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Site characterization of seismic stations based on downhole tests to 30 m depth in South Korea

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ABSTRACT: Earthquake ground motions inducing catastrophic losses are strongly influenced by the local site characteristics. To observe the ground motions during an earthquake, seismic monitoring stations have been installed at a number of locations, not only in strong seismicity regions but also in moderate seismicity regions, including the Korean Peninsula, where most sites have shallow bedrock depths of less than 30 m. As part of the evaluation of seismic responses of regional seismic stations, this study carried out a series of site investigations involving borehole drilling and downhole seismic tests at 53 stations in South Korea. The site conditions at the seismic stations were categorized using several earthquake engineering parameters, which can be determined using the shear wave velocity (V_S) profile to 30 m depth or to bedrock depth. Most of the stations in Korea were site class C based on the mean V_S to 30 m depth for earthquake-resistant design, rather than site class B indicating rock condition. In terms of engineering parameters and their correlations, the site characteristics of the seismic stations in Korea were compared with those in other strong seismicity regions. The regional comparisons showed that the Korean seismic stations have region-specific geotechnical characteristics differing from those of regions with strong seismicity.

1 INTRODUCTION

The Korean Peninsula is a region of the Eurasian plate with moderate seismicity (Sun et al. 2005). Since seismic monitoring began in the late 1970s and early 1980s, few earthquake motion data recorded in Korea have shown substantial magnitudes or intensities. Therefore, the reference earthquake ground motion is determined from seismic hazard maps based on historical earthquake records. To obtain earthquake hazard data for the Korean Peninsula, additional seismic monitoring stations have been installed and there are now more than 100 stations in South Korea. Most stations are operated by the Korea Meteorological Administration (KMA) and Korea Institute of Geoscience and Mineral Resources (KIGAM) and their data are shared in real-time.

This paper examined the site characterization of the seismic response by performing in situ geotechnical dynamic investigations composed of borehole drillings and downhole seismic tests at 53 seismic monitoring stations in South Korea. Besides the borehole drilling or invasive methods, the characterization of seismic stations has been carried out using nondestructive methods, such as surface wave techniques and microtremor survey. Particularly, the microtremor observation is usually adopted to H/V (horizontal to vertical) spectral ratio indicating fundamental frequency (or site period) at a site, and for the seismic monitoring station, the H/V ratio would be determined using earthquake records or continuous noises (Nakamura 2008). In this study, the direct seismic method in a borehole was however applied not only for site characterizing but also for obtaining shear wave velocity (V_S) profile to be utilized in site-specific seismic response analyses.

The downhole seismic tests measured the V_S profiles of the near-surface materials at each seismic station. As a representative in situ dynamic property, the V_S profile has a profound influence on the characteristics of earthquake ground motion, which may be recorded at a seismic station. Moreover, site conditions such as bedrock depth (H) and soil stiffness associated with V_S affect the amplification of ground motions, because the earthquake motions of bedrock can be drastically modified in frequency and amplitude during propagation of the seismic waves through the soil column over the bedrock. Based on the in situ investigation results, region-specific site conditions, related to the seismic site effects and resulting in the amplification of earthquake ground motions, were assessed in terms of several geotechnical earthquake engineering parameters at 53 seismic monitoring stations in Korea.

2 SITE INVESTIGATIONS AT SEISMIC MONITORING STATIONS IN KOREA

The Korean Peninsula, located at the eastern margin of the Eurasian continent, is an ancient landform in geomorphological formed by continual erosion. This erosion is especially prominent in inland areas of Korea, which are mainly covered by plains, hills, and small mountains (Fig. 1). The peninsula is covered by various geological strata formed from the Precambrian to the Cenozoic Era. The southern part of the peninsula is composed of crustal blocks of Archean to middle Proterozoic high-grade gneisses and schists (Sun 2015). The surface soils over the bedrock in the region were generally formed by fluvial actions or weathering processes and are alluvial and weathered residual soils.

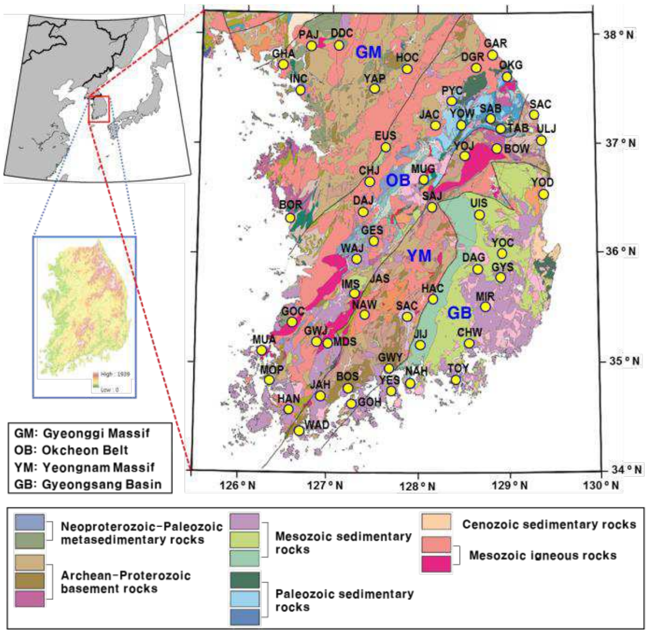

Figure 1. Geographic locations of the seismic stations subject to in situ investigations with a base map of the geological setting of South Korea.

