to have roughly 2%, 5%, and 10% probabilities in the next 10, 30, and 50 year period are estimated for each seismic province. We select a 30-year period among three periods to construct the seismic risk map of the Korean Peninsula because the life-time for most of important construction facilities in Korea is assumed to be about 30 years.[8]

There are several attenuation formulas published by Kawashima et al.[11], Boore et al.[12], Campbell[13], and Baag et al.[9], etc. We compute maximum ground accelerations at all grid points ($0.5^\circ \times 0.5^\circ$) taking into account the attenuation models of Kawashima et al.[11], Boore et al.[12], Campbell[13], and Baag et al.[9]. The seismic risk contour map of the Korean Peninsula and the seismic risk map of Seoul and the capital area (37°-38°, 126°-127.5°E) are constructed.

2. Earthquake Catalogue

The terminology of the historical and instrumental earthquakes in Korea are based on the date of installation of a modern seismograph in Inchon, the year 1905. Earthquakes occurred in and/or after this year are called instrumental earthquakes, even though the number of stations are few and the recording quality was poor in the early periods, especially before the year 1978. There were some historical literatures and documents in Koryo Dynasty (917-1391) and Chosun Dynasty (1392-1904) which described the states of earthquake occurrences and damages. Wada[14] extracted information on earthquakes occurred during the period of A.D. 2-1912 from the historical literatures to construct a catalogue of 1659 historical earthquakes. Musha[15] gathered historical records of earthquakes and volcanoes occurred in Japan, Korea, and northeastern China, and made a catalogue. Kim[16] reevaluated the historical and instrumental earthquakes of the period A.D. 2-1978 using the previous documents and some catalogues. A few researchers and some institutes published the Korean earthquake catalogues.[4] Kim and Gao[10] published the Korea earthquake catalogue based on the Chosun earthquake catalogue of DPRK[17] and KMA (Korea Meteorological Administration) catalogue.[18] Among the Korea earthquake catalogues, we found that there are large differences, and some erroneous mistakes in papers and reports of previous researcher's. We make the readjusted earthquake catalogue with a 1/4 magnitude unit in order to minimize the systematic difference of magnitude redetermined from relationship between North and South Korea catalogues. Fig. 1 shows the relation between magnitudes of North and South Korea for the periods of Samguk era (A.D. 2-917), Koryo Dynasty (918-1391), Chosun Dynasty (1392-1904), and early instrumental earthquakes (1905-1977). For the period of 1978-1998, KMA has been operating a seismic network of 12 short period vertical seismographs starting from two stations in 1977. We used KMA catalogue to construct the seismic risk map without unifying or changing magnitudes because the earthquake catalogue (1978-1998) of South Korea is more reliable than that of North Korea.[10]

The time span of the seismic data in Korea

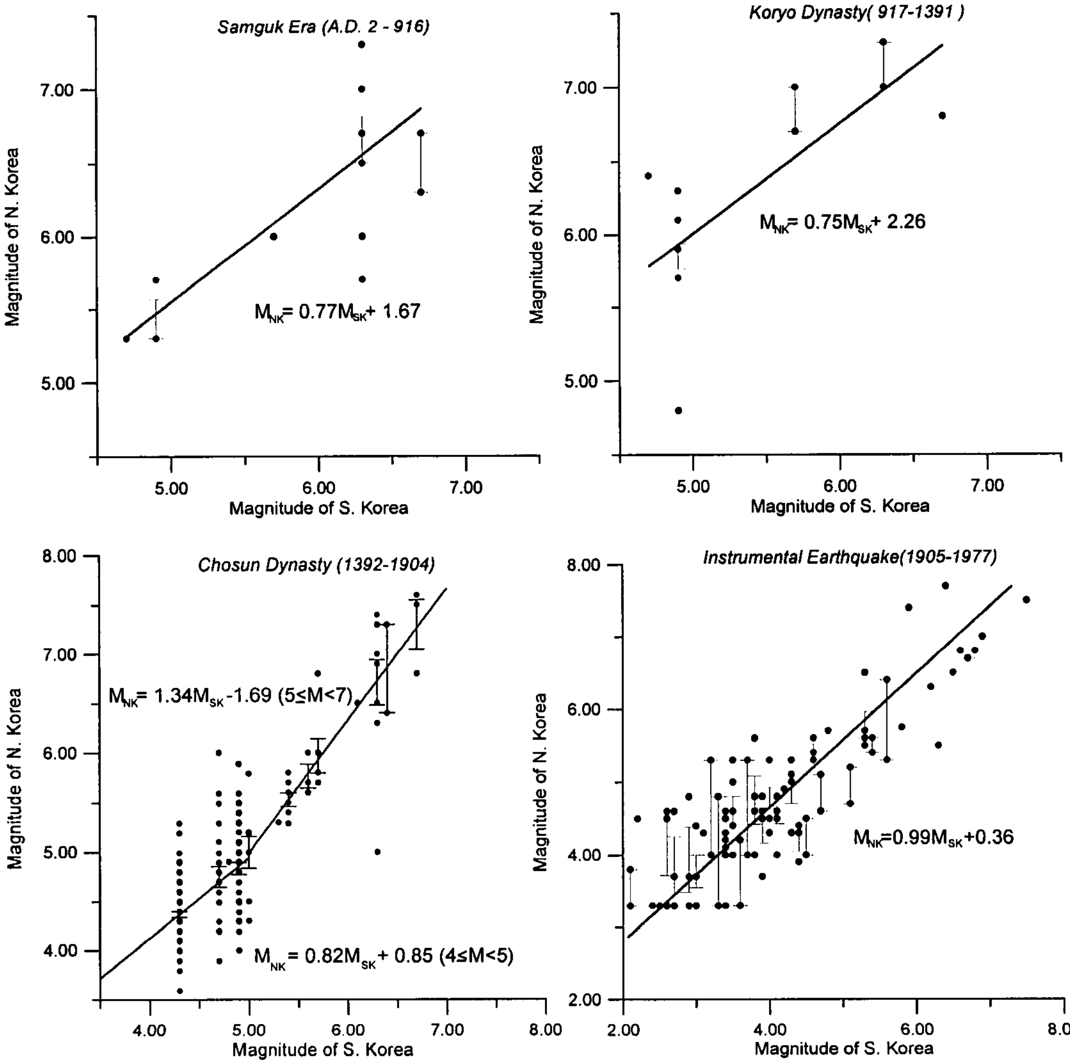


Fig. 1 Linear regressions between North and South Korea magnitudes for the given periods of Samguk era(A.D. 2-916), Koryo Dynasty(917-1391), Chosun Dynasty(1392-1904), and early instrumental earthquakes(1905-1977)

reaches up to 2000 years from A.D 2 to 1998. Although the data set for the events before 14th century is poor in completeness, historical documents of description of earthquakes from Chosun Dynasty reveal very consistent to keep the facts on earthquakes occurrences. The seismicity during the 15th - 18th century was very active compared to other centuries. (see Table 1) In the 20th century, there are no significant large damaging earthquakes although the instrumental recordings are possible. The characteristic earthquakes occurred in the Korea in the 20th century are Mt. Chiri (7/4/1936, M5.3), Mt. Sokri (9/16/1978, M5.2), Hongsung (10/7/1978, mb5.0), Uiju (1/7/1980, mb5.3), Pohang (4/15/1981, M4.8) Sariwon(Anak) (2/14/ 1982, M4.5), Youngwol (12/13/1996, mb4.8, Mw 5.2), and Kyongju (6/25/1997, mb4.7, Mw

Table 1 Event number distribution of historic and instrumental earthquakes in a given period

Period \ Mag.	3≤M<4	4≤M<5	5≤M<6	6≤M<7	7≤M	Total	Remark
Samguk era (A.D. 2 - 916)	-	68	18	12	1	99	
Koryo Dynasty (917 - 1391)	121	28	18	5	-	172	
Chosun Dynasty (1392 - 1399)	-	6	-	-	-	6	
15C (1400 - 1499)	7	115	113	14	-	249	
16C (1500 - 1599)	44	240	424	26	1	735	
17C (1600 - 1699)	18	205	238	22	2	485	
18C (1700 - 1799)	4	83	123	11	-	221	
19C (1800 - 1899)	2	9	3	3	-	17	
1900 - 1909	24	-	1	-	-	25	
1910 - 1919	12	19	4	3(Deep)	-	38	
1920 - 1929	12	40	6	1(Sea)	-	59	
1930 - 1939	48	16	26	1(Deep)	-	91	Mt. Chiri (7/4/36, 5.2)
1940 - 1949	11	5	5	-	-	21	
1950 - 1959	-	3	1	-	-	4	
1960 - 1969	37	25	7	-	-	69	
1970 - 1979	49	5	2	1(Deep)	-	57	Mt. Sokri (9/16/78, 5.2) Hongsung (10/7/78, 5.0)
1980 - 1989	144	13	2	0	0	159	Uiju (1/8/80, 5.3) Pohang (4/15/81, 4.8) Sariwon (2/14/82, 4.5)
1990 - 1998	79	12	0	0	0	91	Youngwol (12/13/96, 4.8) Kyongju (6/25/97, 4.7)
A.D. 2 - 1998	612	892	991	99	4	2598	

4.8), which M, mb, and Mw indicate local, body wave, and moment magnitudes, respectively. Unfortunately, no accelerograms have been recorded during shaking of these earthquakes due to absence of accelerometer stations.

