Seismic hazard analysis in low and moderate seismic region-Korean peninsula

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Abstract

In low and moderate seismic regions, seismic activities have not been well defined. Unexpected large future earthquakes might occur in these regions, and structures can be severely damaged and collapsed since most structures in these regions were designed by considering only gravity loads. The objective of this study is to construct a uniform hazard response spectrum (UHRS) and to generate synthetic uniform hazard ground motions at a site with low and moderate seismicity for evaluating seismic performance of structures located at the site. The Seoul city hall was chosen as a site to simulate ground motions and construct a UHRS. To achieve this objective, this study simulates the epicenters and magnitudes of future earthquakes within 50,000 years based on those of past earthquakes recorded during the last 614 years. This study assumes that the site is affected only by earthquakes that occur within 100 km from the site. For 50,000 years, 36,645 earthquakes occur on the Korean peninsula, of which 4288 occur within 100 km of the selected site. Thus, 4288 ground motions are generated at the site considering earthquake attenuation and soil profiles at the site. Then uniform hazard response spectra (UHRS) are constructed at the site for 10% and 2% probabilities of exceedance over the next 50 years. This study also selects 10 ground motions for a response history analysis of structures, which best fit the UHRS.

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1. Introduction

Large unpredicted earthquakes can occur in low and moderate seismic regions, e.g., the 1811 Mississippi valley earthquake and the 1886 Charleston earthquake in the US structures located in low and moderate seismic regions are more vulnerable to damage from large unexpected earthquakes since the structures in these regions were generally constructed with less stringent design and detail requirements than those in high seismic regions; many structures were designed by considering only gravity loads. Low, moderate and high seismicity can be defined using seismic design category (SDC) [1]. According to ACI 318 note [2], SDC of C is defined as moderate seismicity.

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According to the study by Whittman [3], in the eastern US, the ratio of peak ground accelerations of maximum credible to maximum expected earthquake is about six whereas that ratio in the western US is about 1.25. It is also reported that the size of maximum considered earthquake (2% in 50 years) in Charleston and Memphis is similar to that in Los Angeles and San Francisco even though the size of earthquakes with 10% probability of exceedance in 50 years in Charleston and Memphis are much smaller than that in Los Angeles and San Francisco [4].

Performance evaluation procedures of existing buildings require accurate prediction of future earthquakes. In low and moderate seismic regions, available earthquake records are very limited. In these regions ground motions recorded in high seismic regions have often been used after scaling the ground motions, which may not be representative ground motions for low and moderate seismic regions. It is reported that seismic demands can vary significantly according to different EQGM sets even though those sets were obtained at sites with similar soil conditions [5]. Wen and Wu [6] constructed a uniform hazard response spectrum for Mid-American cities which are classified as regions of moderate seismicity.

The objective of this study is to construct a uniform hazard response spectrum (UHRS) for probabilities of exceedance of 10% and 2% in 50 years, and select ground motions having their acceleration response spectrum closely fitting to the constructed UHRS. For this purpose this study generates synthetic ground motions of future earthquakes for 50,000 years accounting for actual seismicity in Korea based on earthquake records for 1932–2005. First, future earthquakes were simulated by defining the epicenters and magnitudes of earthquakes for a given period of time. The Korean peninsula, located between 33°–43° latitude and 123°–131° longitude is divided into 8991 grids sized 0.1° × 0.1° to specify the epicenters of the future earthquakes. This study simulates ground motions at the Seoul city hall considering earthquake attenuation and the local site effect of the selected site, which are produced by earthquakes occurred within 100 km of the site. During 50,000 years, 4288 earthquakes occur within 100 km of the site. Thus, 4288 ground motions are generated at the site, from which the uniform hazard spectrum at the site is constructed according to 2% and 10% probabilities of exceedance in 50 years. In this study, the point source model is used to generate ground motions.

