SEISMIC RESPONSE EVALUATION AT THE SITE OF FIVE-STOREY STONE PAGODA DAMAGED BY 1936 SSANG-GYE-SA M 5.0 EARTHQUAKE IN MODERATE SEISMICITY REGION, KOREA

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ABSTRACT :

An earthquake of magnitude 5.0 occurred at a Buddhist temple, Ssang-gye-sa, located near the southern border of the Korean peninsula on 4 July 1936. It resulted in severe damage of several buildings and structures in Ssang-gye-sa, which lie in a mountain valley. Particularly, the top component of a five-storey stone pagoda in the temple was tipped over and fell down during the earthquake. In order to estimate the intensity of the 1936 Ssang-gye-sa earthquake from the pagoda damage, intensive site investigations including borehole drillings and seismic tests such as crosshole test and SASW were performed in the temple area. Based on the site characteristics, site-specific seismic response analyses using various input motions were conducted in the pagoda site by means of both equivalent-linear and nonlinear one-dimensional schemes with six input rock outcrop acceleration levels ranging from 0.044g to 0.220g. The resultant site-specific responses indicated the amplified ground motions in the short-period band, particularly near the site period of the pagoda site, which can be recognized as the seismic site characteristics in the mountain or hilly area. The intensity of the 1936 earthquake, especially for the pagoda site, considering the site effects was quantitatively evaluated by combining between the site responses analysis results in this study and the full-scaled seismic pagoda model test in the prior study.

KEYWORDS: Seismic hazard, Site effects, Seismic response, Site characterization, Site period

1. INTRODUCTION

When an earthquake occurs, seismic waves radiate away from the source and reach the ground surface on which waves produce shaking. The surface ground shaking, which man has practically experienced, is capable of causing seismic hazard such as casualties and property damage. Although sites are in the same distance from the source of an earthquake, the extent of the seismic hazards results from the seismic load at particular site which greatly depends upon the characteristics of the site. In particular, soil layers on bedrock tend to amplify significantly the seismic motion at certain period band matching with the fundamental frequency of a site. In other words, the site effects related to the local geologic and site conditions at a site have a profound influence on the amplification potential of earthquake ground motion and the corresponding response spectrum. Structures may be more severely damaged if their natural periods happen to be close to the resonant site periods and thus the site effects are an important factor for quantifying earthquake intensities based on structural damages on ground surface.