Intensive site investigations involving borehole drilling and downhole seismic tests were conducted to obtain V_S profiles, with the goal of understanding the geological conditions at 53 seismic monitoring station sites in South Korea (Fig. 1). The boreholes were drilled to at least 30 m depth at the sites with bedrock shallower than 30 m, and to bedrock at the sites with bedrock deeper than 30 m. The depth of 30 m from the ground surface is used to compute the mean V_S to a depth of 30 m (V_{S30}), as a criterion for site classification of earthquake-resistant designs (Dobry et al. 2000). After borehole drilling at a site, a downhole seismic test inside the PVC-encased borehole was conducted to obtain seismic wave signals, including the shear wave, according to increasing depth, as depicted in Figure 2. V_{S30} is calculated from the time taken by a shear wave to travel from a depth of 30 m to the ground surface. For a profile consisting of n soil or rock layers, V_{S30} can be calculated as

$$V_{S30} = 30 / \sum_{i=1}^{n} \frac{d_i}{V_{Si}} \tag{1}$$

where d_i and V_{Si} are the thickness and V_S of each soil or rock layer to a depth of 30 m (30 m = Σd_i), respectively.

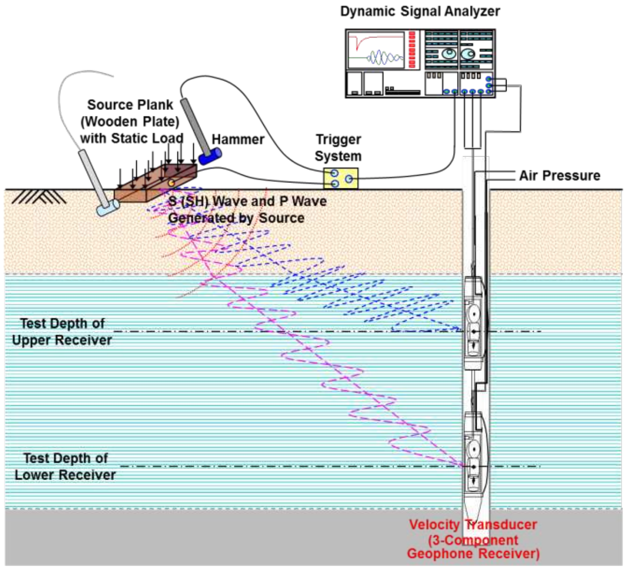

Figure 2. Schematic diagram of an in situ downhole seismic test in a borehole.

The two methods used most commonly for determining the ground motion are site classification based on V_{S30} and site-specific seismic response analysis using the V_S profile of soil strata and the unique V_S of infinite-assumed bedrock. Recently several researchers (Rodriguez-Marek et al. 2001; Sun 2010) have proposed another method of site classification that uses the site period (T_G) determined by equation (2). The site period is based on the thickness of the soil layers overlying the bedrock at each site and their V_S values:

$$T_G = 4\sum_{i=1}^{n} \frac{D_i}{V_{Si}} \tag{2}$$

where D_i and V_{Si} are the thickness ($H = \sum D_i$) and V_S, respectively, of the ith layer above bedrock.

Table 1 lists the site characteristics at the seismic stations assessed using boring investigations and downhole tests. Lee et al. (2012) suggested using the mean V_S of the soil layers above bedrock ($V_{S,soil}$) in Table 1 as a parameter to classify site conditions including the depth to bedrock (H). $V_{S,soil}$ can be calculated from equation (3). More than half of the station sites in this study fall within site class C based on V_{S30}, because the sites are located in the inland region. Of the 53 station sites, 11, 32, and 10 sites were site classes B, C and D, respectively.

$$V_{S,soil} = \sum_{i=1}^{n} D_i / \sum_{i=1}^{n} \frac{D_i}{V_{Si}} \quad (3)$$

Table 1. Site parameters derived from in situ investigations at 53 seismic stations in South Korea.