2. Earthquake catalogue of Korean peninsula

This study adopts the earthquake catalogue (1–1996 year) provided by the Korean Ministry of Construction [7] and the catalogue (1997–2006 year) provided by Korean Metrological Administration [8]. The size of earthquakes in these catalogues is represented by the Richter magnitude, $M_L$. Fig. 1 shows the number of earthquakes that occurred in each century. According to this figure, more earthquakes occurred after the 14th century. However, the authors suspect that many earthquakes were omitted in early historical documents. Table 1 shows the cumulative number of earthquakes having a magnitude greater than $m$ for the time

![Fig. 1. Number of earthquakes occurred in each century.](image-url)
periods of 1–1391 (pre-Chosun dynasty), 1392–1904 (Chosun dynasty), and 1905–2005 (post-Chosun dynasty).

Using the data in Table 1, the coefficients of the Gutenberg–Richter formula are determined by the regression analysis [9,11]. From the Gutenberg–Richter formula shown in Eq. (1), annual occurrence rate \( \lambda_m \) of earthquakes with a magnitude \( M \) greater than \( m \) is calculated,

\[
\log \lambda_m = a - bm
\]

where \( N_m \) is the number of earthquakes with magnitudes greater than \( m \), \( T \) is the period of time in year, and \( a \) and \( b \) are the coefficients determined from the regression analysis using the value of \( \lambda_m \) in Table 1. Table 2 summarizes coefficients \( a \) and \( b \) determined from the regression analysis for three different time windows (1–1391 (pre-Chosun dynasty), 1392–1903 (Chosun dynasty), 1904–2006 (post-Chosun dynasty)).

Fig. 2 shows actual and calculated \( \lambda_m \) for the three different time windows. As mentioned earlier, this figure shows that the annual earthquake occurrence rate \( \lambda_m \) for 1–1392 is much lower than those for 1392–1904 and 1904–2006 whereas \( \lambda_m \) for 1904–2006 is the greatest. This indicates that possibly not all earthquakes were recorded in the early historical documents. This study does not consider the earthquakes recorded during

<table>
<thead>
<tr>
<th>Period</th>
<th>( N_4 )</th>
<th>( \lambda_4 )</th>
<th>( N_{4.5} )</th>
<th>( \lambda_{4.5} )</th>
<th>( N_5 )</th>
<th>( \lambda_5 )</th>
<th>( N_{5.5} )</th>
<th>( \lambda_{5.5} )</th>
<th>( N_6 )</th>
<th>( \lambda_6 )</th>
<th>( N_{6.5} )</th>
<th>( \lambda_{6.5} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–1391</td>
<td>35</td>
<td>0.025</td>
<td>16</td>
<td>0.011</td>
<td>15</td>
<td>0.010</td>
<td>13</td>
<td>0.009</td>
<td>8</td>
<td>0.005</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1392–1904</td>
<td>354</td>
<td>0.690</td>
<td>152</td>
<td>0.296</td>
<td>32</td>
<td>0.062</td>
<td>18</td>
<td>0.035</td>
<td>4</td>
<td>0.008</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1904–2005</td>
<td>96</td>
<td>0.941</td>
<td>53</td>
<td>0.520</td>
<td>19</td>
<td>0.186</td>
<td>7</td>
<td>0.069</td>
<td>5</td>
<td>0.049</td>
<td>2</td>
<td>0.020</td>
</tr>
</tbody>
</table>

\( N_m \) is the number of earthquakes with \( M > m \), \( \lambda_m = N_m / T \), and \( T \) is duration in year.

Table 2

<table>
<thead>
<tr>
<th>Period</th>
<th>( a )</th>
<th>( b )</th>
<th>( \lambda_4 )</th>
<th>Actual ( \lambda_4 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1–1391</td>
<td>-0.583</td>
<td>0.274</td>
<td>0.021</td>
<td>0.025</td>
</tr>
<tr>
<td>1392–1903</td>
<td>3.730</td>
<td>0.964</td>
<td>0.748</td>
<td>0.690</td>
</tr>
<tr>
<td>1904–2005</td>
<td>2.705</td>
<td>0.681</td>
<td>0.957</td>
<td>0.941</td>
</tr>
</tbody>
</table>

Fig. 2. Annual rate of earthquakes with \( M > m \), \( \lambda_m \).
Fig. 3. Flow chart of the study.

