STATUS OF THE PSHA IN KOREA FOR NUCLEAR POWER PLANT SITES

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This paper introduces the status of and issues related to the PSHA (Probabilistic Seismic Hazard Analysis) of Korean Nuclear Power Plant sites. PSHA was first introduced to the nuclear industry in the mid-1980s. The Korean PSHA is based on Cornell and accommodates the modern approach for eliciting expertise and statistical treatment. Due to the low seismicity in Korea, large uncertainties exist in the PSHA database including seismic source maps, seismicity parameters of seismic sources, and attenuation formulae. Though research in seismology, geology, and earthquake engineering since the mid-1990s has significantly reduced uncertainties, a considerable amount still exists. Considering the low seismicity of the Korean Peninsula, especially the lack of strong motion data, further reduction will take several decades.

KEYWORDS : PSHA, Uncertainties, Seismic Source Maps, Seismicity Parameters, Attenuation Relations

1. INTRODUCTION

Until the early 1980s, the seismic hazards in Korea were evaluated by a so-called deterministic method which assumed the location and size of a maximum earthquake of a known seismic source (or zone). The results, however, suffered from criticism regarding the adequacy of the locations and sizes of maximum earthquakes. This situation would not be much different in other regions of low-to-moderate seismicity. In 1986, the first PSHA (Probabilistic Seismic Hazard Analysis) was introduced for the Sanpo NPP (Nuclear Power Plant) candidate site [1] to manipulate uncertainties inherent in the seismic characteristics of the peninsula. Since then, more than ten PSHAs have been performed for construction permits of new NPPs. However, Korean regulations, still require the determination of design earthquakes by the deterministic method. The probabilistic method is recommended by the regulatory authorities for analyzing uncertainties associated with determined design earthquakes.

In this paper, we briefly introduce the seismic characteristics of the Korean Peninsula, the status of Korean PSHA, and issues related to Quaternary faults, seismicity parameters, and attenuation formulae.

2. SEISMIC CHARACTERISTICS OF THE KOREAN PENINSULA

2.1 Outline of Tectonic Environments

The Korean Peninsula comprises three major Precambrian massifs viz., Nangrim, Kyonggi, and Yongnam massifs (Fig. 1). The Nangrim and Kyonggi massifs are separated by the Imjingang Belt, a narrow suture zone that recorded high-grade metamorphic events in the late Permian-early Triassic. The Kyonggi and Yongnam massifs are separated by the Okchon Fold Belt. The Cretaceous Kyongsang Basin in the southeastern part of the peninsula comprises gently eastward-dipping successions. A Tertiary sequence was deposited in the Pohang Basin formed in association with back-arc opening in the East Sea (Sea of Japan) [2].

The most prominent orogeny in the peninsula took place in the late Jurassic which is called Daebo orogeny [3]. It accompanied massive intrusions of syn-orogenic granitoids (Daebo granite) with the Sinian direction (NE-SW) and involved thrusts and folding of older rocks [2]. It was the major compressional tectonics in the peninsula with NW-SE trending maximum horizontal compression due to the subducting proto-Pacific plate further south. The Korean Peninsula and present-day Japan formed an