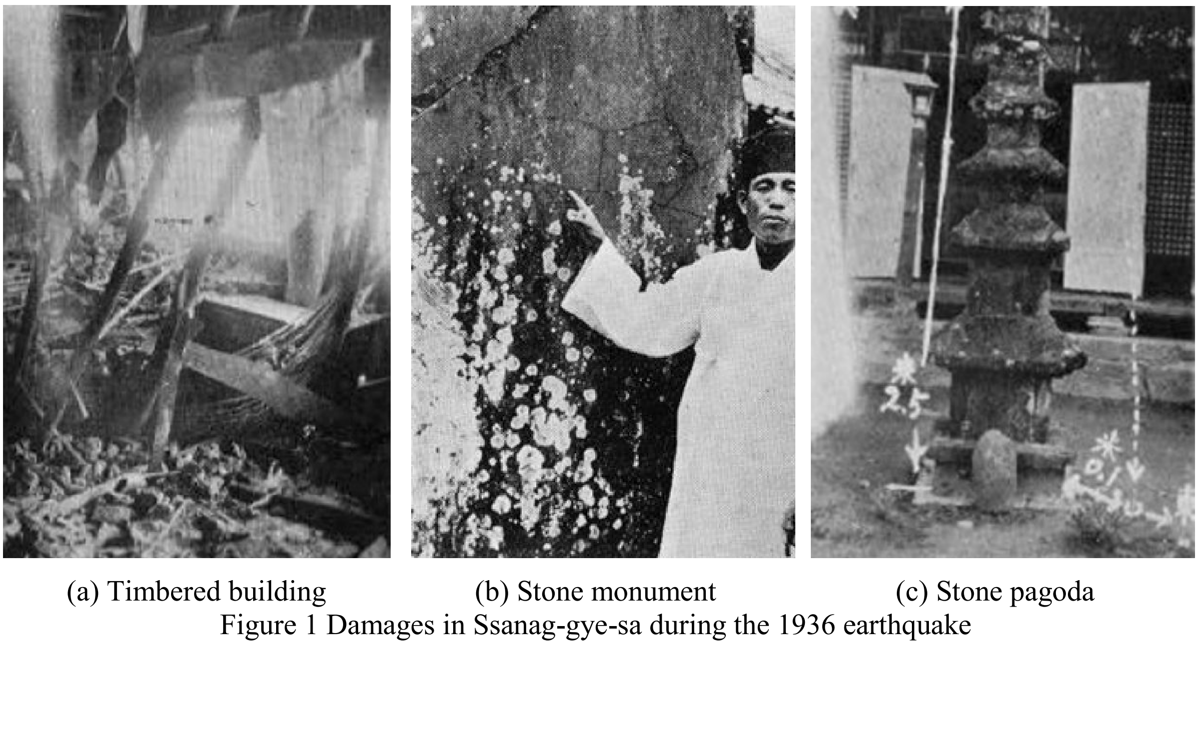
The Korean peninsula belongs to a region of moderate seismicity located inside the Eurasian plate, differing from strong seismic regions: western US, Japan, southern China, Taiwan, and so on. Since few earthquake motion data showing substantial magnitude and intensities were recorded in Korea, the ground motions in the seismic design guide were determined based on historical earthquake events

(Sun et al., 2005) Most of historical earthquake events described in the historic documents were experienced at the ground surface of the soil sites and the amplifications by the site effects were possibly included in the earthquake intensities (Kim and Ryu, 2003). Therefore, the quantitative evaluation of site effects is required particularly at the site having structural damages among major instrumental earthquake events in Korea, although the events are moderate in size and practically do not have useful seismogram data but damage figures or photos together with seismological analysis documents. In this study, a site damaged by an instrumental earthquake was selected to quantitatively evaluate the site effects and correspondent seismic response, because a quantitative structural damage was recorded at the site.

A moderate size earthquake, M 5.0, occurred on 4 July 1936 at a mountain of Jirisan in the southern part of Korea. The epicenter was a narrow region surrounding a famous and beautiful Buddhist temple, Ssang-gye-sa (Kim and Ryu, 2003). This earthquake caused a considerable amount of damage in the epicentral region including the Ssang-gye-sa area, in which several structures were damaged by the earthquake. Particularly, the top component of a five-storey stone pagoda in Ssang-gye-sa fell on the ground (Kim and Ryu, 2003). As part of the evaluation of the intensity of the 1936 Ssang-gye-sa earthquake, the site characterization in the temple area was carried out using the field tests composed of borehole drillings and seismic tests and the laboratory resonant column test. Based on the site characteristics determined representatively for Ssang-gye-sa from the field and laboratory tests, site-specific seismic response analysis for evaluating the site effects was performed by adopting both equivalent-linear and nonlinear schemes.

2. DAMAGES OF STRUCTURES IN SSANG-GYE-SA

Ssang-gye-sa, the Buddhist temple, is located on the southern foot of Jirisan, which is a mountain in the southern region of the Korean peninsula. Jirisan is designated as national park and considered the southern end of the Baekdudaegan mountain range across the Korean peninsula. Ssang-gye-sa lies at a mountainous area of the confluence of two valleys. On July 4th, 1936, an earthquake of which the magnitude was estimated into 5.0 after several decades, struck the southern region of Korea. Its epicenter was located at 35.14ºN and 127.39ºE and near Ssang-gye-sa in Jirisan. Major damages were concentrated on Hwagye-myeon, Hadong-gun including the temple site. The most severe damages were mainly observed in and near Ssang-gye-sa in Woonsoo-ri, Hwagye-myeon (SNU, 1999).