Collect past earthquake records for a given period time (T=614 years) (magnitude (M) and epicenter of earthquakes)

Divide Korean peninsula by 0.1°x0.1° grids

Assign adresa (i, j) to each grid point

Estimate occurrence number of earthquakes N_m (i, j) having M>m at (i, j)

Calculate annual occurrence rate of earthquake (λ_m) having M>m at (i, j) λ_m (i, j) = N(m) / T

Smoothing process for λ_m (i, j)

Select time period of time T=50,000 years for simulating future earthquakes

Calculate total number of earthquakes for 50,000 years N = N_m,0 x T

Estimate cumulative distribution function of magnitude F_M (m) [Eq. (8)]

Convert λ_m (i, j) into P (k, i, j) [Eq. (3)]

Estimate cumulative distribution function F_X (k, i, j) = Σ P (k, i, j) [Eq. (7)]

Generate i th random numbers representing F_M (m), F_X (k, i, j) i = 1 - N

Determine m for each random number (i) using the estimated F_M (m)

Determine k, i, j for each random number (i) using the estimated F_X (k, i, j)

Convert k, i, j into (i, j)

Plot M at (i, j)

Select a site (city hall of seoul)

Draw circle with a diameter of 200km from the site

i < N

i = N

Generate the earthquake ground motions at a site considering local site effect soil profiles [Eq. (9)]

For all generated ground motions construct acceleration response spectra

At all 91 periods, determine S_a value for 10% and 2% of probability of exceedance in 50 yrs.

Connect S_a values, which is UHRS

Select ground motions which have these S_a to UHRS

d_i = ∑ (log S_a, UHRS - log S_a, j)^2
1–1392. Even though $k_m$ for 1392–1904 is smaller than $k_m$ for 1904–2006, earthquakes during 1392–1904 is considered in this study with the earthquakes for 1904–2006 due to the lack of earthquake records across Korean peninsula. Thus, this study considers 450 earthquakes occurred during 1932–2006 (614 years).

Fig. 3 shows the flowchart for constructing a UHRS and selecting ground motions for 10% and 2% probability of exceedance in 50 years.

3. Prediction of future earthquakes

This study simulates future earthquakes by predicting the epicenters and magnitudes of earthquakes based on past earthquakes recorded over 614 years (1392–2005).

3.1. Annual occurrence rates and epicenters of earthquakes

The Korean peninsular (33°–43° latitude and 123°–131° longitude) is divided into 0.1° × 0.1° grids. Thus, the latitude and longitude are divided into 81 grid lines ($=(131–123)/0.1 + 1$) and 111 grid lines ($=(44–33)/0.1 + 1$), respectively. The total number of grid points that cross the grid lines is 8991 ($=81 \times 111$). At each grid point, the number of earthquakes between 1392 and 2005 with a magnitude ($M_L$) greater than 4.0 is determined ($N_4(i,j)$). Then, the number is divided by the period of time ($T = 614$ years), which is defined as the annual occurrence rate ($\lambda_4(i,j)$) of earthquakes at the grid point ($i,j$).

Fig. 4a shows $\lambda_4(i,j)$. However, it is difficult to use discrete $\lambda_4(i,j)$ of earthquakes in statistical application for predicting future earthquake epicenters. Thus, annual occurrence rates are smoothed by a smoothing process similar to a process by Frankel et al. [10]. First, a weighting matrix, $W$, is defined as shown in Eq.

![Figure 4](image.png)

Fig. 4. Annual occurrence rates $\lambda_4(k_0)$ of earthquakes (1392–2005). (a) Before smoothing, (b) after smoothing.
The smoothed $\lambda_4(i,j)$ is obtained using Eq. (4). The smoothing process is applied 10 times to obtain the smoothed $\lambda_4(i,j)$ shown in Fig. 4b,

$$W = \begin{bmatrix} 1/16 & 1/8 & 1/16 \\ 1/8 & 1/4 & 1/8 \\ 1/16 & 1/8 & 1/16 \end{bmatrix}$$  \hspace{1cm} (3)

$$\lambda_4(i,j) = \sum_{i'=i-1}^{i+1} \sum_{j'=j-1}^{j+1} \lambda_4(i',j') \times W_{i'-i,j'-j}$$  \hspace{1cm} (4)