We reconstruct the readjusted magnitude earthquake catalogue with a 1/4 unit of magnitude scale from relationship between North and South Korea earthquake magnitudes. The historical earthquake magnitudes are determined based on 1/4 unit magnitude scale assuming that the uncertainty of converting historical earthquake intensity to magnitude scale is 0.25.

The earthquake catalogue of Samguk era (A.D. 2-916) consists of 100 events. We selected 18 events data among 100 events whose magnitudes are equal to or greater than 4.0 (M≥4.0) to calculate the readjusted magnitudes from relationship between North and South Korea earthquake magnitudes. The linear regression formula is $M_{N.K} = 0.77M_{S.K} + 1.67$, where $M_{N.K}$ and $M_{S.K.}$ represent the North and South Korea magnitudes, respectively. In general, magnitudes of North Korea is 1 unit magnitude greater than those of South Korea and the differences of magnitude are ranged from 5.7 to 7.3 for South Korea magnitude 6.3. (Fig. 1) The largest earthquake occurred at Kyongju on April, A.D. 779 (readjusted magnitude 7.25) during Samguk era.

The earthquake catalogue of Koryo Dynasty (917-1391) consists of 172 events. We selected 20 events (M≥4.0) among 172 events. We can calculate the linear regression formula as $M_{N.K} = 0.75M_{S.K} + 2.26$. The earthquake magnitudes of North Korea are ranged from 4.8 to 6.4 for magnitude 5.0 of South Korea. (Fig. 1) The largest earthquake during this period was M6.75 occurred near Kaesong on 6/24/1298 and 3/4/1298.

The catalogue of Chosun Dynasty (1392-1904) is relatively more complete and reliable than the other historical catalogue(A.D. 2-1391). The data set in this period consists of 1654 historical events and we selected 216 events (M≥4.0) among 1654 events to calculate the linear regression formulas which are divided into two parts because magnitude distributions are different at magnitude 5.0. We found the linear regression formulas are as follows:

$$M_{N.K} = 0.82M_{S.K} + 0.85 \quad \text{for } 4.0 \le M_{S.K} < 5.0,$$
$$M_{N.K} = 1.34M_{S.K} - 1.69 \quad \text{for } 5.0 \le M_{S.K} < 7.0$$

The relation of North and South Korea magnitudes using early instrumental earthquakes (1905-1977) is shown on Fig. 1. We selected 103 events to calculate the linear regression formula which is $M_{N.K} = 0.99M_{S.K} + 0.36$. This result is similar with that of Kim and Song(7), i.e. $M_{N.K.} = 0.98M_{S.K.} + 0.21$.

From the results, we found that the historical earthquake magnitudes from A.D. 2 to 1391 show a very low correlation of magnitudes between North and South Korea, otherwise those of Chosun Dynasty show higher correlation than those of Samguk and Koryo Dynasty. We can make the readjusted magnitude earthquake catalogue based on magnitude relations between North Korea and South Korea catalogues.

3. Seismic Risk Map

We employ Gumbel's modified first asymptotic function to compute the predictive parameters of extreme earthquakes.(3) We estimate the maximum potential earthquakes at each seismic province. We calculate maximum earthquakes which are expected to occur with 2%, 5%, and 10% exceeding probability within

10, 30, and 50 years, respectively. We choose the finite seismic sources taking into account the seismotectonic informations and historically significant earthquakes of the study area. (see Table 2)

Peak ground accelerations (PGA) at all grid points ($0.25^{\circ} \times 0.25^{\circ}$) are computed by using attenuation functions presented by Kawashima et al., Boore et al., Campbell, and Baag et al.[(9),(11)-(13)] We construct Korea Seismic Risk Map with a 10% exceeding probability within 30 years using the data of 1392-1904, and 1905-1998.

3.1 Seismic Provinces and Sources

In general, epicenters, time and magnitudes of historical earthquakes have a lot of uncertainties. To construct the Seismic Zonation, it should be considered with seismic activity, geologic types, deep and major faults, and geophysical and tectonic characteristics, however, tectonic characteristics of the Korean Peninsula, taking into account seismicity is not well understood. By the reasons of those, we reconstruct the presumed seismic provinces based on tectonic division of the Korean Peninsula.[(19),(20)] and the result of Kim and Gao[(10)] using the seismic gap theory.

Seismic province 1 :

The seismic province(S1) lies on the northeastern part along the Chugaryong rift zone including Hamkyong-do and northern part of Kangwon-do provinces. In the seismic province S1 (see Fig. 2), there are frequently occurred deep-focus earthquakes (h>300km) and historical seismicity of the Pyongbuk-Kaema massif is considerably lower than in other tectonic

Table 2 The Seismic provinces and 16 finite seismic source points

Seismic provinces	Finite source point	Location		Remark
		Latitude	Longitude	
S1	Samsu	41.40	128.45	10/06/1597 (M 6.50)
	Near Wonsan	39.60	127.70	06/20/1727 (M 5.75)
S2	Uiju	40.18	124.80	01/08/1980 (M 5.30)
	Kangdong	39.10	126.00	06/30/1546 (M 6.75)
	Pyongyang	38.92	125.90	06/25/1681 (M 6.75)
	Sariwon	38.40	125.80	02/14/1982 (M 5.10)
	Kaesong	38.05	126.40	03/06/1298 (M 6.75) 08/01/1385 (M 6.25)
S3	Seoul	37.50	127.05	07/02/1518 (M 7.00)
	Kwangju, Kyonggi-do	37.40	127.20	12/00/0027 (M 6.75)
	Hongsung	36.55	126.67	07/20/1594 (M 6.50) 10/07/1978 (M 5.00)
	Mt. Sokri	36.49	127.88	09/17/1978 (M 5.20)
S4	Mt. Chiri	35.20	127.60	07/04/1936 (M 5.30)
	Ulsan	35.60	129.30	06/09/1643 (M 6.75)
	Kyongju	35.80	129.20	A.D. 34, 100(M 6.75) A.D. 779 (M 7.25)
	Youngwol	37.20	128.50	02/14/1699 (M 5.50)

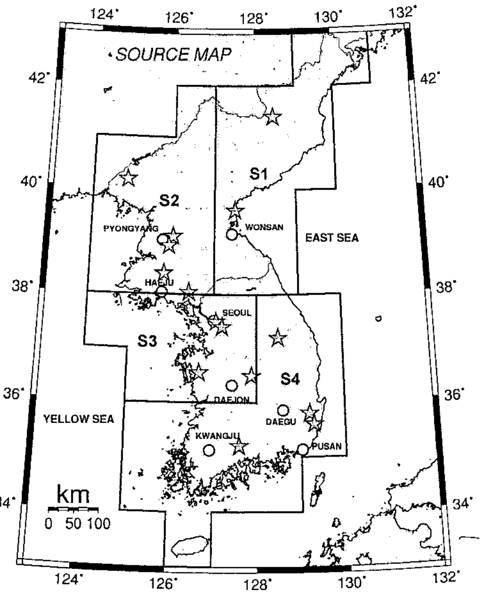


Fig. 2 The map of 4 seismic provinces and 15 finite seismic source points in Korea

provinces of the Peninsula. Great fault zones are not developed in the Kwanmo massif separated from Nangnim massif. There are many faults which are Susongchon fault zone, Paektusan fault zone, Puktaechon fault, Jangphari fault (from Hyesan to Iwon), and Hochongang fault (boundary between Nangnim massif and kwanmo massif). Of faults with a NW direction the Paektusan fault is large.[20] The whole Heysan-Iwon group of super-imposed geosyncline zones. There was the Samsu earthquake on the mesozoic fault system with M6.5 in 1597. The northern part of Kangwon-do located at the southernmost boundary includes a part of Kyonggi massif and Imjingang fold zone where the Wonsan-Seoul fault zone is located. We picked out an independent seismic source of high concentration of earthquakes with M5.75 in 1727 near Wonsan. (see Fig. 3)