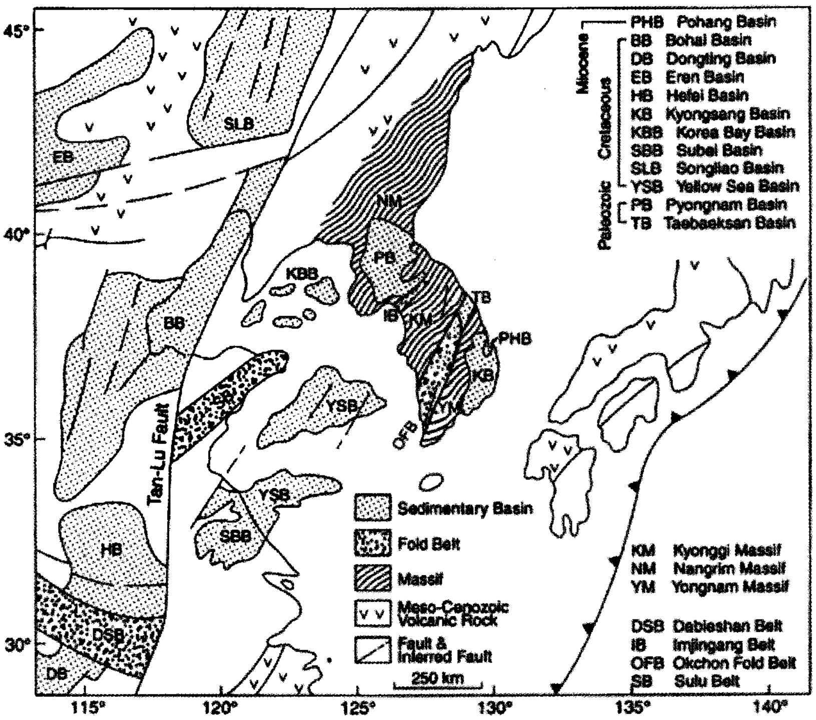

Fig. 1. Outline of Major Sedimentary Basins, Orogenic Belts, Cratonic Blocks (Massifs), and Other Geological Features in the Northeast Asian Margin (Chough et al., 2000)

arc-trench system as an active margin with prevailing NW-SE compressional stress.

After a massive India-Eurasia collision in the early Eocene, the extensional tectonics prevailed in east-northeastern Asia until the middle Miocene [4]-[6]. In the late Miocene, a new compressional stress regime set in much of the peninsula mainly due to plate-driving forces acting on the downgoing slab (slab-pull force) along the Japan trench and inhibiting forces balancing it [7]. This ultimately led to the formation of an incipient subduction zone at the eastern margin of the newly formed East Sea in the early Quaternary [8]. The present-day NE Japan arc and much of the southern part of the Korean Peninsula are everywhere under E-W compression.

2.2 Seismic Characteristics

Currently, the Korean Peninsula belongs to the stable continental region [9] which is characterized by the low seismicity. From the instrumental earthquake data, the average annual earthquake occurrence rates are estimated to be 9 for magnitude larger than 3, 1 for magnitude larger than 4, and 0.2 for magnitude of 5 or larger. No earthquake larger than magnitude 6 has been experienced since the 20th century. Table 1 compares the earthquake occurrence rate of Korea with those of other regions. On the other hand, historical documents of about 1,900 years reveal that the peninsula had relatively high earthquake activity from the 16th to the 17th century. Still, it is conjectured that no large earthquakes have occurred greater than magnitude 7 because of neither severe damages nor large death tolls reported.

Table 1. Average Annual Earthquake Occurrence Rates

Magnitude	Korea [10]	Japan [11]*	World [12]
M≥3	9	3,500	144,500
M≥4	1	370	14,500
M≥5	0.2	50	1,470
M≥6	-	7	150

* for events occurred in 130°～145° E and 30°～45° N

Figure 2 shows the epicenters of earthquakes which occurred during 1978 to 2008. At a glance, the epicenter distribution does not seem to correlate with tectonic structures trending NNE-SSW. In fact, no earthquake has been reported to occur along those faults exposed at the surface. This is not strange because the tectonic province maps are based on the tectonic events that occurred before the Cenozoic Era (e.g., [13]). Earthquake data are rapidly accumulating from the modern seismic network deployed since the mid 1990s. However, they are not sufficient yet to identify seismic sources. Especially, the lack of strong