For convenience, the two dimensional $\lambda_4(i,j)$ is converted to a one dimensional $\lambda_4(k_{ij})$ using the following equations:

$$k_{ij} = (i-1)N_c + j, \quad i = 1 - 81, \quad j = 1 - 111, \quad N_c = 81$$  \hspace{1cm} (5)

Thus, annual occurrence rates $\lambda_4(k_{ij})$ of earthquakes ($M > 4$) at a location $k_{ij}$ are calculated as follows:

$$\lambda_4(k_{ij}) = \lambda_4((i-1)N_c + j) = \lambda_4(i,j)$$  \hspace{1cm} (6)

where $N_c$ is 81 and $N_R$ is 111.

Cumulative distribution probability of $\lambda_4(k_{ij})$ ($F_\lambda(k_{ij})$) at a location $k_{ij}$ is calculated using Eq. (7):

$$F_\lambda(k_{ij}) = \sum_{i=1}^{k_{ij}} P(k_{ij})$$  \hspace{1cm} (7)

Fig. 5 shows $\lambda_4(k_{ij})$ and $F_\lambda(k_{ij})$ at a location $k_{ij}$.

![Graphs showing annual occurrence rates of earthquakes and their cumulative distribution probability](image)

Fig. 5. Annual occurrence rates of earthquakes. (a) $\lambda_4(k_{ij})$, (b) cumulative distribution probability $F_\lambda(k_{ij})$. 
Epicenters of future events are generated using cumulative distribution probability $F_{ij}(k_{ij})$ in Fig. 5b. First, uniformly distributed random numbers between 0 and 1 are generated that represent $F_{ij}(k_{ij})$. For example, for a random number 0.6 representing $F_{ij}(k_{ij})$, the corresponding $k_{ij}$ is 3375 as shown in Fig. 5b, that represents the earthquake epicenter of an earthquake. Then, $k_{ij} (= 3375)$ is converted in to $(i, j)$ using Eq. (5) and plotted in the map as shown in Fig. 6b. To verify this process, 450 random numbers are generated, which represent the total number of earthquakes that occurred during 1392–2005 (see Table 1). Fig. 6a shows the distribution of actual earthquakes. Comparing Fig. 6a and b, the distribution of simulated epicenters is similar to the epicenters of actual earthquakes.

3.2. Prediction of earthquake magnitude

For predicting the magnitudes of future earthquakes, the Gutenberg–Richter formula is used (see Eq. (1)). The cumulative distribution probability of magnitude ($F_{M}(m)$) can be calculated using Eq. (8). This study considers earthquakes occurred during 1392–2005 (614 years),

$$F_{M}(m) = P[M < m|M > m_0] = \frac{\lambda_{m_0} - \lambda_{m}}{\lambda_{m_0}}$$

(8)

where $\lambda_{m}$ is the annual occurrence rate of earthquakes with a magnitude ($M$) greater than $m$ on the Korean peninsula (Eq. (1)), where $m_0$ is 4.

The procedure for predicting magnitudes of future earthquakes is similar to that used for predicting the epicenters of future earthquakes. First, a new set of 450 random numbers is generated from 0 to 1, which represent $F_{M}(m)$ for 450 earthquakes during 614 years. A magnitude corresponding to each cumulative distribution probability is determined using Fig. 7. For example, a magnitude of 4.76 is determined corresponding to a random number of 0.8 ($= F_{M}(m)$). The 450 simulated magnitudes are paired with the previously generated 450 epicenters.

Fig. 6. Epicenters and magnitudes of earthquakes during 614 years. (a) Actual earthquakes (1392–2005), (b) simulated earthquakes (614 years).
In Fig. 6b the 450 pairs of epicenters and magnitudes are plotted. By comparing Fig. 6a and b, one can see that the procedure used in this study accurately predicts epicenters and magnitudes of earthquakes.

4. Ground motion model

Since information on fault structures in Korea is very limited, seismic source is modeled as the point source. Ground motions are simulated by the point source simulation using the SMSIM software developed by Boore [12]. This study adopts modeling parameters of the point source model for the Korean peninsula proposed by Noh and Lee [13,14] and stress drop proposed by Jo and Baag [15].