(a) Timbered building (b) Stone monument (c) Stone pagoda

Figure 1 Damages in Ssanag-gye-sa during the 1936 earthquake

The 1936 Ssang-gye-sa earthquake resulted in the damages of numerous roads and masonry buildings nearby the epicenter and the intensity of maximum V in JMA scale (SNU, 1999). Near Ssang-gye-sa, large landslides occurred by this earthquake. In Ssang-gye-sa, the gate to the temple was suffered severe damages in roof and walls and tilted to the north. A traditional timbered building with tiled roof collapsed and a stone monument which is designated as national treasure had new cracks. Moreover, a 3 m tall stone pagoda composed of five-stories damaged by ground shaking and the top component was tipped over and fell to the ground. The reconnaissance on the Ssang-gye-sa earthquake damages was carried out by seismologists at that time and contains very clear photos on the damages (SNU, 1999; Kim and Ryu, 2003). The latter three damages in Ssang-gye-sa described above are shown as the photos in Figure 1. Figure 1(a) and (b) indicate the damage of a traditional timbered building and a stone monument, respectively. Figure 1(c) illustrates the fall of the top component (bell-shaped stone) of five-storey stone pagoda. The pagoda was located on the front of Geumdang during the 1936 earthquake and was relocated to present location on the front of Daewoongjeon. Thus they stone pagoda is still standing in the temple, Ssang-gye-sa. Based on the seismic damage of the pagoda during the 1936 earthquake, in this study, the site-specific seismic response characteristics are evaluated with the numerical approaches by performing the intensive site characterization in the temple site.

3. SITE INVESTIGATION IN SSANG-GYE-SA

The topography of Ssang-gye-sa is characterized as mountainous and hilly area. In this area, two creeks from valleys join and flow downward. The geology of the temple area is mainly covered by granite, which is commonly observed in the mountain of Jirisan. The topographical characteristics in and near the temple make the development of the weathered layer composed of the upper weathered residual soil and the lower weathered rock over the bedrock as well as the alluvium or colluviums on the weathered layer by accumulating the circumferential soils and rock fragments.

In order to determine the local geological and geotechnical characteristics and estimate the corresponding site effects, various filed and laboratory tests were performed at three sites in the temple area. For the geotechnical site characterization in Ssang-gye-sa, 2 boring investigations including standard penetration test (SPT) with 1.5 m interval in depth, one crosshole seismic test, and 3 SASW (spectral analysis of surface waves) tests were conducted. An exploratory borehole for subsoil examination and crosshole test was drilled to at least, the depth of 4 m below the soft rock underlying weathered rock for determining the engineering properties including the shear wave velocity (V_S) from soil surface to bedrock (Sun et al. 2005).

Figure 2 Location and geomorphology of Ssang-gye-sa and contents of in-situ investigations

The geographic location and circumferential geomorphology of Ssang-gye-sa are illustrated in Figure 2, together with the locations and contents of in-situ tests in the temple. The temple area could be sorted into three zones: FG, KU and LU. The FG represents a wide zone, in which main buildings are located and a non-invasive SASW test was performed. The KU indicates a higher zone for the Geumdang, on which the top component of the stone pagoda was fallen during the 1936 earthquake and a SASW test was conducted. And the LU is a narrow zone between the FG and KU zones, at which the boring investigation and crosshole test were carried out together with a SASW test because of the cultural properties protection in the both FG and KU zones. From these site investigations in the field, the subsurface geologic constitutions with depth and the V_S profile representing the geotechnical dynamic properties are determined and provided as the input for the site-specific seismic response analyses. In the laboratory, resonant column tests were performed to determine the nonlinear modulus reduction and damping curves by reconstituting the samples of alluvial and weathered residual soils obtained from the SPT in the field.