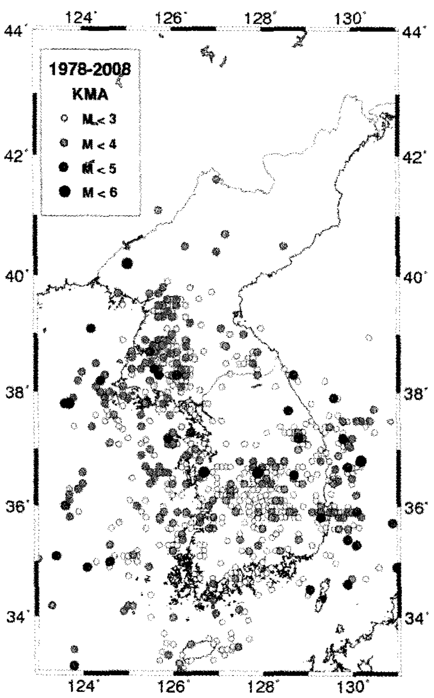

Fig. 2. Epicenters of Earthquakes which Occurred from 1978 to 2008 (KMA, 2009)

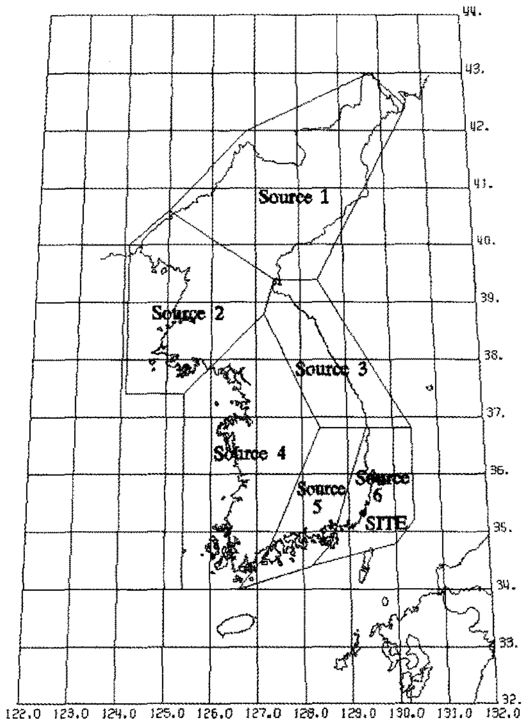

Fig. 3. Typical Map of Tectonic Structure and Seismic Sources

motion data is an obstacle in the development of attenuation formulae of ground motions.

3. STATUS OF PSHA IN KOREA

PSHA for NPP sites in Korea has been performed since the mid-1980s and is based on the method by Cornell [14]. Special efforts were made to manipulate uncertainties in the PSHA database, including seismic source maps, seismicity parameters of seismic sources, and attenuation formulae of ground motions. Expertise for the PSHA database was elicited from the expert panel. Recently, we began to apply a team-based approach for the expert panel, where the panel is composed of seismicity team(s) and attenuation-formula team(s). Each expert or expert team is allowed to recommend the best estimate and multiple alternatives together with weights. Seismic hazards are calculated for all combinations of inputs by experts (or expert teams) and statistically processed using a logic-tree method. A sensitivity analysis is usually performed to address the relative contributions of major uncertainties.

In the early stage of PSHA, seismic source maps were almost identical to the tectonic setting. As mentioned in Section 2, however, the correlation of the tectonic setting and seismic sources was weak. The degree of the resemblance between the tectonic setting and seismic source maps gradually decreases owing to related research since the mid-1990s. Some tectonic units are further divided or merged by taking into account earthquake activities and other geophysical and geological features. Figure 3 shows a typical seismic source map obtained from one of the recent PSHAs where only area sources were considered. In 2007, a capable fault was introduced as a seismic source in the PSHA for the Wolsong NPP site (see Figure 5). Here, a capable fault is the fault that should be considered in the seismic design of NPP by Korean regulations. Details of the Quaternary faults are described in Section 4.1.