Seismic province 2 :

The seismic province S2 (see Fig. 2) is located in the western part of the Chugaryong rift zone including the Nangnim massif and Pyongnam Basin. Faults in the area of Nangnim massif trend NE and NW. There are many faults which are Amnok river fault zone, Kanggye-Hwaphyong fault, Chongchongang fault, Yesonggang-Taedonggang fault, and Pyongbuk fault zone. The fault structures inclined abruptly with a NWW strike of Pyongnam Basin are developed mainly in the west with the Yesonggang faults, in the east the fault with a NNE strike predominates.[20] The western and central parts of Pyongan-do and Hwanghae-do provinces turn out to be highly seismic in the Korea. The seismic province S2 coincides with the "Pyongyang gap" of Kim and Gao.[10] There are great historical earthquakes which are Kangdong earthquake (M6.75) in 1546, Pyongyang earthquake(M6.75) in 1681, Kaesong earthquakes(M6.75 in 1298, M6.25 in 1385). In historical seismicity of the Peninsula, the 99 earthquakes swam activity (from September 6 in 1956 to January 26 in 1566) in the vicinity of Sangwon (near Pyongyang) in the Pyongnam Basin.[21] The latest large earthquakes were Uiju earthquake(M5.3) in 1980 and Sariwon earthquake (M4.5) in 1982. From 1989 to October 1995, many earthquakes of magnitude with $2 \leq M \leq 5$ concentrated in this region. It may indicate an active seismic cycle at the present time. So we picked out the independent seismic sources (Uiju, Kangdong, Pyongyang, Sariwon, Kaesong) as finite sources. (Table 2)

Seismic province 3 :

Seismic province S3 (see Fig. 2) is located on the Kyonggi massif which is bounded by the Imjingang fold belt and Okchon fold belt in the north and south respectively. In the Kyonggi

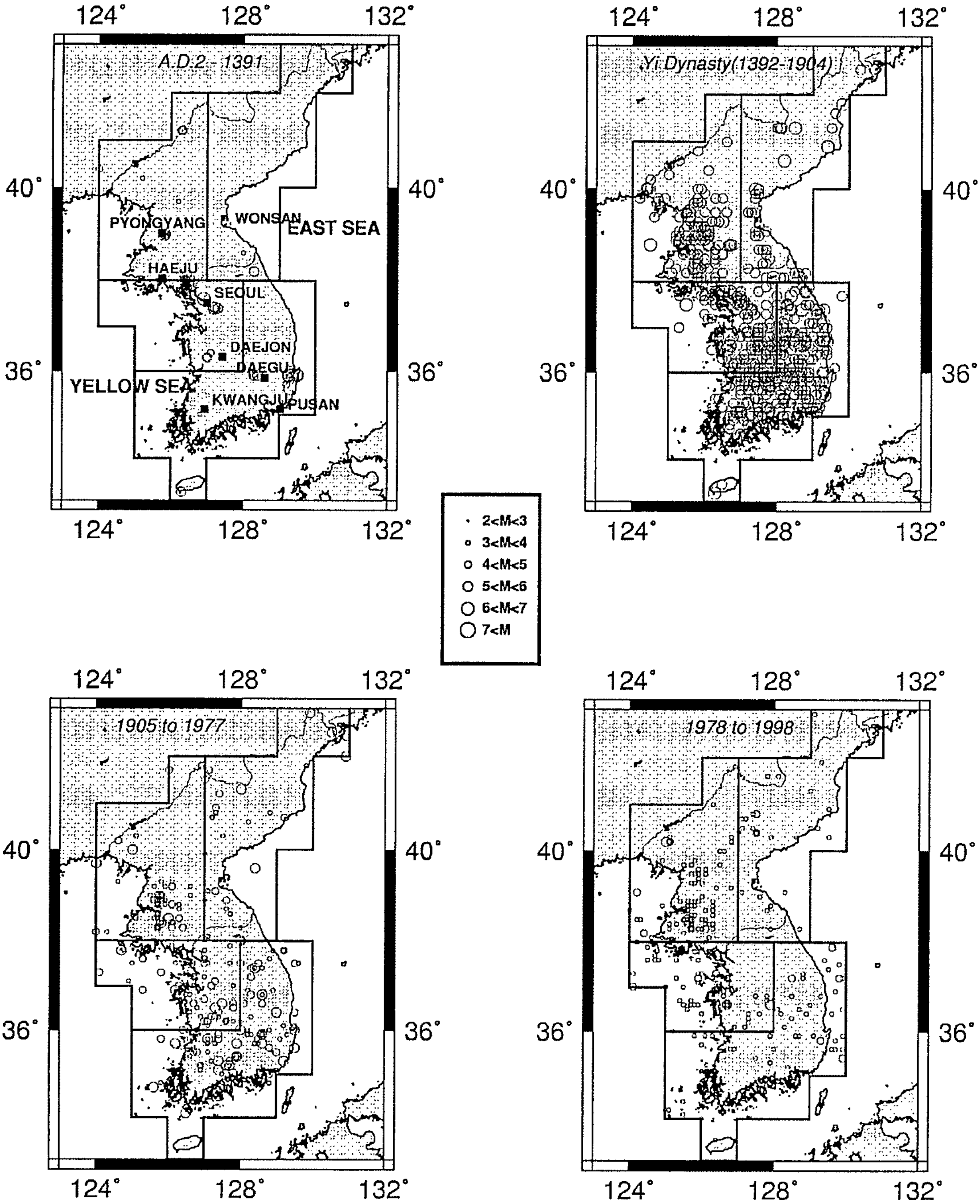


Fig. 3 The maps of seismic provinces and earthquake distribution with magnitude scale for the given periods as mentioned in Fig. 1

massif, the mesozoic intrusions which are mesozoic superimposed products are intruded along the deep fault with a NE-SW direction and in the graben type tectonic basin with the same direction is present the Taedong system, too. The fault structure has largely two directions. One is parallel to the tectonic direction of the massif, a NE one (Kimpo-Kansong fault zone and Kongju fault), the other has a NNE direction(Wonsan-Seoul fault zone). The typical example is the Wonsan-Seoul fracture (the Chugaryong fault zone). This province S3 also consists with the "Seoul gap" devised by Kim and Gao.[10] According to the historical earthquake data, there were large earthquakes occurred in Seoul(M7.0) on 7/2/1518, at Kwangju(M6.75) in Kyonggi-do on A.D. 27. There were two medium-size earthquakes at Mt. Sokri(M5.2) on 9/16/1978 and Hongsung(M5.0) on 10/7/1978 in Chungchong-do province since 1900.

Seismic province 4 :

Seismic province S4 (see Fig. 2) includes Okchon fold belt, Ryongnam massif, Kyongsang Basin, and a eastern part (Kangwon-do) of Kyonggi massif. Here are developed fault structures with NE-NNE, NNW and nearly EW-NEE directions. Faults with a NE-NNE trend are distributed in the west of the Ryongnam massif. In this area the faults are not large in scale and the faults with a NE direction predominate on the southwest side and the faults with a NNE direction is the Yangsan fault group.[20] There were many large historical earthquakes which are Kyongju earthquakes (M6.75 in A.D. 34, M6.75 in A.D. 100, and M7.25 in 779), Ulsan earthquake (M6.75 in 1643). All the earthquakes in the Kyongsang Basin and Ryongnam massif can be divided into two series, the one took place mainly along the Pusan lineament and the other occurred along or near either the Ulsan fault system or Kwangju fault system. The most destructive earthquake since 1905 was the Mt. Chiri earthquake(M5.3) occurred on July 4, 1936. The medium and small sized many earthquakes were concentrated in the southeast part of this region. In recent year, there were two earthquakes of Youngwol(M4.8) on 12/13/1996 and Kyongju(M4.7) on 6/25/1997.

