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Uniform Hazard Spectrum(UHS) for performance based seismic design

*Jun-Kyoung Kim[1)], Soung-Hoon Wee[2)] and Seong-Hwa Yoo[2)]

[1)] Department of Fire Protection and Disaster Prevention, Semyoung University, Jechon 27136, Korea
[2)] Earthquake Research Center, KIGAM, Daejeon 34132, Korea
[1)] kimjk3926@gmail.com

ABSTRACT

Since Northridge (1994) and Kobe earthquake (1995), the concept of performance-based design has been actively introduced to design major structures and buildings. Therefore, Uniform hazard spectra (UHS), with annual exceedance probabilities, corresponding to the performance level are required for performance-based design. Using the method of probabilistic seismic hazard analysis (PSHA), the uniform hazard spectra for 5 major cities in Korea, with recurrence period of 500, 1,000, and 2,500 years and, corresponding to frequencies (0.5, 1.0, 2.0, 5.0, 10.0) Hz and PGA, were analyzed. According to sensitivity analysis, the parameter of spectral ground motion prediction equations has more impact on seismic hazard than seismo-tectonic models do.

1. Introduction

Seismic design is to protect human life, structures, and buildings from seismic disasters. The design response spectrum, which is the most fundamental element of seismic design, was presented in the form of a standard design response spectrum in the early stage of seismic design. A representative example is the standard design response spectrum provided by the Regulatory Guide 1.60 (USNRC, 1973) that is applied to the seismic design of nuclear power plants and their relevant structures.

Recently, the concept of performance-based design has been positively introduced to the design of buildings and various facilities. Hence, the uniform hazard spectrum (UHS) of annual occurrence frequency appropriate for each performance level of structures and buildings is applied. Among the Korean seismic design laws and regulations related to performance-based design, Article 10-2 (Matters Commonly Applied to Earthquake-Proof Design), Chapter 4, “Seismic Countermeasures” of the Enforcement Decree of the Act on the Preparation for Earthquakes and Volcanic Eruptions, states that the national seismic performance goals should be established for

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[1)] Professor
[2)] Senior Engineer
[2)] Senior Engineer

each level, including “operation performance,” “immediate occupancy,” “life safety,” and “collapse prevention.”

Particularly in the seismic design of nuclear power plants, the performance-based design techniques have been introduced to the Reg. Guide 1.208 technical standards, which apply the uniform hazard spectrum corresponding to the annual occurrence frequency of 10^{-5} as the design ground motion. In addition, ASCE (American Society of Civil Engineers) 43-5 (US AEC, 2007) also applies the horizontal and vertical design factors (DF) to regulate the uniform hazard spectrum.

The concept of performance-based design has also been gradually introduced to the fire protection facilities in Korea. According to Article 9, Paragraph 2 of the Act on Prevention and Installation, Maintenance, and Safety Control of Fire-Fighting Systems, the Seismic Design Standards for Fire-Fighting Systems (notified by the Ministry of Public Safety and Security) have been applied since January 25, 2016. Hence, fire-fighting facilities, including indoor fire hydrant facilities, sprinkler facilities, and water sprayers should be properly installed appropriately for the regulations determined by the standards or higher standards. However, appropriate performance levels required for the performance-based design of fire-fighting facilities have not been specifically provided yet by the Seismic Design Standards for Fire-Fighting Systems (notified by the Ministry of Public Safety and Security). Therefore, studies may need to be conducted with regard to the performance levels of fire-fighting facilities. During the Kobe Earthquake that occurred in Japan in 1995, the damage by fire to the entire city for one week was more severe than the immediate damage by the earthquake. This gives a lesson that seismic performance-based design is critical to major fire-fighting facilities.

The analysis was performed in the present study with two types of input data provided by an expert panel including ten earthquake and ground motion prediction equation (GMPE) experts. The spectral GMPEs developed in Korea and other countries and various seismotectonic provinces (Seismotectonic Province) of Korea were used to perform the probabilistic seismic hazard analysis with respect to 3 major cities having high population and industrial density.

To solve the problems pointed out by a previous study (Kim et al., 2016), especially the abnormalities at a low frequency, several feedback procedures were taken in the present study. Thus, the largest difference of the present study from previous studies is that the expert panel was involved and several feedback procedures were applied in the presented study. Based on this, the seismic hazard was re-analyzed, and a new uniform hazard spectrum was presented.