Three major historical earthquake catalogs, KIER [15], Kim et al. [16], and Lee [17] have been used for PSHAs together with the instrumental earthquake catalogs. Recently, Lee and Yang [18] published a historical catalog, a revised version of Lee [17]. Historical catalogs exhibit a very large variation in the number, epicenters, and intensities of events. For example, KIER's catalog contains 309 records with MMI≥III for the period from 27 A.D. to 1904, while Kim et al.'s catalog lists 389 events with MMI≥V. However, Lee and Yang's catalog compiles 2186 earthquakes with MMI≥III for 2 A.D. to 1904, which also included aftershocks. The maximum sizes of the historical earthquake in the catalogs of KIER, Kim et al. and Lee and Yang are MMI VIII, IX, and IX, respectively. Historical earthquakes are considered to be the main source of uncertainties in the seismicity parameters. Seo et al. [19] have shown that the effect of a- and b-values on hazard level and uncertainty is comparable to that of the attenuation formula. This issue

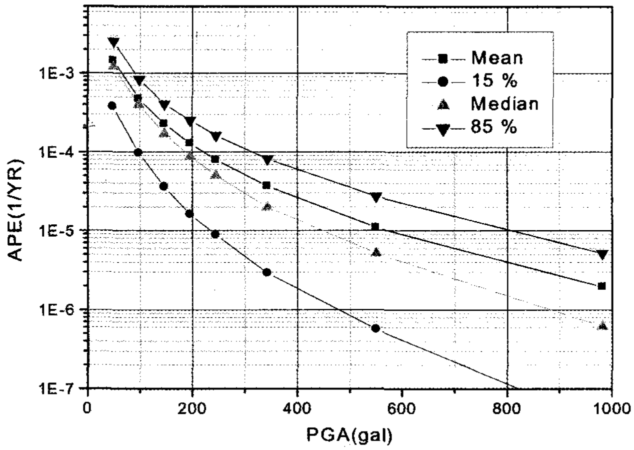

Fig. 4. Seismic Hazard Curves, Uljin Nuclear Units 5&6

is described in Section 4.2.

The instrumental earthquake catalog of KMA [20] lists events which occurred after 1978 in the Korean Peninsula and offshore. Records for earthquakes occurred from 1905 to 1977 are usually obtained from the International Seismological Centre [21]. Though the uncertainties of instrumental earthquakes are much smaller than those of historical earthquakes, considerable uncertainties exist in the origin parameters of instrumental earthquakes. Uncertainties of instrumental earthquakes are mainly due to the heterogeneity of seismic networks as well as magnitude scales.

Most of the Korean attenuation equations were developed by stochastic simulations due to the lack of strong motion data. Several attenuation formulae developed in the USA, China, and Japan are still used but with low weights. The issue of the attenuation formulae is discussed in Section 4.3.

Deficient seismic data were the largest obstacle in the probabilistic method as well as in the deterministic method. The PSHA database including seismic source maps, seismicity parameters of seismic sources, and attenuation formulae were very diverse in the early stage, which resulted in the large uncertainty band (15th to 85th percentile) of the calculated hazard. The lack of information also led to conservative judgments of the input data. Figure 4 shows the typical hazard curves for the Uljin NPP site. The mean and median annual probability of exceeding the ground acceleration of 0.2g (design level) were 3.8×10^{-4}, 1.0×10^{-4}, respectively.

4. MAJOR ISSUES RELATED TO PSHA IN KOREA

4.1 Quaternary Faults in the Korean Peninsula

There are two major faults, the Yangsan and the Ulsan faults, in the southeastern part of the Korean Peninsula (Fig. 5). The Yangsan fault, which is about 200 km in length, runs in the NNE direction. As the Yangsan fault has been reported to be an active fault by some research groups, and some field evidence of Quaternary faulting has been discovered along the Yangsan fault, the Ulsan fault, and the eastern coastline, efforts have been concentrated on geological, geochronological, seismological and paleoseismological studies [22-24]. Up to now, the outcrops of the Quaternary faults which have been identified in the southeastern Korean Peninsula number about 50 sites, and these faults are mostly located along the Yangsan fault, the Ulsan fault and the eastern coastal line.