Finite seismic source points in each seismic province (see Fig. 2 and Table 2) are estimated under the assumption that major earthquakes would repeat their activities where they have occurred in the past. The finite source points are also assumed as places of dense concentration of moderate earthquakes concerning the area of faulting which can produce destructive events. Maximum potential earthquakes of each seismic provinces are contingent to the size of the finite seismic source points. Fig. 2 represents the four seismic provinces and fifteen seismic source points in the Korean peninsula. (see Table 2)

Fig. 3 shows the seismicities of Samguk era and Koryo Dynasty(A.D. 2-1391), Chosun Dynasty(1392-1904), early instrumental earthquakes data(1905-1977), and instrumental earthquakes (1978-1998). The historical earthquakes are mainly distributed in and near the capitals of historical era because the places of habitation are limited in the ancient era. Especially, the seismic activity of the Korea during 15th-18th century was very high compared to other centuries.(see Table 1) Whereas in the 20th century, there have been no significantly large damaging earthquakes although instrumental recordings are possible.

3.2 Basic Theory of Largest Value

It is well known that the theory of extreme values is formulated generally under the assumption that (1) prevailing conditions must be valid in the future, and (2) the observed larger values are independent of each other, i.e. aftershocks are not considered.

According to the modified first asymptotic function[3], the probability that all the earthquakes have magnitudes x within the given time period becomes

$$G^1(x) = \exp[-e^{-\beta(x-u)}\{1-e^{-\beta(v-x)}\}] \quad x<v,\ u<v \tag{1}$$

where u is the characteristic largest value, β is the extremal intensity function, v the upper limit of the magnitude.

The asymptotic distribution of extremes for the third type[22] was given by the formulas

$$G^3(x) = \exp[-\{(w-x)/(w-u)\}^k] \quad k>0,\ x\le w,\ u<w \tag{2}$$

where u is the characteristic largest value, k is the shape parameter, and w is the upper limit of the largest values.

The return period for the exceedence of x as annual extremes is shown by

$$T(x) = 1/(1-G(x)) \tag{3}$$

The statistical parameters for the expected values of maximum potential earthquakes are determined by Eqs. (1) and (2).

An exceedence probability of the maximum magnitude x within a given t years is of great importance in constructing a seismic risk map on the basis of the life-time of the structure. The exceedence probability of the return period $T(x)$ during t years becomes

$$Pt(x) = 1-\exp[-t/T(x)] \tag{4}$$

The maximum magnitude of the exceeding probability within t years can determined by following equations.

For the modified first asymptotic function,

$$Vt = -1/\beta \times \ln[\exp(-\beta v)+\exp(z-\beta u)],$$
$$z = \ln[-\ln G(x)] \tag{5}$$

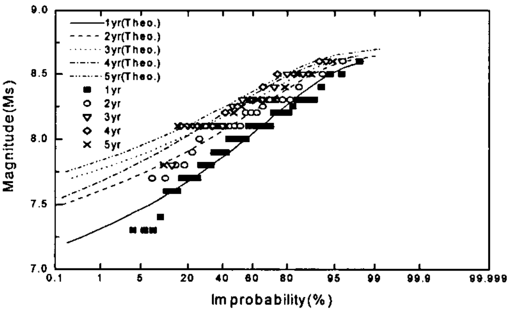
For the third asymptotic function,

$$Wt = w-(w-u)\exp(z/k) \tag{6}$$

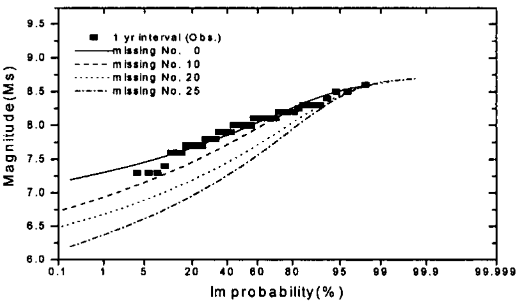
Kim[3] developed a computer algorithm using the modified first asymptotic function and applied to the historical and instrumental earthquakes of Tokyo, Guatemalan, Managua, and Los Angeles. The modified first asymptotic function gives more reasonable maximum potential earthquakes and more optimum evaluation in seismic risk map than the third one.[3]

The relation between magnitude and frequency of earthquakes is assumed to be distributed by Poisson distribution, whereas the distributions of some area are not well fitted because abnormal earthquakes were frequently occurred. Especially, in case of historical earthquake catalogue, we found that large portions of data are missed because of no events or no records at that time. Such a large portions of missing data have an effect on determining the statistical parameters of the asymptotic function. In order to avoid or to reduce the effect of missing data, we classify historical catalogue by many time series data sets with an equal time intervals of 1, 2, 3, 4, 5 years, or various intervals. The more sampling time intervals are enlarged, the more the number of missing data can be reduced, whereas data quality and data distributions become worse and distorted.

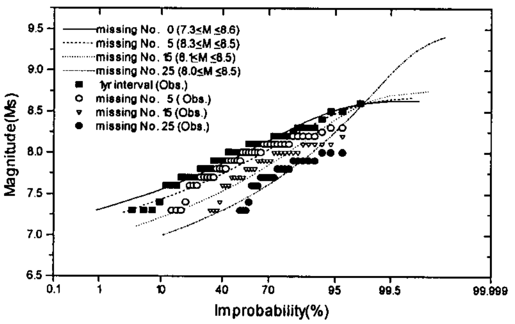
In this study, we test the convergence or divergence of the asymptotic function using various interval data sets (worldwide data during 1928-1977) represented by Howell.[23] Fig. 4 (a) shows the results of estimated maximum



(a) the maximum potential earthquake estimation using sampling interval of 1, 2, 3, 4, and 5 year, respectively without missing data



(b) data set with 10, 20, 25 missing data of 1 year interval



(c) the data sets are not converged which are consist of 5, 15, and 25 missing data among 50 events in a given magnitude range (see text)

Fig. 4 Test of convergence or divergence using world-wide earthquake data from Howell(1981)

potential earthquakes using the classified data sets by time intervals of 1, 2, 3, 4, and 5 years, the curves are well fitted with observed data and converged into a finite value. Fig. 4 (b) shows the results using the data sets including missing data which are 10, 20, and 25 missing data among 50 events. These data sets are also well converged into a finite value. However, Fig. 4 (c) shows the results which are not converged. We make the four data sets to test a convergence of asymptotic function which are consist of 1) without missing data set among 50 events in the range of $7.3 \leq Ms \leq 8.6$, 2) 5 missing data among 7 events in the range of $8.3 \leq Ms \leq 8.5$, 3) 10 missing data among 21 events in the range of $8.1 \leq Ms \leq 8.5$, (4) 25 missing data among 28 events in the range of $8.0 \leq Ms \leq 8.5$. From the result in Fig. 4 (c), we found that the number of missing data of historical earthquakes has an effect on the determination of maximum potential earthquake. It is hard to estimate the maximum potential earthquakes using the data set in case of many missing data. Especially, there are no appropriate mathematical functions to represent relations between earthquake magnitude and frequency. Therefore it is so difficult to predict earthquakes because earthquake phenomena are non-linear problems. Thus, in order to well estimate the maximum potential earthquake using historical data of long duration, the number of missing data and missing magnitudes should be considered. The well optimized data intervals are selected by a limitation as follows:

$$G(x_j) = (j+n)/(N+1), \quad j=1,\ldots,N-n, \quad N \geq 2n$$

where, N=No.of observation, and n=No.of missing data.

3.3 Attenuation of Seismic Waves

In the range of 40-150km from epicenter, the elastic energy is mainly propagated by P and S waves. At longer range, the energy is propagated by Rayleigh and Love waves and at the near-field of the source, the maximum ground acceleration is dependent on the fault movement. The vertical accelerations are generated by P and SV waves at near-field, and a horizontal accelerations are generated by SH wave. In this study, we do not say about the fault movement except for seismic risk analysis in Seoul and Kyonggi area. There are so many empirical attenuation formulas by magnitude, intensity, hypocentral distance, and local site conditions. For coefficients of the attenuation formula, the commonly used form of the formula.[9]

$$\ln PGA = c_0 + c_1 M + c_2 \ln \triangle + c_3 \triangle$$

where $\triangle$ is hypocentral distance in km, M is magnitude of local earthquake.