In the present study, the uniform hazard spectrum was analyzed and provided with respect to three major return periods, which were 500, 1,000, and 2,500 years, except the return period of 4,800 years corresponding to the highest design performance level of “collapse prevention.” After the maximum performance level required for the performance-based design of specific fire-fighting facilities is defined in the future, adequate return periods may need to be included in the analysis. In the US, the PGA and the national seismic hazard are provided for three return periods of 500, 1,000, and 2,500 years, considering the performance levels of general structures, not the fire-fighting facilities. The results of the present study were compared with those of previous studies (Hahm, 2012; Kim et al., 2016).

2. Probabilistic Seismic Hazard Analysis

The probabilistic seismic hazard analysis method was used to analyze the annual exceedance probability for an arbitrary ground motion level calculated by considering the earthquake magnitude and epicentral distance of all earthquakes that may occur at a certain site or in the entire Korea. Three types of input variables are used for the seismic hazard analysis, and the input variables contain intrinsic uncertainty that seismic data have. In the probabilistic seismic hazard analysis, the seismic hazard analysis is generally performed by using a logic tree to effectively reflect the uncertainty of the input variables.

In the probabilistic seismic hazard analysis, the areal seismic source was first divided into grids of an equal size to analyze the seismicity of each grid. Since the uncertainty of linear seismic sources, such as a fault, is still high in Korea, only areal sources were taken into consideration in the present study. The seismicity is defined with the variables of the Gutenberg-Richter (1944) relation of Equ. (1):

$$\mathbf{log}(\boldsymbol{N}) = \boldsymbol{a} - \boldsymbol{b} \cdot \boldsymbol{\varphi} \qquad \mathbf{(1)}$$

, where M denotes the magnitude and N the annual number of times of earthquakes exceeding the earthquake magnitude, M, per unit seismic area. In addition, a and b, the G-R constants, respectively denote the intersect and the slope of the curve representing the relation between the seismic magnitude and the cumulative number of earthquakes.

Analysis of the magnitude of ground motion by an earthquake that will occur in the future in an arbitrary region requires a GMPE, which expresses the PGA or the spectral acceleration as a function of seismic magnitude and epicentral distance. The annual exceedance probability of specific design ground motion values was calculated at individual sites of analysis by using each seismicity variable of all the grids inside the seismotectonic province models provided by the ten experts as well as the GMPE.

Most of the seismotectonic province models provided by the ten experts consisted of one or several smaller areal sources. The smaller areal source regions were divided into grids of 0.1° latitude and longitude, and the a, b, maximum earthquake magnitude and minimum earthquake magnitude were analyzed and assigned to each grid. This was performed by calculating and summing the seismic hazard values from all the areal sources at each of the corners of the grids.

3. Seismic Input Data

3.1 Earthquake Catalogs

To calculate and analyze the a, b, maximum earthquake magnitude and minimum earthquake magnitude in each of the seismotectonic province models, the ten experts suggested one or a combination of two or three of three earthquake catalogs that are currently available, including Lee and Yang (2006), Korea Meteorological Agency (2012), and Korea Institute of Geoscience and Mineral Resources (2014), considering the reliability of earthquake catalogs.

3.2 Seismotectonic Province Model (Areal Source Model)

The seismic hazard analysis was performed by using the various seismotectonic province models provided by the ten experts. A majority of the experts suggested one or a combination of two or three of three existing earthquake catalogs, while some of the experts suggested their own seismotectonic province models.

3.3 Determination of a, b, Maximum and Minimum Magnitude

Considering the completeness of the earthquake catalogs, different weights were given to the seismotectonic province models provided by the ten experts, according to the observation period, such as entire historical earthquakes, earthquakes observed in the era of Joseon, Goryeo, and Three Kingdoms, and the instrumental earthquakes from 1903. The weight for each era of the earthquake catalogs was applied to analyze the a, b, maximum earthquake magnitude and minimum earthquake magnitude.