The subsurface geologic conditions and the V_S profile for the site representing Ssang-gye-sa area were determined from the results of in-situ geotechnical investigations. The V_S profiles deduced from in-situ seismic tests at three testing sites are presented in Figure 3, together with the representative V_S profile for Ssang-gye-sa area. Also, the profile on geotechnical layers investigated from the borehole drillings at the LK site is shown in Figure 3. The subsurface layers were composed of coarse and fine alluvial materials with 5 m thick overlying thin (2 m thick) fill and relatively thick weathered layers containing the weathered residual soil of 3 m thick and the weathered rock of 6 m thick. The soft rock was observed in the depth of 16 m, but the depth to bedrock (H) was determined as the depth of 12 m, from which the value of V_S is correspondent with that (V_S > 750 m/s) of the seismic engineering bedrock (Sun et al., 2005). The V_S value of the bedrock at Ssang-gye-sa site is 1,100 m/s, which is fall within the common range of V_S values for the bedrock in Korea (Sun et al., 2005). The representative V_S profile having about 600 m/s more from 4 m deep indicates the seismic amplification potential near the short period.

The site-specific seismic response characteristics can be predicted by examining the geotechnical earthquake engineering indexes such as the depth to bedrock (H), the site period (T_G), and the mean shear wave velocity to a depth of 30 m (V_S30) for categorizing site class in the current seismic design guidelines (Sun et al., 2005). The site effects can be explained first by differences in the V_S between the soil layers and the underlying rock, which represent an impedance contrast, and second by the thickness of soil layers or the depth to bedrock. Seismic site response analysis techniques have incorporated these concepts, particularly the phenomenon by which the largest amplification of earthquake ground motion at a nearly level site occurs at approximately the lowest natural (fundamental) frequency (Rodriguez-Marek et al., 2000). The period of vibration

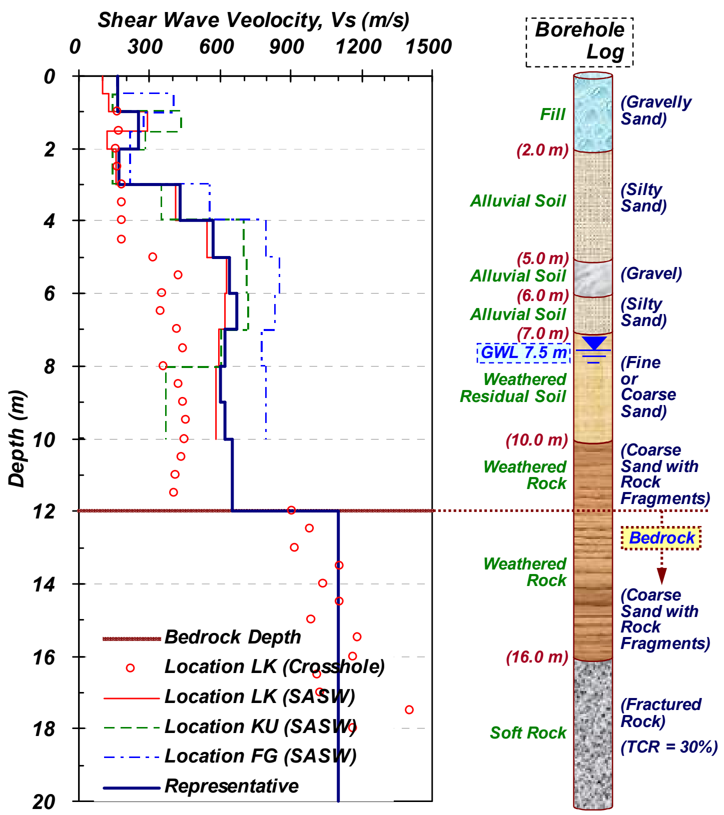


Figure 3 Subsurface layers and shear wave velocity profile at Ssang-gye-sa site

corresponding to the fundamental frequency is called the site period, T_G (Sun et al., 2005). For seismic design in accordance with site conditions, correlations between mean V_S of the upper 30 m (V_S30) and site amplification factors (F_a for short-period between 0.1 s and 0.5 s and F_v for mid-period between 0.4 s and 2.0 s) in specific earthquakes, including the 1989 Loma Prieta earthquake, were established based on empirical and numerical studies (Borcherdt, 1994; Dobry et al., 1999). Accordingly, in the current seismic codes (Dobry et al., 2000; Sun et al., 2005), the site characterization for a site class is based only on the top 30 m of the ground. The site class is determined solely and unambiguously by one parameter, V_S30 (Sun et al., 2005).