We compute peak ground acceleration(PGA) at all grid points using the attenuation functions of Kawashima et al.[11], Boore et al.[12], Campbell[13], and Baag et al.[9] We also construct a seismic risk map with 10% exceeding probability within 30 years using Chosun Dynasty (1392-1904) and instrumental earthquakes(1905-1998) data.

Baag et al.[9] calculated attenuation formulae based on well-documented intensity data occurred in the southern part of Korea.

$$\ln a = 0.40 + 1.2M - 0.76 \ln \triangle - 0.0094 \triangle$$

where $\triangle$=hypocentral distance in km. It is based on weighting factors 1, 3, 3, 3 for Ssanggeysa, Pohang, Hongsung, and Youngwol earthquakes, respectively.

The work of Kawashima et al.[11] was carried out using JMA(Japan meteorological agency) magnitudes in Japan area.

$$PGA = 403.8 \times 10^{0.265M} \times (R+30)^{-1.218}$$

where R is epicentral distance in km, M is magnitude

The work of Boore et al.[12] is to estimate peak ground acceleration and response spectra for Western North America using moment magnitude, distance, and local site conditions for strike-slip, reverse-slip, or unspecified faulting mechanism, and the site conditions which are represented by the shear velocity averaged over the upper 30m that is recommended in the natural earthquake hazards program codes.

$$\ln PGA = -0.242 + 0.527(M-6) + b_3(M-6)^2 + b_5 \ln r + b_v \ln V_s / V_a$$

where, $b_3 = 0$, $b_5 = -0.778$, $b_v = -0.371$, Va=1390m/sec, Vs=310m/sec, $r = \sqrt{r_{jb}^2 + h^2}$, r_{jb}=the closest horizontal distance, h=5.57.

The empirical attenuation of Campbell[13] is presented for predicting free-field horizontal and vertical component of peak ground acceleration(PGA) for moment magnitudes for shallow-focus earthquakes(h≤60km) in active tectonic regions and he recommended ground motion models combined by the attenuation relationships of Campbell[24] and Campbell and Bozorgnia.[25]

$$\begin{aligned}\ln(PGA) = &-3.512 + 0.904M \\ &- 1.328 \ln \sqrt{R_{seis}^2 + [0.149 \exp(0.647M)]^2} \\ &+ [1.125 - 0.112 \ln(R_{seis}) - 0.0957M]F \\ &+ [0.440 - 0.171 \ln(R_{seis})]S_{SR} \\ &+ [0.405 - 0.222 \ln(R_{seis})]S_{HR} + \varepsilon\end{aligned}$$

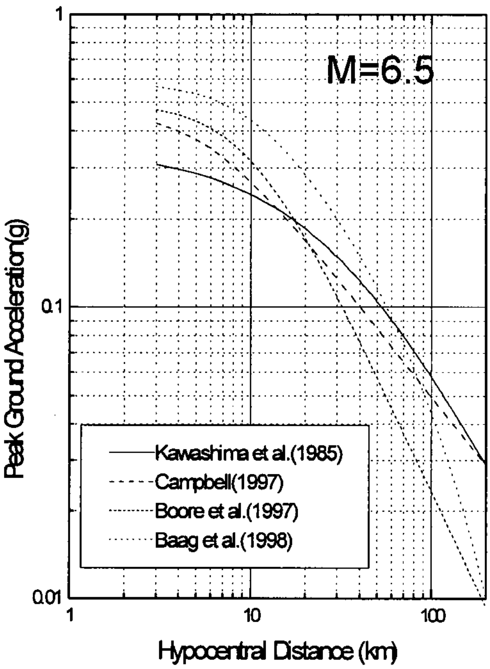
where, R_{seis} is the shortest distance between the recording site and the presumed zone of seismogenic rupture. F is 0 for strike-slip faulting, 1 for reverse, thrust, reverse-oblique, and thrust-oblique faulting, 0.5 for a half way between that of strike-slip and reverse-faulting earthquakes. S_{SR} and S_{HR} are local site conditions, $S_{SR}=0$, $S_{HR}=0$ for firm soil, $S_{SR}=1$, $S_{HR}=0$ for Soft Rock, and $S_{SR}=0$, $S_{HR}=1$ for Hard Rock.

In order to construct the seismic risk map of the Seoul and Kyonggi area, we considered the fault type and local site conditions to calculate the peak ground acceleration. We assumed input parameters to calculate the PGA for each grid which $F=0.5$ because of no information of focal mechanism of this region, local site conditions are divided into three types, firm soil for Alluvium area, soft rock for Pre-Cambrian Kyonggi gneiss complex, and hard rock for Jurassic Daebo granite.

Fig. 5 (left) shows attenuation curves of peak ground acceleration for M6.5. Baag's model shows higher PGA values within hypocentral distance 100km than the others. Fig. 5 (right) shows peak ground acceleration with distance and local site conditions from the attenuation relationship recommended by Campbell.[13] For the distance of greater than 15 km, the PGA of firm soil is higher than those of soft and hard rocks. It is indicated that the ground conditions for various rock types act an important role to resist the big earthquakes.

3.4 Construction of Seismic Risk Map

We construct seismic risk maps of Chosun Dynasty from 1392 to 1904 and instrumental earthquakes from 1905 to 1998. We calculate the PGA at each grid point with a limitation



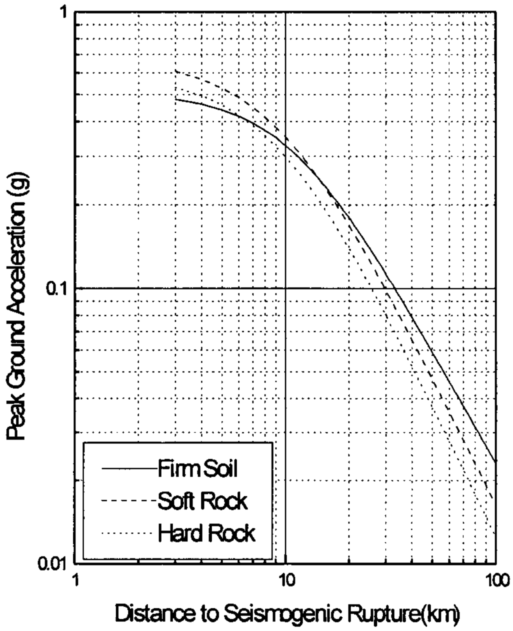


Fig. 5 (Left) Comparison of attenuation relations. (Right) Peak ground acceleration by local site conditions which are firm soil, soft rock, and hard rock using Campbell's formula (1997)

distance of 30km for the whole Korean Peninsula and 20km for Seoul and Kyonggi area. In this study, we only consider for the land hazard estimation and not for the offshore hazard estimation. So the seismic risk contour map looks like the sudden truncation and wrapping along the sea-land boundary because the seismic sources are located in land.