Site name	H (m)	V_{S30} (m/s)	$V_{S,soil}$ (m/s)	T_G (s)	Site class*
PAJ	13.5	784	533	0.1050	B
WAJ	6.0	749	301	0.0797	C
MDS	4.0	852	384	0.0416	B
DGR	3.2	607	268	0.0448	C
TAB	2.0	611	339	0.0236	C
MUG	0.8	1122	507	0.0079	B
GYS	2.5	925	282	0.0426	B
MIR	13.0	533	378	0.1377	C
CHW	1.5	901	259	0.0309	B
TOY	10.0	560	300	0.1334	C
HOC	14.2	452	292	0.1916	C
GAR	15.2	302	188	0.3196	D
OKG	7.0	679	309	0.0905	C
SAC	7.5	433	199	0.1608	C
SAB	3.0	686	283	0.0425	C
PYC	12.5	435	270	0.1929	C
JAC	28.8	384	378	0.3067	C
EUS	5.0	812	259	0.0772	B
DAJ	16.0	473	343	0.1866	C
CHJ	36.0	291	308	0.4677	D
BOR	27.5	286	272	0.4121	D
IMS	16.7	513	367	0.1853	C
NAW	24.2	471	424	0.2262	C
JAS	34.0	387	412	0.3299	C
GWY	11.5	397	288	0.1667	C
YES	19.5	323	246	0.3255	D
BOS	30.0	212	212	0.5670	D
JAH	34.7	309	328	0.4273	D
WAD	5.5	865	312	0.0768	B
HAN	36.1	273	301	0.4783	D
MOP	6.6	488	239	0.1170	C
MUA	17.5	434	331	0.2177	C
GOC	12.0	433	248	0.1936	C
GWJ	20.5	380	305	0.2750	C
GHA	33.0	331	339	0.3889	D
GOH	5.6	746	390	0.0615	C
GES	30.0	305	305	0.3932	D
HAC	30.0	279	279	0.4295	D
NAH	20.0	414	281	0.2993	C
DDC	10.5	804	543	0.0811	B
SAC	13.3	437	270	0.1923	C
INC	9.0	511	336	0.1071	C
JIJ	0.7	765	313	0.0128	B
YOW	4.5	599	247	0.0808	C
DAG	2.0	708	217	0.0369	C
BOW	7.0	631	307	0.0912	C
SAJ	25.5	469	441	0.2361	C
YOD	0.5	787	486	0.0082	B
YOJ	27.0	442	419	0.2575	C
YOC	3.5	775	342	0.0468	B
ULJ	30.5	523	526	0.2358	C
UIS	5.7	534	289	0.0831	C
YAP	29.0	624	1133	0.1024	C

* Sites are categorized based on the site classification system with the criterion of V_{S30} adopted in current codes such as NEHRP and IBC.

3 STATISTICAL DISTRIBUTION OF SITE PARAMETERS IN KOREA

The depth to bedrock at each seismic monitoring station site was examined based on borehole drilling and the V_S profile was determined by performing a downhole test. To analyze the continuous V_S profile according to depth at a site, the discrete data per meter of depth were stored in a spread sheet. Figure 3 shows the V_S profiles for the 53 station sites in South Korea, together with the average V_S profile to 30 m depth and two V_S profiles reflecting the standard deviation (SD). As expected, the profiles show that V_S increases with depth.

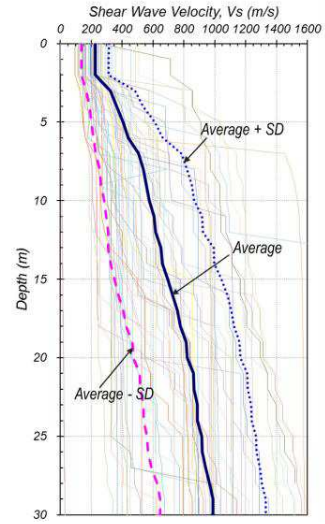

Figure 3. Average V_S profile to 30 m depth based on the V_S profiles at the sites in South Korea.

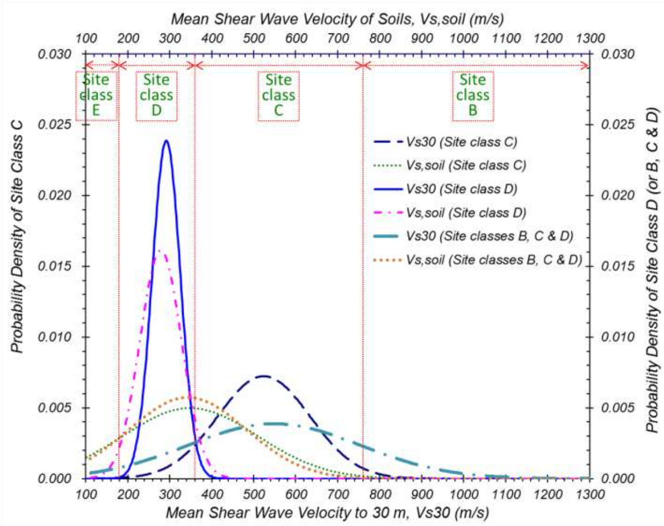

Figure 4. Probability distributions of V_{S30} and $V_{S,soil}$ for seismic station sites in South Korea.