Determining the geotechnical earthquake engineering indexes for Ssang-gye-sa site from the results of in-situ tests, the H is 12.0 m, and the T_G and V_S30 are 0.124 s and 633 m/s, respectively. The Ssang-gye-sa falls into site class C (Sun et al., 2005), which stands for the potential of some seismic amplification. Particularly, the relatively larger amplification of ground motion would be expected near the short period of 0.1 s and more because the T_G at the site is about 0.12 s.

4. SITE-SPECIFIC SEISMIC RESPONSE ANALYSES FOR SSANG -GYE-SA

In order to estimate site-specific earthquake ground motions, site response analyses of the representative Ssang-gye-sa site were conducted using one-dimensional equivalent-linear analyses with SHAKE91 (Idriss and Sun, 1992) and nonlinear analyses with NERA (Bardet and Tobita, 2001). Input parameters for the analyses are based on the composition and V_S profile of the entire soil column determined from the in-situ boring and seismic investigations (see Figure 3) and the normalized shear modulus (G/G_0) reduction and damping curves obtained from the laboratory resonant column tests (SNU, 1999). Low to moderate seismicity regions including the Korean peninsula lack any detailed information concerning potential causative faults and any representative accelerograms (Sun et al., 2005). For this reason, to merely consider the various frequency contents and the prior seismic model test of five-storey stone pagoda at Ssang-gye-sa (Kim and Ryu, 2003) in the analyses, a total of nine earthquake accelerograms, of which the shapes of acceleration response spectra are presented in Figure 4, were used as input ground motions. These consisted of one artificial synthetic earthquake motion and eight strong-motion recordings of both NS and EW components at four stations. The input rock-outcrop accelerations were modified to a total of six levels composed of three OLE (operation level of earthquake; 0.044g, 0.063g, 0.080g) and three CLE (collapse level of earthquake; 0.110g, 0.154g; 0.220g) for seismic zone I on the Korean seismic hazard map (MOCT, 1997). Among the input motions, the strong motion recordings consist of Coalinga, El Centro, Taft and Whittier Narrows earthquake motions, which are adopted especially for comparing with the prior seismic test of five-storey stone pagoda model (Kim and Ryu, 2003) and quantifying the seismic intensity of the 1936 Ssang-gye-sa earthquake.