3.4.1 Chosun Dynasty (1392-1904)

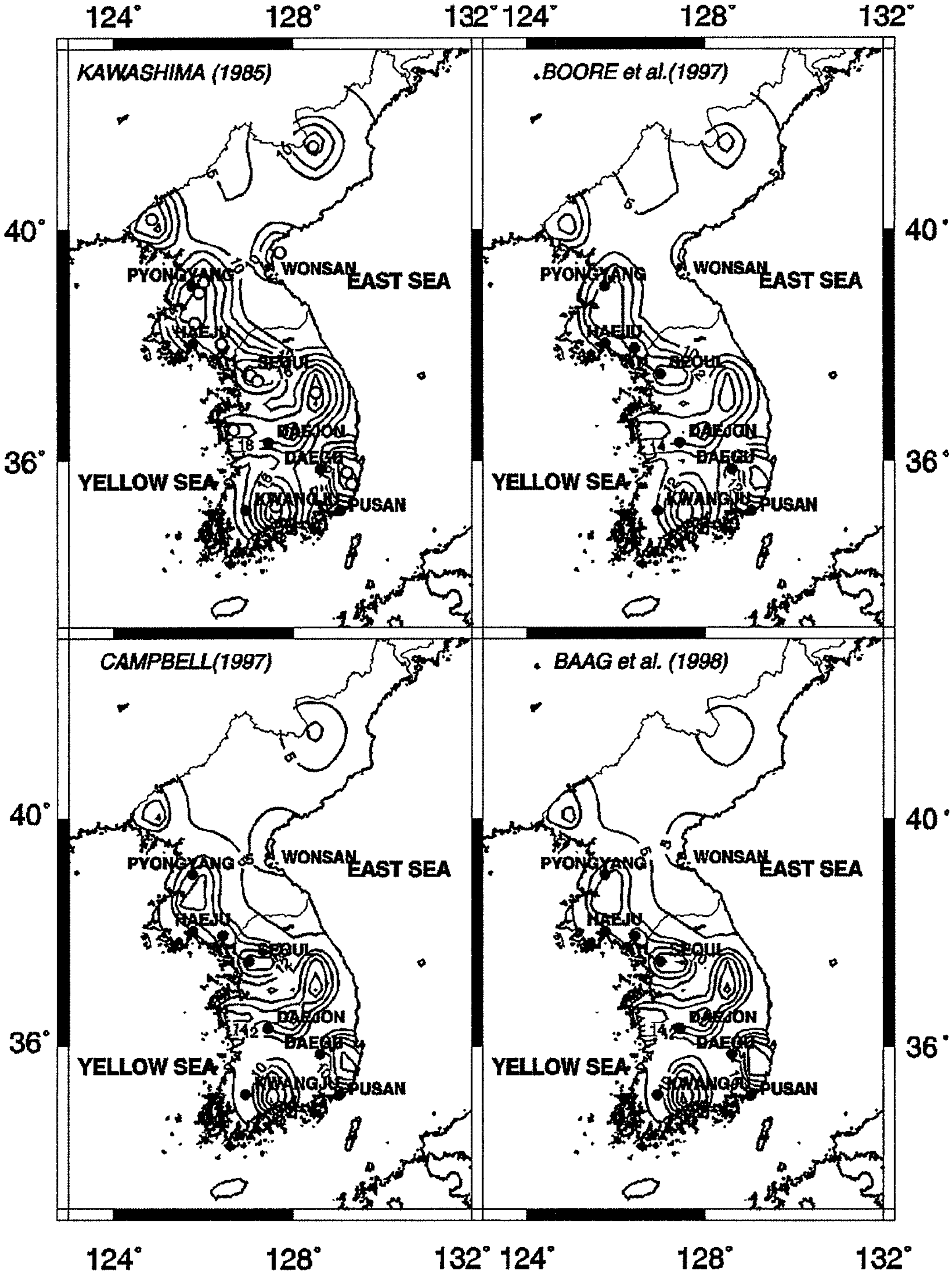
The statistical parameters of each seismic zone are given in Table 3. The maximum potential earthquakes for the seismic provinces of S1, S2, S3 and S4 are found to be 6.59, 6.98, 7.18, and 7.18 using the 14 year, 3 year, 14 year, and 14 year interval data, respectively. The maximum earthquakes of a 10% exceeding probability within 30 years are also found to be 6.60, 6.83, 7.15, and 7.16 for the seismic provinces S1, S2, S3 and S4, respectively. The maximum ground accelerations are estimated 0.22-0.23g using Kawashima model, 0.16-0.18g using Boore and Campbell's models, and 0.22-0.23g for Baag's model, respectively (Fig. 6 (a)). The maximum peak ground accelerations in this study are higher than the result(0.18g) of Baag et al.[9]

3.4.2 Instrumental Earthquake (1905-1998)

The statistical parameters of each seismic province are given in Table 3. The maximum potential earthquakes for the seismic provinces of S1, S2, S3 and S4 are 5.59, 5.66, 5.40, and 5.90, respectively. The maximum earthquakes (V30) of a 10% exceeding probability within 30 years are also found to be 5.54, 5.63, 5.38, and 5.88 for the seismic provinces S1, S2, S3 and S4, respectively. The maximum ground peak accelerations are estimated of 0.10-0.12g in Kyongju area, 0.08-0.10g in area of Pyongyang, Youngwol, and Mt. Chiri, and the other areas has less than 0.08g by using Kawashima model.(Fig. 6 (b) and 6 (c)) Fig. 6 (c) shows the

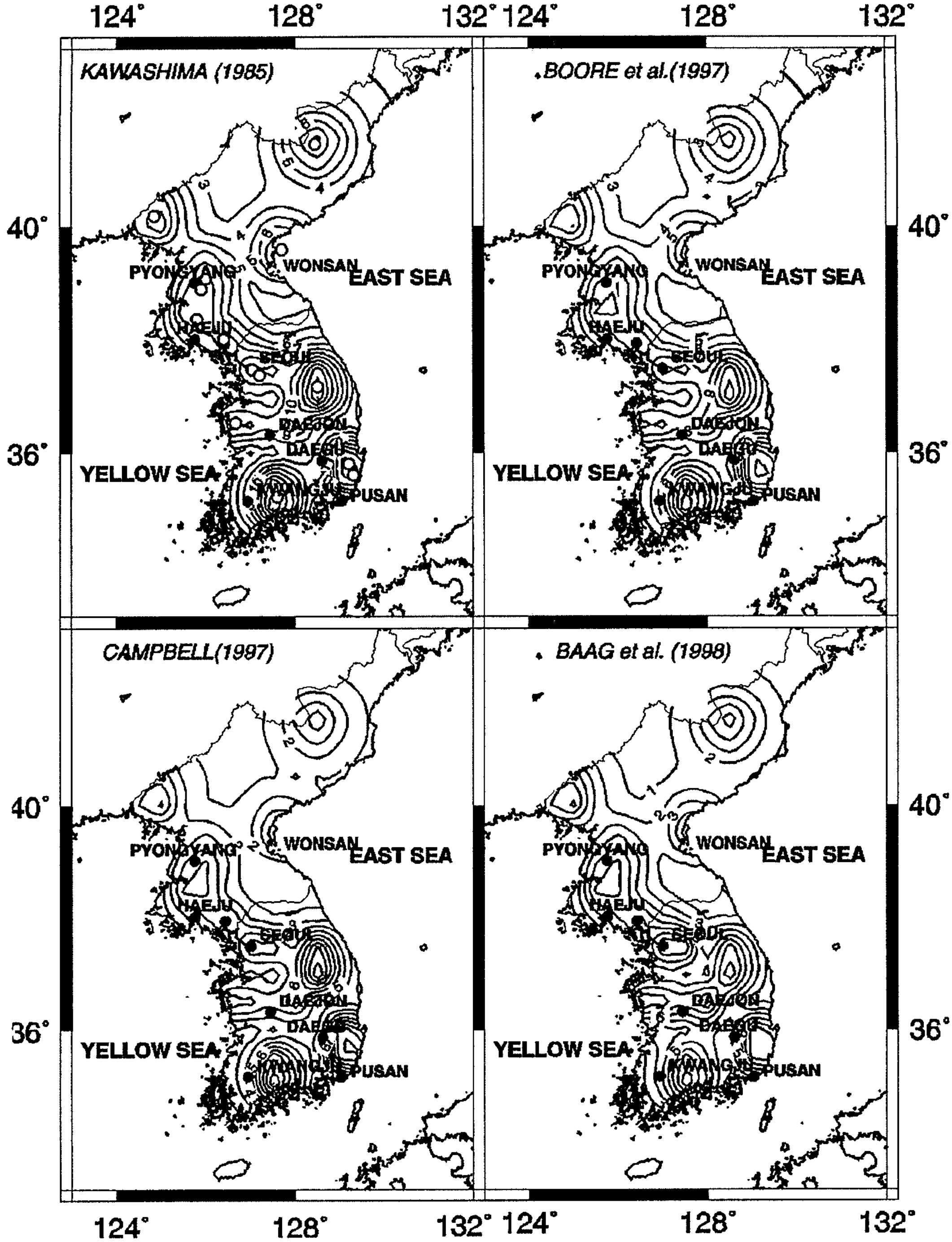
Table 3 Statistical parameters and maximum earthquakes within 10, 30, and 50 years using the readjusted Korean earthquake catalogue