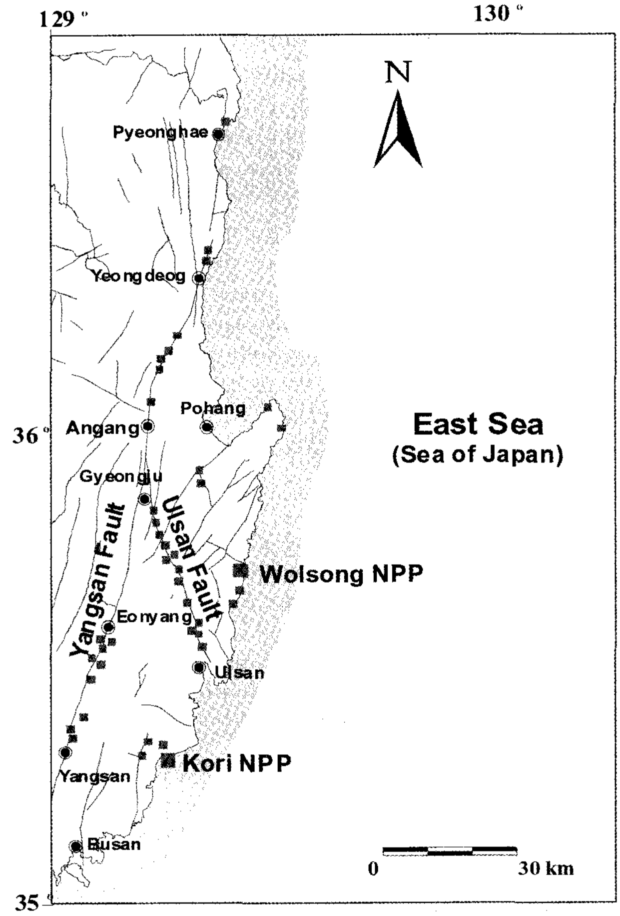

Fig. 5. Locations of the Quaternary Faults (Red Box) in the Southeastern Part of the Korean Peninsula

Extensive paleoseismological studies have been performed by trench investigations along the Yangsan and the Ulsan faults and the eastern coastline. In 1993, the first paleoseismological studies in Korea were carried out at the Eonyang-Tongdosa area, which is located in the middle of the Yangsan fault. The results of a trench survey of the site showed the geological and geomorphological evidence of the Quaternary reactivation, and the average vertical slip rate based on paleo-events was inferred to be about 0.02-0.07mm/yr in this area [24]. The activity period of the Yangsan and Ulsan faults using the ESR dating within the range of 1 Ma was estimated about 100-200 ka and 100-400 ka, respectively [25].

The results of the age dating and fault slip analysis of the Quaternary faults along the Yangsan and the Ulsan faults show that these faults have experienced a strike-slip movement parallel to the fault strike and reverse movement normal to the fault strike under the ENE-WSW current stress regime during the faulting process. The Yangsan fault could be divided into at least 5 segments with a length of about 25-30 km [26], whereas the Ulsan fault could be divided into at least 8 segments with a length of about 2.5-12km [27].

Some Quaternary faults, such as the Upcheon and the Suryum faults, were discovered near the Wolsong NPP site. As such, geological and seismological research have been focused on these Quaternary faults. In addition to these paleoseismological studies, studies have been performed to evaluate earthquake size from the fault parameters ([28]).

4.2 Seismicity Parameters

In PSHA, magnitude 7.0 has been generally considered as an upper limit for the Korean Peninsula. The maximum magnitude of instrumental earthquakes since 1905 is about M 6, which occurred in 1952 in the northwestern part of the peninsula. Exceptions are deep earthquakes in the East Sea which are attributed to the Pacific plate subducting beneath the Japan islands. Since their focal depths are more than 500 km, they impose no seismic hazard. Though magnitude estimates of historical earthquakes show significant differences among different catalogs, there were no earthquakes larger than magnitude 7 during 2 A.D.-1904. Therefore, we consider, for PSHA purposes, magnitude 7 a reasonable upper limit for historical and instrumental earthquakes. Recent inland earthquakes have had a focal depth of about 10 km. The focal depth of 3-15 km was assumed by experts during PSHAs.