3.4 GMPE Models

Each of the ten experts suggested various GMPE models with the weight. The input data were used to perform the seismic hazard analysis. Some experts suggested combinations of models, including the model developed for the Mid-Eastern region of the US, (Abrahamson and Silva, 2008; Campbell, 2003; Atkinson and Boore, 1997; Toro et al. 1997; Atkinson & Silva, 2000; Boor and Atkinson, 2008; Boore and Atkinson, 2011), while other suggested combinations of multiple models, including the seismic motion attenuation models developed in Korea (Noh and Lee, 1995; Lee, 2002; Jo and Baag, 2003; Yun et. al., 2005) and the model developed for the Mid-Eastern region of the US. The seismic motion attenuation characteristics of Korea has been known to be more similar to that of the relatively stable Mid-Eastern region of the US than that of the geologically active Western region of the US (Abrahamson and Silva, 2008).

The seismic hazard was defined for the National Earthquake Hazards Reduction Program (NEHRP) B/C ground (760 m/sec, V_S30) by considering the GMPE models used. Hence, when applying an actual seismic hazard to an arbitrary region, the site amplification characteristics should be considered in addition to the seismic hazard defined for the NEHRP B/C ground according to the properties of the ground.

Although a number of records of strong earthquakes that were actually observed are required to develop the GMPE models for individual frequencies, a stochastic simulation method is generally used in regions such as Korea where there is no record of a strong earthquake of a magnitude of 6.0 or higher. However, detailed information of the grounds of the observatories in Korea is needed to effectively apply the stochastic simulation method. The uncertainty of the GMPE is extremely high because of the lack of strong ground motion observation data from earthquakes of a magnitude of 5.0 or higher and the limitations in the range of the epicentral distance of observed ground motion as well as in the observation regions.

Since various types of input variables are used in the probabilistic seismic hazard analysis, including the seismic sources and GMPE, a sensitivity analysis should be performed with regard to the effect of individual input variables on the seismic hazard to verify the reliability of the results. Generally, the results are analyzed by fixing various weighted seismic input variables and varying only one of the variables.

4. Uniform Hazard Spectrum

Fig. 1 to 3 show the seismic hazard and the PGA calculated for 3 major cities, for three return periods at each city (500, 1,000, and 2,500 years) at frequencies of 0.5, 1, 2, 5, and 10Hz. In Fig. 1 to 3, the horizontal axis represents the frequency, and the vertical axis represents the seismic hazard. As described above, since the PGA hazard is related to zero period acceleration (ZPA), the frequency should be infinite. However, referring to the general notation used in other reports, the PGA hazard was presented as the value at 100.0 Hz. The uniform hazard spectrum was analyzed by using the seismic hazard corresponding to return periods of 500 years (2.0E-03 /yrs.), 1,000 years (1.0E-03/yrs.), and 2,500 years (4.0E-04 /yrs.), which may be most frequently applied periods for consideration of the seismic design performance of important fire-fighting facilities, including indoor fire hydrant facilities, sprinkler facilities, and water sprayers.

Fig. 1 shows the uniform hazard spectrum for the region of Seoul at return periods of 500, 1,000, and 2,500 years. The seismic hazard was gradually increased as the return period was increased. Fig 1. shows the specific seismic hazard values. In all three uniform hazard spectra, the seismic hazard was lowest at the starting point, 0.5 Hz, and gradually increased in parallel as the frequency was increased, and then reached a peak at 10 Hz. After the peak, the seismic hazard decreased to converge to the PGA value (about 1/2 of the seismic hazard at 10 Hz). When compared with the results for Seoul in previous studies (Hahm, 2012; Kim et al., 2016), the values were slightly higher in the present study at all frequencies of interest and at the PGA.

Fig. 2 shows the uniform hazard spectrum for the region of Daejeon. Similarly to the results of Seoul, as the return period was increased, the seismic hazard reached the peak at 10 Hz, and then converged to the PGA value. The PGA values for the return periods of 500, 1,000, and 2,500 years were 0.088g, 0.125g, and 0.185g, respectively, indicating that the hazard was slightly higher than that of Seoul at each return period. Similarly to the results of Seoul, the values were slightly higher and the shape characteristics were similar when compared with the results from a previous study (Kim et al., 2016).