Area	Data period	Seismic province	β	u	$Vmax$	10yr			30yr			50yr			rms error	Interval (yr)
						2%	5%	10%	2%	5%	10%	2%	5%	10%		
Korea	A.D.2 -1391	S2	0.48	3.91	7.04	7.02	7.00	6.95	7.04	7.03	7.01	7.04	7.03	7.02	0.2672	50
		S3	0.44	3.27	7.44	7.41	7.37	7.29	7.43	7.42	7.39	7.43	7.43	7.41	0.2980	50
		S4	0.35	5.70	7.44	7.43	7.41	7.38	7.44	7.43	7.42	7.44	7.43	7.43	0.2143	50
	1391 -1904	S1	0.98	5.40	6.62	6.61	6.60	6.58	6.61	6.61	6.60	6.62	6.61	6.61	0.1057	14
		S2	2.07	4.87	6.98	6.91	6.82	6.68	6.96	6.92	6.86	6.97	6.94	6.91	0.1205	3
		S3	1.24	5.32	7.18	7.16	7.14	7.10	7.17	7.16	7.15	7.17	7.17	7.16	0.1372	14
		S4	1.64	5.80	7.18	7.17	7.15	7.12	7.17	7.17	7.16	7.17	7.17	7.16	0.0946	14
	1905 -1998	S1	0.92	2.85	5.59	5.56	5.52	5.46	5.58	5.57	5.54	5.59	5.58	5.56	0.2139	2
		S2	1.13	3.57	5.66	5.64	5.61	5.57	5.65	5.65	5.63	5.66	5.65	5.64	0.1140	2
		S3	0.80	3.82	5.40	5.39	5.38	5.35	5.40	5.39	5.38	5.40	5.39	5.39	0.0736	3
		S4	0.51	3.93	5.90	5.89	5.87	5.84	5.89	5.89	5.88	5.89	5.89	5.89	0.0874	3
Seoul · Kyonggi	1905 -1998	Z1	0.32	2.10	4.81	4.79	4.77	4.73	4.80	4.79	4.78	4.80	4.80	4.79	0.1674	5
		Z2	0.52	2.30	4.99	4.98	4.95	4.91	4.99	4.98	4.97	4.99	4.99	4.98	0.1769	5
		Z3	0.28	1.30	5.36	5.33	5.30	5.24	5.35	5.34	5.32	5.35	5.35	5.33	0.1173	4
		All	1.00	3.48	5.26	5.25	5.23	5.20	5.26	5.25	5.24	5.26	5.25	5.25	0.0759	5



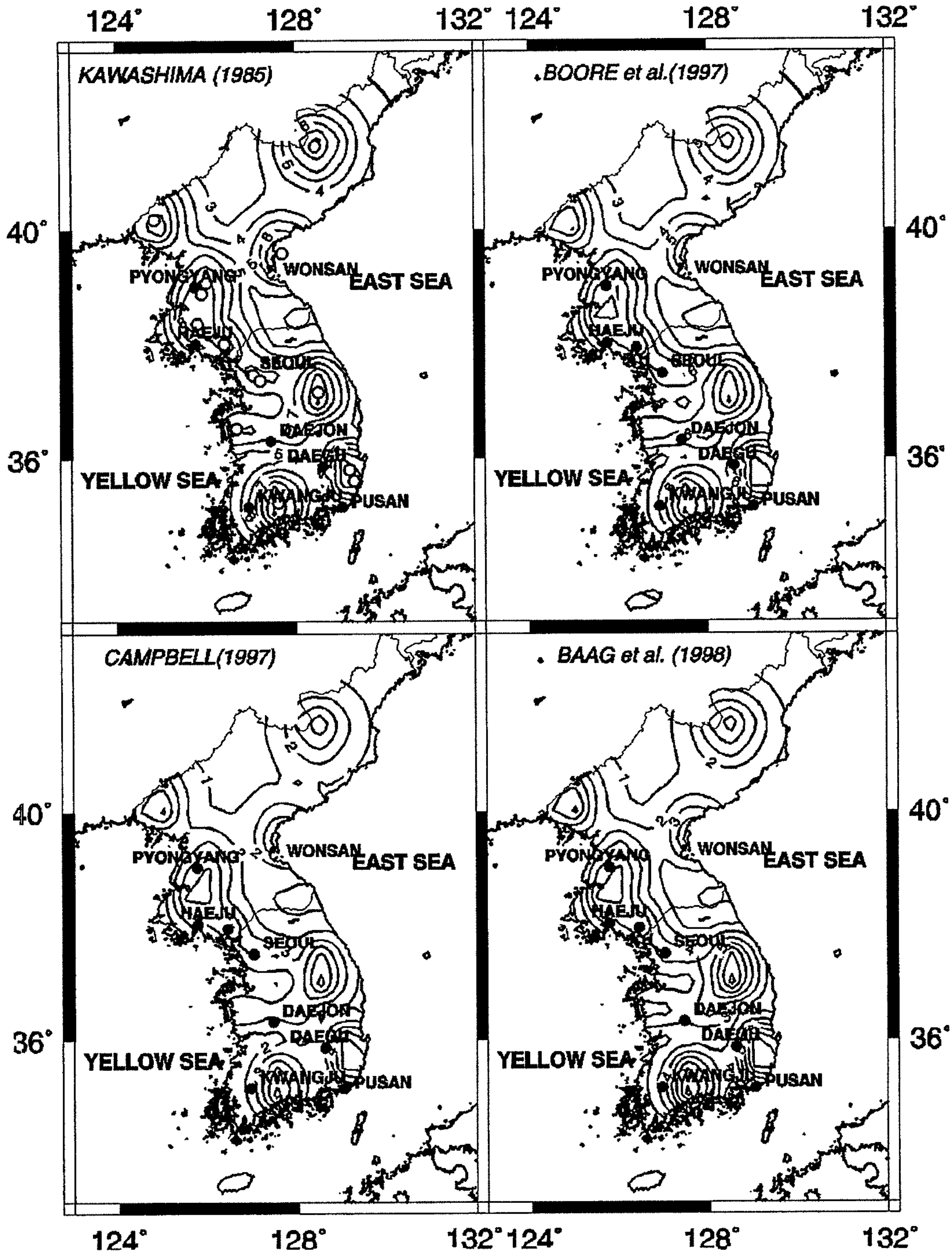
(a)

Fig. 6 Seismic risk maps using the data periods of 1392-1904 (Fig. 6a) and 1905-1998 (Figs. 6b and 6c). Contour intervals of Fig. 6a are 5 for 0-10 percentage of gravity and 2 for 10-24 percentage of gravity, and those of Figs. 6b and 6c are 1 for all ranges of percentage of gravity. Fig. 6c is a modified seismic risk map which data sets are modified for an earthquake magnitude (5.3) of Mt. Chiri earthquake on 7/4/1936 for seismic province S4 (continue)



(b)

Fig. 6 Seismic risk maps using the data periods of 1392-1904 (Fig. 6a) and 1905-1998 (Figs. 6b and 6c). Contour intervals of Fig. 6a are 5 for 0-10 percentage of gravity and 2 for 10-24 percentage of gravity, and those of Figs. 6b and 6c are 1 for all ranges of percentage of gravity. Fig. 6c is a modified seismic risk map which data sets are modified for an earthquake magnitude (5.3) of Mt. Chiri earthquake on 7/4/1936 for seismic province S4 (continue)



(c)

Fig. 6 Seismic risk maps using the data periods of 1392-1904 (Fig. 6a) and 1905-1998 (Figs. 6b and 6c). Contour intervals of Fig. 6a are 5 for 0-10 percentage of gravity and 2 for 10-24 percentage of gravity, and those of Figs. 6b and 6c are 1 for all ranges of percentage of gravity. Fig. 6c is a modified seismic risk map which data sets are modified for an earthquake magnitude (5.3) of Mt. Chiri earthquake on 7/4/1936 for seismic province S4 result when the magnitude of Mt. Chiri changed into M5.3(South Korea) because this earthquake was well documented in South Korea. Anyway, we can assume that the maximum peak ground acceleration between two results is possible to reach 0.10-0.12g.

3.4.3 Seoul and Capital Area with Instrumental Earthquake (1905-1998)

Seismic risk map of Seoul and Kyonggi area is constructed using the instrumental earthquakes (1905-1998) catalogue within the area of 38°- 39° N, 126°- 127.5°E. We made the grid model($0.25^{\circ} \times 0.25^{\circ}$) to compute peak ground accelerations at all points. The geologic backgrounds of Seoul and Kyonggi area included in Kyonggi massif are covered with Daebo granite for Jurassic, Kyonggi gneiss complex for Pre-Cambrian, and alluvium of Quaternary along the Han river. There were significant earthquakes occurred Kwangju earthquake (readjusted magnitude 6.75) in Kyonggi province on December, A.D. 27 and Seoul earthquake (readjusted magnitude 7.0) on 7/2/1518 during the historical era. From 1905 to 1977, there are earthquakes near Koyang on 1/25/1937 (readjusted magnitude 5.0) and near Seoul on 8/11/1959(readjusted magnitude 4.75). From 1978 to 1998, there are only small-size magnitude earthquakes($M \leq 3.0$) occurred in and near Kyonggi bay.