4.1. Point source model

The mathematical model of the Fourier amplitude spectrum of the point source model is defined as follows:

$$A(f) = C \cdot S(f) \cdot D(f) \cdot I(f)$$

(9)

where $C$ is the scaling factor that defines the spectral amplitude, and $S(f)$ is the source spectral function that defines spectral shape of earthquake ground motions at a site, $D(f)$ is the diminution function of spectral amplitudes as waves propagate to a site, $I(f)$ is the type of motion being computed: acceleration, velocity, or displacement, and $f$ is the frequency. Noh and Lee [13,14] suggested the parameters of the point source model for the Korean peninsula as follows:

1. Scaling factor, $C$

$$C = \frac{R_{\theta \phi} \cdot F \cdot V \cdot 1}{4\pi \rho \beta^3} \frac{1}{\gamma}$$

(10)

where $R_{\theta \phi}$ is the average radiation pattern (=0.63), $F$ is the free surface effect (=2), $V$ is the partition factor of the horizontal component (=0.71), $\rho$ is the soil density (=2.7 g/cm$^3$), $\beta$ is the shear wave velocity (=3.5 km/s) and $\gamma$ is the distance scaling factor accounting for geometric spreading of body waves radiated from a point source.

2. Source spectral function, $S(f)$

$$S(f) = \frac{M_0}{1 + (f/f_c)^2}$$

(11)

where $M_0$ is the seismic moment, $f_c$ is the corner frequency (=4.9 x $10^6 \beta(\Delta\sigma/M_0)^{1/3}$), and $\Delta\sigma$ is the stress drop (=100 bar).
\( D(f) = \exp(-\pi \kappa_d f R) \cdot \exp(-\pi \kappa_q f), \quad \kappa_s = 1.4 \times 10^{-2}(\pm 3.8 \times 10^{-3}), \quad \kappa_q = 1.6 \times 10^{-4}(\pm 3.9 \times 10^{-5}) \) \tag{12}

\( I(f) = (2\pi f)^p \) \tag{13}

where \( p \) is 0, 1, and 2 for displacement, velocity and acceleration, respectively.

4.2. Local site effect

This study considers soil amplification induced by local site effects. In the SMSIM software, the local site effect is reflected by Site_amp subroutine program. For determining input parameters, this study uses soil profiles and shear wave velocity \((V_s)\) measured at 25 different locations (see Table 3) near four sites, which are provided by the Korean Ministry of Construction and Transportation [16]. Fig. 8 shows the calculated soil amplification at the 25 locations. In this figure, the thicker line represents mean soil amplification, which is used for generating ground motions in the following sections.

4.3. Verification of the parameters

To verify the point source model and model parameters including local site effects, earthquake ground motions recorded at four different sites (see Fig. 9a–d) during the 1996 Youngwol earthquake (moment