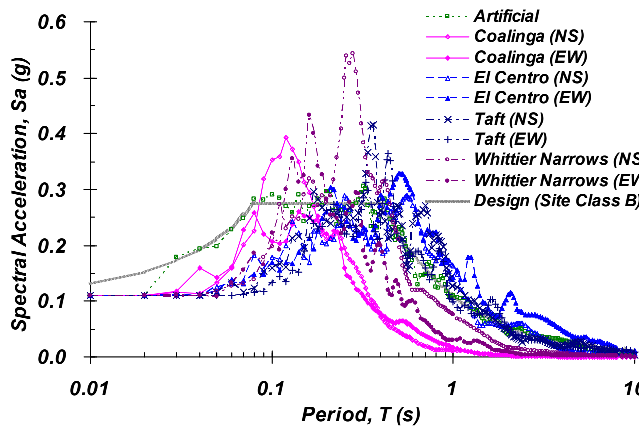


Figure 4 Acceleration response spectra of input rock-outcrop motions with 0.110g

The peak ground accelerations (PGAs) were determined based on equivalent-linear and nonlinear analyses with a total of six acceleration levels on rock outcrop adopting various nine input motions. Average PGAs and maximum and minimum PGAs with the acceleration levels are summarized in Table 1, together with the average ratio of peak accelerations on ground surface to bedrock outcrop. In most of the ratio of peak accelerations on ground surface to rock outcrop simply representing the amplification of earthquake ground motion, the ratios ranging from 1.8 to 2.0 of equivalent-linear analyses are larger than those ranging from 1.6 to 1.7 of nonlinear analyses because of the simulation of strain accumulation in the nonlinear analysis scheme. In general, the difference between the equivalent-linear and nonlinear analyses increases as the rock-outcrop acceleration level increases. As presented in Table 2, the ratio of peak ground acceleration to rock-outcropping peak acceleration is different with each input motion. The ratios of both components of Coalinga motion and Artificial motion are larger than those of other motions. Especially, the ratio of Coalinga NS motion is the largest because its dominant period is similar to the site period (about 0.12 s) of Ssang-gye-sa site.

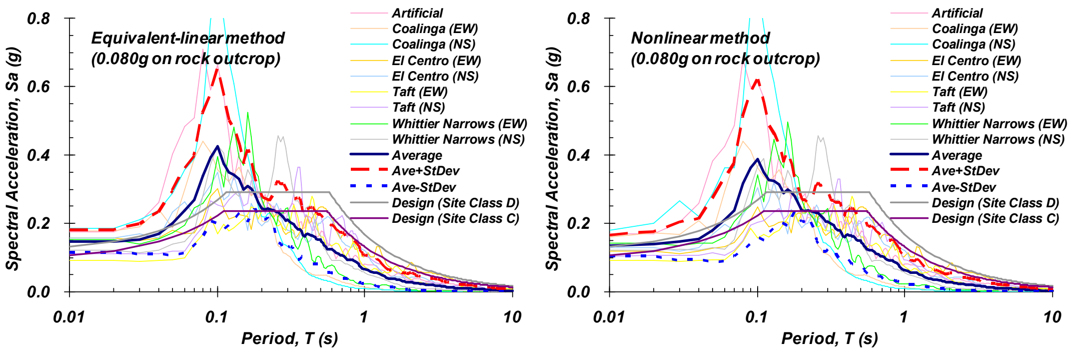
Table 1 Peak ground acceleration from site response analyses for Ssang-gye-sa site

Specification	Peak ground acceleration (PGA) of equivalent-linear (EL) and nonlinear (NL) method with rock-outcrop peak acceleration (ROPA) level											
ROPA (g)	0.044		0.063		0.080		0.110		0.154		0.220	
Analysis method	EL	NL	EL	NL	EL	NL	EL	NL	EL	NL	EL	NL
Minimum (g)	0.049	0.048	0.071	0.071	0.090	0.091	0.124	0.130	0.176	0.185	0.260	0.268
Maximum (g)	0.099	0.096	0.146	0.136	0.186	0.179	0.253	0.246	0.425	0.369	0.701	0.516
Average (g)	0.080	0.072	0.115	0.105	0.148	0.134	0.202	0.188	0.296	0.256	0.459	0.375
Stand. deviation (g)	0.019	0.017	0.027	0.024	0.033	0.030	0.046	0.037	0.077	0.056	0.134	0.080
Ratio (PGA/ROPA)	1.816	1.641	1.826	1.662	1.848	1.681	1.832	1.710	1.925	1.661	2.088	1.706