The data sets of zone 2 and 3 are not converged into a finite value because number of earthquakes are not good enough for use of Gumbel theory. So we changed the all seismic zones into one, the results of estimating the maximum potential earthquake are well converged into a finite value. In this case, we used the weighting method to determine the maximum earthquakes in all grids which maximum magnitudes occurred within a small block are scaled by the reference magnitude (maximum earthquake occurred in this region) like the spatial smoothing technique.[26] We selected the maximum potential earthquake in this region when the data interval is taken as 5 years with the least RMS error.

In this study we evaluated the seismic risk map of Seoul and Kyonggi area using the seismic wave attenuation formula recommended by Campbell.[13] Fig. 7 shows the result of ignoring surrounding geological status and Fig. 8 shows the result of considering surrounding geological conditions (e.g. alluvium, soft rock, and hard rock) using Campbell's model.[13] We also set up as a line source for faults or linearments area and a finite point source for other areas. The top figure on Fig. 7 and 8 show geologic map in the study area, which local site conditions are divided into three types(Alluvium, Daebo granite, the others area include Kyonggi gneiss complex) based on the geology map published by KIGAM[27] and DPRK Tectonic Map.[28]

From Figs. 7 and 8, the maximum PGA (0.09-0.11g) shows near Kimpo and Koyang-gun and the PGA of the area along the Han river and Kangnam area shows 0.09g, and the PGA of northwestern part of Kanghwa island is about 0.08-0.09g. Whereas those of the areas covered with Daebo granite (Uijungbu, Bukhansan area, Ichon, Ansung, and Suwon cities) show relatively lower maximum ground acceleration value than surrounding areas.

Thus, we know that the PGA of the Korean Peninsula shows higher value for seismic province S4 than those for others. The higher ground motion acceleration is

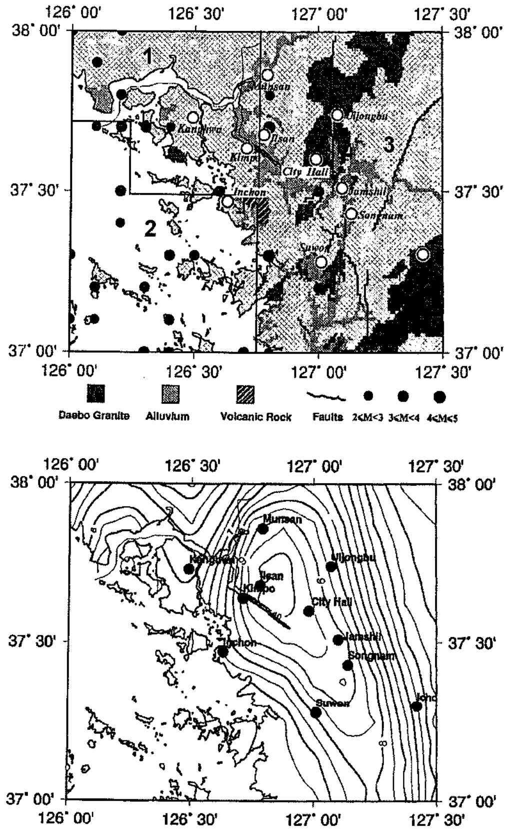


Fig. 7 The microseismic risk map of Seoul and Kyonggi area is not considered with local site condition effects. (Top) geologic map and earthquakes events occurred during 1905 to 1998. (Bottom) Numbers indicate a percentage of gravity values, and the higher PGA values of 0.09–0.10 g are showing at Kimpo and Kangnam near the Han river

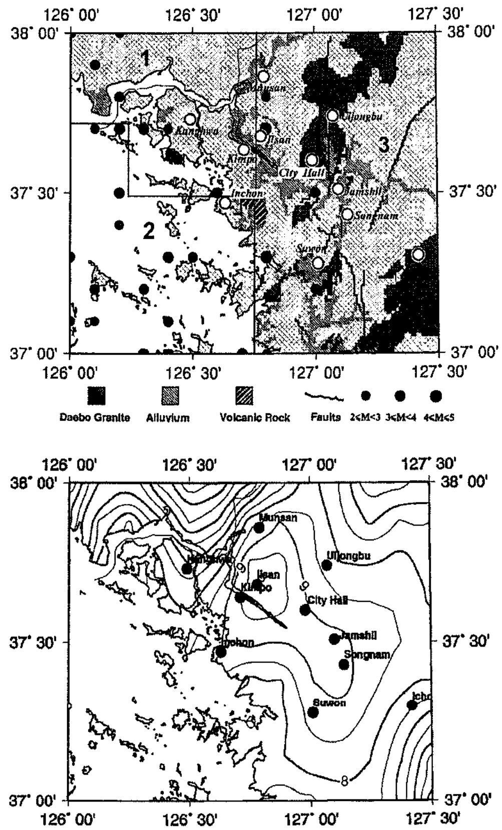


Fig. 8 The microseismic risk map of Seoul and Kyonggi area is considered with local site condition effects. (Top) geologic map and earthquakes events occurred during 1905 to 1998 in study area. (Bottom) Numbers indicate a percentage of gravity values, the higher PGA values of 0.09–0.10 g are showing at Kimpo, Jamshil, Kangnam near the Han river. The PGA values of Daebo granite area are low, whereas the PGA values of alluvium area are relatively high (details in text)

spread out in the Kyongju, the central Seoul area, and the Pyongyang area from the results of Chosun Dynasty and instrumental earthquake data. The seismic risk map of Seoul and Kyonggi area shows that the peak ground acceleration is high along the area covered with Alluvium of the Han river and Kangnam area. The value of PGA in Seoul and Kyonggi area is very much close to 0.10 g. Other researchers[(29),(30)] have found similar results as ours.

4. Conclusion and Discussion

The readjusted magnitude earthquake catalogue is reconstructed by using historical earthquake data from South and North Korea. We calculate maximum potential earthquakes for each period and each seismic province using Gumbel's extreme value theory. In order to well estimate the maximum potential earthquake using historical earthquake data of long duration, the number of missing data and missing magnitudes should be considered and selected the well optimized data intervals. In order to well evaluate seismic risk map, it should be considered as followings;

1. The accuracy of earthquake catalogue is the most important factor to evaluate an maximum potential earthquake using historical earthquakes, so the magnitude must be uniformly estimated
2. In the case of the data set including a lot of missing data, in order to estimate the maximum potential earthquake using Gumbel's the modified first asymptotic function, at first, the data sets must be classified by various-time intervals(the number of observed data is much greater than the number of missing data). Although the data set is satisfied with the above conditions, sometimes it is hard to estimate the maximum potential earthquake because the earthquake distributions are changed or distorted by large abnormal earthquake distribution. In this case, the data periods or the seismic provinces are adequately configured for the maximum potential earthquake to be a finite value.
3. Effects of local site conditions such as the soil and rock types of surface geology, fault systems, and adequate attenuation formulas should be considered to construct a resonable seismic risk map for a small province.

The ground motion using the historical data (1392-1904) shows maximum value of 0.24g at the seismic province S4, and the ground motion using the instrumental earthquake data (1905-1998) shows the maximum value of 0.10-0.12g at the sites near Kyongju, Ulsan, and Taegu cities. The trend of higher PGA shows in Kyongsang Basin and Ryongnam massif and near Pyongyang and Haeju cities, it well agrees with the present seismicity.

The seismic risk map with a 10% exceeding probability within 30 years using instrumental observation (1905-1998, about 100 year) at Seoul and Kyonggi area shows relatively high values of 0.09-0.10g along the Han river and the Kangnam area covered with alluvium of Quaternary. However, for the results of Chosun Dynasty and historical era, it is possible to reach 0.18-0.20g of PGA in this area. From this study we found that instrumental earthquakes are more reliable than historical earthquakes in the light of data quality, so we recommend the seismic risk map using instrumental earthquakes as a reliable one in Korea. Furthermore the seismic risk map presented here can be modified or improved by developing the seismic hazard evaluation method and enhancing a quality of historical and instrumental data set.

Acknowledgement

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