Table 3
Representative soil profile near four selected sites

<table>
<thead>
<tr>
<th>Location</th>
<th>Alluvium ((V_s, m/s))</th>
<th>Weathered rock ((V_s, m/s))</th>
<th>Soft rock ((V_s, m/s))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location 1</td>
<td>3.5</td>
<td>0</td>
<td>26.5</td>
</tr>
<tr>
<td>Location 2</td>
<td>6.5</td>
<td>0.5</td>
<td>23.0</td>
</tr>
<tr>
<td>Location 3</td>
<td>0.5</td>
<td>5.5</td>
<td>24.0</td>
</tr>
<tr>
<td>Location 4</td>
<td>11.8</td>
<td>0</td>
<td>18.2</td>
</tr>
<tr>
<td>Location 5</td>
<td>10.0</td>
<td>0</td>
<td>20.0</td>
</tr>
<tr>
<td>Location 6</td>
<td>5.0</td>
<td>1.0</td>
<td>24.0</td>
</tr>
<tr>
<td>Location 7</td>
<td>3.0</td>
<td>3.8</td>
<td>23.2</td>
</tr>
<tr>
<td>Location 8</td>
<td>6.0</td>
<td>5.0</td>
<td>19.0</td>
</tr>
<tr>
<td>Location 9</td>
<td>5.5</td>
<td>0</td>
<td>24.5</td>
</tr>
<tr>
<td>Location 10</td>
<td>4.0</td>
<td>0</td>
<td>26.0</td>
</tr>
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<td>Location 11</td>
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<td>4.0</td>
<td>24.0</td>
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<td>Location 12</td>
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<td>Location 13</td>
<td>1.5</td>
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<tr>
<td>Location 14</td>
<td>3.4</td>
<td>0.4</td>
<td>26.2</td>
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<tr>
<td>Location 15</td>
<td>3.0</td>
<td>0.6</td>
<td>26.4</td>
</tr>
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<td>Location 16</td>
<td>2.9</td>
<td>0.9</td>
<td>26.2</td>
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<td>Location 17</td>
<td>4.9</td>
<td>25.1</td>
<td>0</td>
</tr>
<tr>
<td>Location 18</td>
<td>5.9</td>
<td>1.0</td>
<td>23.1</td>
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<td>4.2</td>
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<td>2.5</td>
<td>1.0</td>
<td>26.5</td>
</tr>
<tr>
<td>Location 25</td>
<td>9.7</td>
<td>1.3</td>
<td>19.0</td>
</tr>
</tbody>
</table>
magnitude = 4.3) are simulated using the SMSIM software. Table 4 summarizes the information for each station. Fig. 10 shows the acceleration response spectrum ($S_a$) of recorded earthquake ground motions and mean $S_a$ of 200 generated earthquake ground motions at each station. The $S_a$ of simulated ground motions is similar to that of actual ground motions. Thus, the point source model can be used for simulating ground motions and constructing a uniform hazard response spectrum in Korea.

Fig. 8. Amplification factors of 25 locations.

Fig. 9. Epicenter and recording stations of the 1996 Youngwol earthquake.
To simulate earthquake ground motions and construct a UHRS at a given site, this study selects the site near Seoul city hall (latitude = 37.52°, longitude = 126.92°, grid number = 3687), and considers simulated earthquakes within 100 km of the site. It is assumed that the site is affected only by earthquakes that occurred within 100 km of the site. For each point source event (earthquake) defined by an epicenter and magnitude, the corresponding ground motion is generated by the SMSIM software which accounts for attenuation and local site effect. Earthquakes with epicenters and magnitudes are generated during a time window of 50,000 years according to the procedure described in the previous sections.

As mentioned earlier, 450 earthquakes occurred during 614 years. Thus the total number of earthquakes during 50,000 years is 36,645 (=450 × 50,000/614 years = 36,645). The number of earthquakes at a grid point \((i,j)\) \(N_d(i,j)\) during 50,000 years can also be calculated by multiplying \(N_d(i,j)\) during 614 years by 81.4 (= 50,000/614 years).

Of the 36,645 earthquakes that occur on the Korean peninsula over 50,000 years, 4288 occur within 100 km of the site. Since the soil test, for determining depth, density and shear wave velocity of soil layers at the Seoul city hall, was not permitted, this study uses soil information obtained when the subway station of the Seoul city hall was constructed (from the database of the Seoul Metropolitan Subway Corporation [17]). The subway station is located about 1000 m from the Seoul city hall. Table 5 summarizes information of soil layers at 14 locations. Fig. 11 shows the soil amplification factor at the 14 locations. This study assumes that mean soil amplification for 14 locations represent soil amplification at the Seoul city hall. The thicker line represents the

---

### Table 4

<table>
<thead>
<tr>
<th>Station name</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Epicentral distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>129.07</td>
<td>35.57</td>
<td>142</td>
</tr>
<tr>
<td>b</td>
<td>129.30</td>
<td>35.57</td>
<td>158</td>
</tr>
<tr>
<td>c</td>
<td>129.15</td>
<td>35.45</td>
<td>169</td>
</tr>
<tr>
<td>d</td>
<td>129.26</td>
<td>35.35</td>
<td>191</td>
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</tbody>
</table>

---

Fig. 10. Acceleration response spectrum of simulated and recorded ground motions.