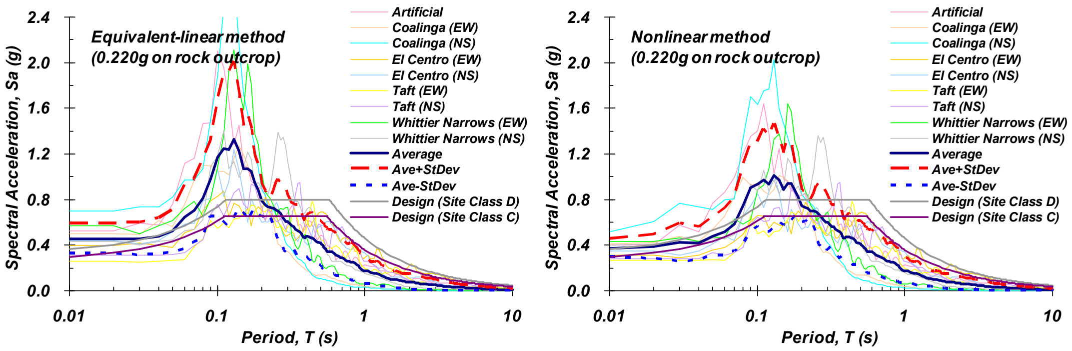
Table 2 Average of the ratio of peak ground acceleration to rock-outcropping peak acceleration

Analysis method	Average of the ratio of PGA to ROPA with input motions*								
	AR	*CG NS*	*CG EW*	*EC NS*	*EC EW*	*TF NS*	*TF EW*	*WN NS*	*WN EW*
EL	2.245	2.523	2.239	1.973	1.911	1.328	1.137	1.619	2.028
NL	1.968	2.249	1.999	1.626	1.448	1.289	1.161	1.571	1.781

* *AR*: Artificial; *CG*: Coalinga; *EC*: El Centro; *TF*: Taft; *WN*: Whittier Narrows; *NS* and *EW*: motion components



(a) Input rock outcropping peak acceleration of 0.080g



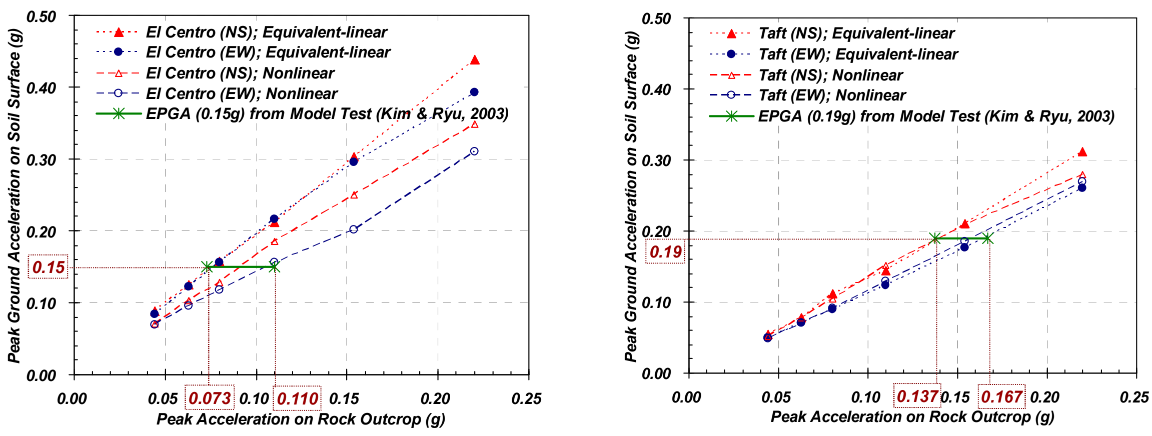
(b) Input rock outcropping peak acceleration of 0.220g