Many researchers ([29],[18],[29-33]) studied the a- and (or) b-values of the whole Korean Peninsula. These are summarized in Table 2. It should be noted that the results of KEPRI [29] and Yun [34] are for South Korea. The b-values of Noh et al. [33], KEPRI [29], and Yun [34], which were obtained from the instrumental earthquake catalog, show little deviation among them. However, Kyung et al. [32] give quite low values compared with the others for instrumental earthquake catalogs. The results of Lee and Yang [18] and Seo et al. [31] for the historical earthquake catalog are quite different in a- and b-values. The gaps stemmed from differences in historical earthquake catalogs, intensity-magnitude conversion, and the treatment of the incompleteness of a catalog considered. The incompleteness of the historical earthquake catalog is large temporally and spatially. However, it is interesting that the results of KEPRI [29], Seo et al.[31], Noh et al. [33], and Yun [34] are very similar.

After the workshop on PSHA held in May 2009, most of the experts agreed that the constant b-value could be applied to all source zones in the Korean Peninsula with an average value of 0.96. Also, they agreed that the incompleteness of a catalog is important to the estimation of the Gutenberg-Richter parameters when they are estimated from the historical earthquake catalog. This consensus among experts is particularly worth noting, because variations in the b-value have been large and one of the main sources of uncertainty in the PSHA performed up to year 2008.

4.3 Attenuation Formulae

Attenuation of ground motions (attenuation formula, hereafter) are one of the most important factors in the seismic hazard analysis. Unfortunately, studies on attenuation formulae in Korea have been hampered due to the lack of seismic data. The lack of seismic data stems from there having been no large earthquakes as well as meager seismic stations in the past.

Table 2. Comparison of a- and b-values for the Korean Peninsula

Researcher	a-value	b-value	Catalog and data period considered
Lee and Jung [30]	-	0.8	Instrumental earthquake catalog (1926-1943)
Noh et al. [33]	5.66	1.11	Instrumental earthquake catalog (1978-2000)
Kyung et al. [32]	4.45-4.27	0.76-0.78	Instrumental earthquake catalog (1978-2007)
Yun [34]	-	0.99-1.04	Instrumental earthquake catalog (1905-2008)
KEPRI [29]	-	0.98	Instrumental earthquake catalog (1905-1989, raw data)
		0.89-0.92	Instrumental and historical earthquake catalogs, complete data
Lee and Yang [18]	6.09	0.71	Historical earthquake catalog (2-1904)
Seo et al. [31]	5.32	0.95	Historical earthquake catalog (2-1904)