5. Simulation of ground motions and uniform hazard response spectrum

To simulate earthquake ground motions and construct a UHRS at a given site, this study selects the site near Seoul city hall (latitude = 37.52°, longitude = 126.92°, grid number = 3687), and considers simulated earthquakes within 100 km of the site. It is assumed that the site is affected only by earthquakes that occurred within 100 km of the site. For each point source event (earthquake) defined by an epicenter and magnitude, the corresponding ground motion is generated by the SMSIM software which accounts for attenuation and local site effect. Earthquakes with epicenters and magnitudes are generated during a time window of 50,000 years according to the procedure described in the previous sections.

As mentioned earlier, 450 earthquakes occurred during 614 years. Thus the total number of earthquakes during 50,000 years is 36,645 (=450 × 50,000/614 years = 36,645). The number of earthquakes at a grid point \((i,j)\) \(N_d(i,j)\) during 50,000 years can also be calculated by multiplying \(N_d(i,j)\) during 614 years by 81.4 (= 50,000/614 years).

Of the 36,645 earthquakes that occur on the Korean peninsula over 50,000 years, 4288 occur within 100 km of the site. Since the soil test, for determining depth, density and shear wave velocity of soil layers at the Seoul city hall, was not permitted, this study uses soil information obtained when the subway station of the Seoul city hall was constructed (from the database of the Seoul Metropolitan Subway Corporation [17]). The subway station is located about 1000 m from the Seoul city hall. Table 5 summarizes information of soil layers at 14 locations. Fig. 11 shows the soil amplification factor at the 14 locations. This study assumes that mean soil amplification for 14 locations represent soil amplification at the Seoul city hall. The thicker line represents the
mean soil amplification that is used for generating ground motions at the Seoul city hall. Corresponding to 4288 earthquakes, 4288 ground motions at the site are generated considering attenuation and local site condition. For each ground motion generated at the site, acceleration response spectrum ($S_a$) is constructed by connecting $S_a$ values calculated at 91 periods. Total 4288 acceleration response spectra are constructed. For each period, a histogram for the acceleration response spectra ($S_a$) is constructed. Fig. 12a shows the histogram of $S_a$ for a period of 0.2 s. An annual occurrence rate $\lambda(S_a > a_j)$ for earthquakes with $S_a > a_j$ is calculated using Eq. (14), and plotted in Fig. 12b,

$$\lambda(S_a > a_j) = \frac{1}{T} \sum_{j=1}^{4288} I(S_a > a_j)$$

where $I(S_a > a_j)$ is the indicator counting when $S_a > a_j$, and $T$ is the time window of 50,000 years in this study.

In current seismic performance evaluation procedures [18], two different seismic hazard levels are generally used, which are defined by probabilities of exceedance of 10% and 2% in 50 years. For these two levels, annual occurrence rates can be calculated using Poisson process shown in Eq. (15):

### Table 5
Representative soil profile at the city hall of Seoul

<table>
<thead>
<tr>
<th>Location</th>
<th>Alluvium</th>
<th>Weathered rock</th>
<th>Soft rock</th>
<th>Hard rock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Depth (m)</td>
<td>$V_s$ (m/s)</td>
<td>Density (kg/m$^3$)</td>
<td>$V_s$ (m/s)</td>
<td>Density (kg/m$^3$)</td>
</tr>
<tr>
<td>Location 1</td>
<td>350</td>
<td>1900</td>
<td>15.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Location 2</td>
<td>650</td>
<td>2100</td>
<td>5.0</td>
<td>6.5</td>
</tr>
<tr>
<td>Location 3</td>
<td>1700</td>
<td></td>
<td>5.1</td>
<td>8.0</td>
</tr>
<tr>
<td>Location 4</td>
<td>2200</td>
<td></td>
<td>6.4</td>
<td>8.0</td>
</tr>
<tr>
<td>Location 5</td>
<td></td>
<td></td>
<td>8.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Location 6</td>
<td></td>
<td></td>
<td>7.5</td>
<td>6.0</td>
</tr>
<tr>
<td>Location 7</td>
<td></td>
<td></td>
<td>11.5</td>
<td>7.0</td>
</tr>
<tr>
<td>Location 8</td>
<td></td>
<td></td>
<td>4.0</td>
<td>7.0</td>
</tr>
<tr>
<td>Location 9</td>
<td></td>
<td></td>
<td>10.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Location 10</td>
<td></td>
<td></td>
<td>11.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Location 11</td>
<td></td>
<td></td>
<td>12.4</td>
<td>8.0</td>
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<tr>
<td>Location 12</td>
<td></td>
<td></td>
<td>11.5</td>
<td>8.0</td>
</tr>
<tr>
<td>Location 13</td>
<td></td>
<td></td>
<td>10.0</td>
<td>8.0</td>
</tr>
<tr>
<td>Location 14</td>
<td></td>
<td></td>
<td>8.0</td>
<td>8.0</td>
</tr>
</tbody>
</table>