Figure 5 Acceleration response spectra on ground surface of Ssang-gye-sa

Acceleration response spectra on ground surface were compared for quantitatively examining the seismic response characteristics with period, and were much different according to input motions, which have very different dominant frequency (period) contents. Among a total of six input acceleration levels, the acceleration response spectra from both analyses methods for two levels (0.080g and 0.220g) are representatively shown in Figure 5. The response spectra in Figure 5 are for each motion, average (Ave) together with considering standard deviation (StDev), and design of site class C and D for comparison. The average spectral accelerations are significantly higher than the design spectral accelerations of not only site class C but site class D, particularly near the Ssang-gye-sa site period of 0.1 to 0.2 s. Whereas the average spectral accelerations at longer periods than about 0.3 s are lower than the design accelerations. These trends in the spectral shape are also observed at the other levels and are recognized as the seismic response characteristics in the mountainous or hilly area (Sun et al., 2005). Accordingly, a temple building, of which the natural period match with the site period of Ssang-gye-sa site, may be susceptible for resonance during earthquakes, and mostly temple buildings are low-rise of one- or two-storey and have 0.1 to 0.2 s for the natural period (Sun et al., 2005). It is also observed that the spectral accelerations of Coalinga NS and Artificial motions are more amplified than those of other motions near the site period. Comparing of the results between equivalent-linear method and nonlinear method, the spectral accelerations from nonlinear method are lower than those from equivalent-linear method, and this trend is prominent as the input rock acceleration level increases.

5. ESTIMATION OF INTENSITY OF THE 1936 SSANG-GYE-SA EARTHQUAKE

The seismic test of the five-storey stone pagoda model by Kim and Ryu (2003) indicated that El Centro and Taft motions among input motions might fall down the top stone at the ground surface. The natural period of the pagoda was suggested as about 0.5 s (2.0 Hz) by Kim and Ryu (2003), which differs from the site period (0.12 s) of Ssang-gye-sa but particularly matches with the first dominant periods of El Centro motion and Taft motion components (see Figure 4). This correspondence between the natural period of the pagoda and the dominant period of the motions may result in the fall of the top component of five-storey stone pagoda.



(a) El Centro motion (b) Taft motion

Figure 6 Peak accelerations on ground surface and rock outcrop for falling the top stone of pagoda

From the results of the seismic test of the pagoda model (Kim and Ryu, 2003), effective peak ground acceleration (EPGA), which is similar to PGA for this study, was determined as 0.15g for El Centro motion and 0.19g for Taft motion. In order to compare with the EPGA on both El Centro and Taft motions from the seismic model test of the pagoda, the PGAs with all rock acceleration levels are plotted in Figure 6. The rock outcropping peak accelerations causing the fall of top stone were estimated into the range between about 0.07g and 0.11g for 0.15g in the PGA of El Centro motion

(Figure 6(a)) and the range between about 0.14g and 0.17g for 0.19g in the PGA of Taft motion (Figure 6(b)). Therefore, an earthquake having the frequency contents similar to El Centro motion with average 0.09g on rock outcrop or Taft motion with average 0.15g may result in damages of buildings and structures including the stone pagoda at the Ssang-gye-sa in 1936. Nevertheless, for more reliably evaluating the intensity of the 1936 Ssang-gye-sa earthquake, multi-dimensional seismic response analyses rather than one-dimensional analyses may be required because the temple area located in a mountain can be affected by surface topographic effects.

6. SUMMARY AND CONCLUSIONS

For evaluating the site-specific seismic response characteristics at the site damaged by the 1936 Ssang-gye-sa earthquake, site characterization was performed at the Buddhist temple, Ssang-gye-sa, by using in-situ and laboratory tests. Site response analyses for a representative temple site were carried out by adopting one-dimensional equivalent-linear and nonlinear methods with various input motions of six acceleration levels. The depth to bedrock was 16 m and thus the site period was 0.12 s indicating short-period. The Ssang-gye-sa site falls into site class C according to 633 m/s in V_S30. The ratio of peak ground acceleration to rock-outcropping peak acceleration simply representing the amplification of ground motion is different with each input motion and analysis method, and ranges from 1.6 to 2.0. In particular, the spectral accelerations were significantly amplified near 0.1 to 0.2 s corresponding to the site period of Ssang-gye-sa. Furthermore, the intensity on rock outcrop was estimated as 0.07g to 0.11g for El Centro motion and 0.14g to 0.17g for Taft motion by comparing between the site-specific seismic response evaluation results in this study and the seismic test results on stone pagoda in the prior study.

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