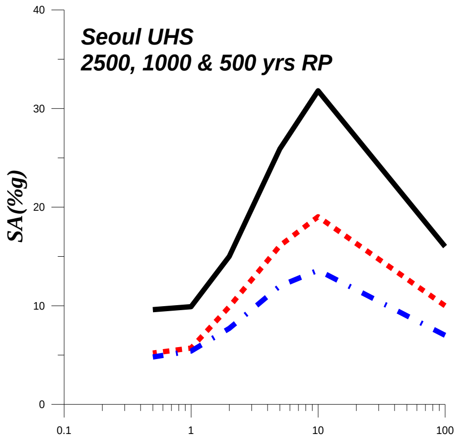

Fig. 1 Uniform *Seismic* Hazard for Seoul

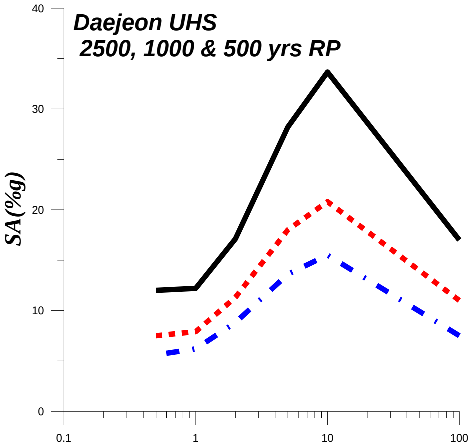

Fig. 2 Uniform Seismic Hazard for Daejeon

Fig. 3 shows the uniform hazard spectrum for the region of Daegu. Similarly to the previous two regions, as the return period was increased, the seismic hazard reached the peak at 10 Hz, and then converged to the PGA value. As shown in Fig. 3, the PGA values for the return periods of 500, 1,000, and 2,500 years were 0.093g, 0.135g, and 0.206g, respectively, indicating that the hazard was highest among the 3 cities. Previous reports have also shown that the highest seismic hazard is found in the region of Daegu (KIGAM, 2012; Hahm, 2012; Kim et al., 2016). Similarly to the results of Seoul, the values were slightly higher and the shape characteristics were similar when compared with the results from previous studies.

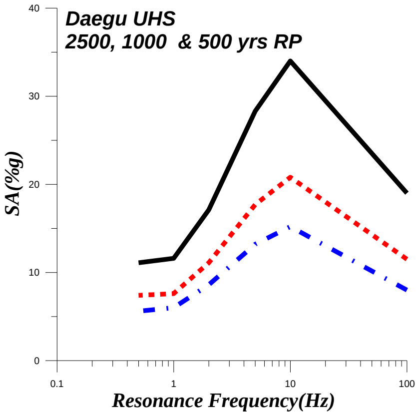

Fig. 3
Uniform Seismic Hazard for Daegu

With reference to the PGA for the return period of 2,500 years, the seismic hazard was highest in Daegu, followed by Daejeon and Seoul. Similarly, with reference to 10 Hz for the return period of 2,500 years, the seismic hazard was highest in Daegu, followed by Daegu and Seoul. The order of seismic hazard at both the PGS and 10 Hz was the same as that of previous studies. In addition, with reference to the PGA, the results were similar to the National Seismic Hazard Map provided by the Ministry of Construction and Transportation (1997).

5. CONCLUSIONS

1. The uniform hazard spectrum was presented for 3 major cities in Korea for three return periods (500, 1,000, and 2,500 years) that are generally required for the seismic performance-based design of fire-fighting facilities. In the seismic hazard data for the three return periods and the 3 major cities in Korea, the maximum value was found at 10.0 Hz, and the seismic hazard increased at each of the frequencies as the return period was increased. At the frequency of 10.0 Hz, where the maximum seismic hazard was found in all the uniform hazard spectra, the seismic hazard for the return periods of 500, 1,000, and 2,500 years was not significantly different between the 3 cities.
2. With reference to the return period of 2,500 years, the seismic hazard was highest in Daegu, followed by Daejeon and Seoul. This result was similar the National Seismic Hazard Map provided by the Ministry of Construction and Transportation (1997). The seismic hazard values of the 3 cities analyzed in the present study, especially the PGA seismic hazard values, were slightly higher than those of previous studies (Hahm, 2012; Kim et al., 2016), but the difference was within the error range, considering the difference with the seismic hazard analysis code and the expert panel.

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