![Fig. 11. Amplification factor at the city hall of Seoul.](image-url)
Fig. 12. Histogram of acceleration response spectrum ($T = 0.2$ s). (a) Histogram, (b) $\lambda(S_a < a_j)$.

Fig. 13. Uniform hazard response spectrum (UHRS).
\[
P(S_a > a_j, t = 50 \text{ years}) = 1 - e^{\lambda(S_a > a_j) \times 50}
\]

The annual occurrence rate, \( \lambda(S_a > a_j) \) is calculated as 0.0021, and 0.0004 corresponding to for 10\% and 2\% probabilities of exceedance in 50 years \( P(S_a > a_j, t = 50 \text{ years}) \). As shown in Fig. 12b, \( S_a \) is determined corresponding to annual exceedance probabilities of 0.0021 and 0.0004, which are 0.23 g and 0.51 g, respectively. By repeating the above process for all 91 periods, a uniform hazard response spectrum is constructed for \( \lambda(S_a > a_j) \) of 0.0021 and 0.0004, which are equivalent with 10\% and 2\% probabilities of exceedance in 50 years, respectively. Fig. 13 shows UHRS.

Also, this study selects representative ground motions for 10\% and 2\% in 50 years. This is achieved by selecting ground motions from 4288 ground motions, which have the least sum of the squared logarithmic dif-

![Graphs showing selected ground motions](image-url)
ference calculated by Eq. (16) at 91 different periods between their acceleration response spectra and uniform hazard spectrum. This procedure is proposed by Shome and Cornell [19]

\[
d_i = \sum_{j=1}^{91} (\log S_{aj}^{\text{UHRS}} - \log S_{aij})^2
\]  

(16)

where \( d_i \) is the sum of the squared logarithmic difference of \( i \)th ground motion \((i = 1-4288)\), \( S_{aj}^{\text{UHRS}} \) is the uniform hazard response spectrum at \( j \)th period \((j = 1-91)\), and \( S_{aij} \) is the response spectrum of \( i \)th ground motion at \( j \)th period.

Fig. 14 shows five selected ground motions for 2% in 50 years. Fig. 15 shows the acceleration response spectrum of 10 selected ground motions and uniform hazard response spectrum, which shows the validity of the selection procedure.

6. Conclusions

In designing new structures and evaluating seismic performance of existing structures, it is important to construct an accurate uniform hazard response spectrum and to simulate representative earthquake ground motions at a selected site. This study simulates future earthquakes defined by magnitudes and epicenters, based on past earthquake records during 1391–2005. Using simulated earthquakes, ground motions are generated at a site using the SMSIM software that can account for attenuation and local site condition. The parameters used for the point source model in the SMSIM software is verified by simulating actual ground motions recorded at four different sites during the 1996 Youngwol earthquake in Korea.

Furthermore, to construct a uniform hazard response spectrum this study simulates earthquakes over 50,000 year periods. This study selects the Seoul city hall as a site. Earthquakes that occur within 100 km of the site are considered. The total number of ground motions generated at the site is 4288 corresponding to 4288 earthquakes, and 4288 acceleration response spectra are constructed at the site. Uniform hazard response spectra are constructed for 10% and 2% probabilities of exceedance in 50 years. This study selects 10 ground motions for 10% and 2% in 50 years. The 10 selected ground motions have the least logarithmic difference between their response spectrum and uniform hazard response spectrum at 91 different periods among 4288 ground motions.

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