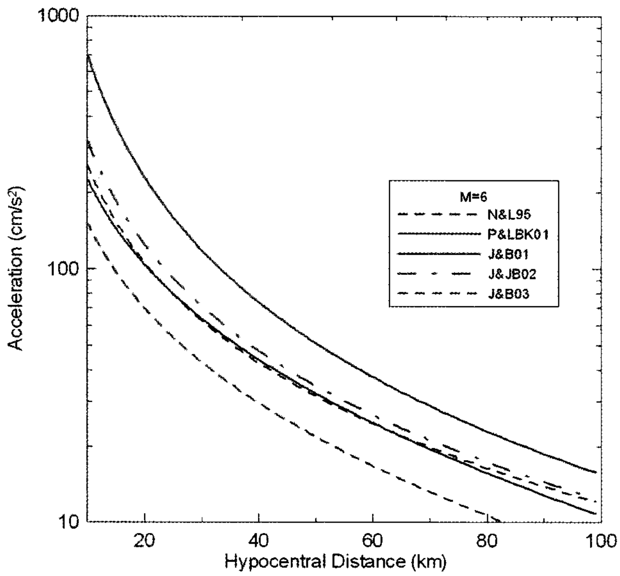

Fig. 6. Attenuation curves of PGAs for a Moment Magnitude 6 Predicted by N&L95 (Noh and Lee, 1995), P&LBK01 (Park et al., 2001), J&B01 (Jo and Baag, 2001), J&JB02(Junn et al., 2002), and J&B03 (Jo and Baag, 2003) (after Noh, 2006)

Before the 1990s, there were few reliable seismic stations in Korea. Intensity data were the only material to work with. In the early 1990s, several modern seismic stations were constructed in Korea. Then, the number of seismic stations drastically increased during the period from 1997 to 2001. Now there are more than one hundred digital stations including borehole and broadband stations. From these seismic stations, a considerable amount of seismic data was recorded from 30 to 40 Korean earthquakes a year. However, the earthquakes were less than magnitude 5 except for a few offshore earthquakes whose magnitudes were about 5. Consequently, the validity of attenuation formulae for larger earthquakes was not confirmed by strong motion data.

For this reason, some researchers have adopted attenuation formulae developed in the other regions, for example, eastern North America, which was conjectured to have attenuation characteristics similar to those of the Korean Peninsula. As Aki [35] pointed out, however, the attenuation formulae of a region cannot be applied directly to other regions even if those regions are geographically contiguous to each other because of possible differences of source mechanisms or medium properties, or both.

An alternative approach to overcome the lack of seismic data was attempted by Noh and Lee [36], who applied the stochastic method of Boore [37] to develop attenuation formulae. Since the approach of Noh and Lee ([36,38]) was considered to be the most promising one in Korea for the time being, many similar research studies (e.g., Park, J.U. et al. [39]; Jo and Baag, [40,41]; Park, D.H. et al. [42]; Junn et al. [43]) followed. The main focus of the subsequent research was the re-estimation of the source and medium properties by using seismic data available then. Figure 6 shows the attenuation curves for peak ground accelerations (PGAs) predicted by N&L95 (Noh and Lee, [36]), P&LBK01 (Park et al., [42]), J&B01 (Jo and Baag, [40]), J&JB02 (Junn et al., [43]), J&B03 (Jo and Baag, [41]). The largest difference in PGAs is observed with a factor of 4 between N&L95 and J&B01. The (Brune) stress drop was suggested to be the most uncertain factor in the development of attenuation formulae by the stochastic method (Noh [44]). The conflicting issues have centered on how the stress drop changes (constant vs. increasing) with increasing magnitude and the level of stress drops (low vs. high) in the Korea Peninsula. The range of stress drops was suggested by several authors (Jun and Kulhánek [45], Kim and Kim [46], and Yun et al. [47]). The large variation of the stress drop was considered to be due to the limited earthquake and the different estimation methods. So, it is necessary to focus future research on the reduction of the uncertainty in the stress drop estimates. Particular care is needed to check whether the stress drop model based on the analysis of small earthquakes is still valid for large earthquakes. However, this will take several decades because, considering the low seismicity of Korea, it is hardly to be expected that sufficient strong motion data from large earthquakes will be accumulated within a few years.

5. CONCLUSION AND DISCUSSION

The deficiencies in earthquake data due to the low seismicity of the country have been the main source of uncertainty of the PSHA in Korea. It has also led to conservative judgments concerning seismicity parameters for raising the seismic hazard. Earthquake data of good quality that were produced from the modern nationwide seismic network have greatly improved the seismological knowledge of the country. As a result, the calculated seismic hazard has been gradually decreased. We recognize that uncertainties are still large, so that we are making efforts to reduce the uncertainties in the existing data. Further reduction of uncertainties by using new seismic data from future earthquakes, however, will take several decades due to the low seismicity of the country.

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