To estimate the distributions of both V_{S30} and $V_{S,soil}$ for site classification, the probabilistic distributions of parameters, V_{S30} and $V_{S,soil}$, were examined for 53 seismic station sites in South Korea, as illustrated in Figure 4. The parameters were assumed to have Gaussian distributions. The V_{S30} and $V_{S,soil}$

for three site classes (B, C and D) have similar distribution ranges to those of site class C, because the seismic stations predominantly fall into site class C ($360 < V_{S30} \leq 760$). The mean values of V_{S30} and $V_{S,soil}$ were roughly 550 m/s and 340 m/s, respectively. However, the $V_{S,soil}$ values for site classes B, C and D are very close to 360 m/s, which is the boundary value between site classes C and D.

In addition, the site period (T_G) was examined based on the probabilistic distributions (Fig. 5). For the T_G of site classes B, C, and D, the distribution has a mean of about 1.8 s, which is similar to that of site class C, rather than site class D. Based on both V_{S30} and T_G for seismic stations in South Korea, the correlation presented in Figure 6 was calculated and compared with a correlation based on the data for historical earthquake hazard sites in Korea suggested by Sun (2010). The decay in the correlation in the present study is greater than that of the correlation calculated by Sun (2010) because the soils of the seismic station sites are stiffer than those of the historical earthquake hazard sites.

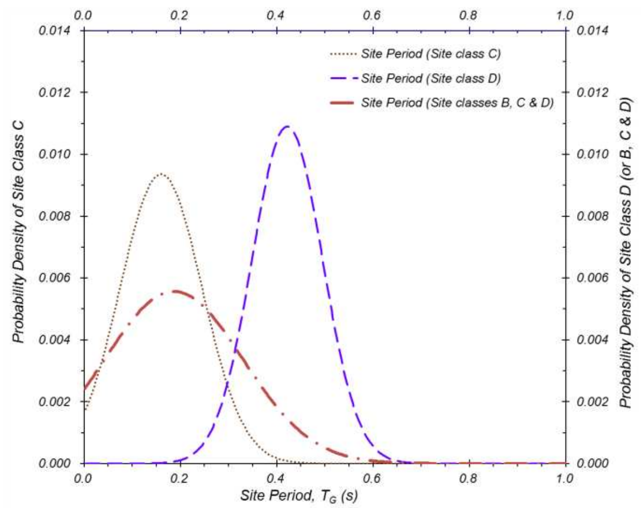

Figure 5. Probability distribution of T_G for seismic stations in South Korea.

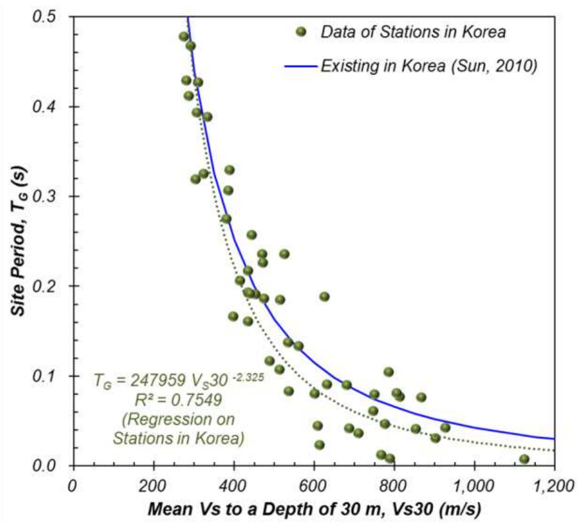

Figure 6 Comparison of the correlations between T_G and V_{S30} in Korea.

4 COMPARISONS OF SITE PARAMETERS BETWEEN KOREA AND OTHER REGIONS

The geotechnical characteristics influencing on the seismic site response differ by region. We evaluated three other V_S profiles and borehole datasets for seismic monitoring stations in strong seismicity regions: western US (WUS), Japan, and Turkey. These were compared with the site response parameters. Figure 7 shows the V_S profiles at sites in WUS, Japan, and Turkey, and their average profiles and SD. The profile data for these three areas were compiled from database websites for the Resolution of Site Response Issue from the Northridge Earthquake (ROSRINE) project (Bardet et al. 1998), the Kiban Kyoshin network (KiK-net) (NIED 2015), and the Strong Ground Motion Database of Turkey (AFAD 2015), respectively.

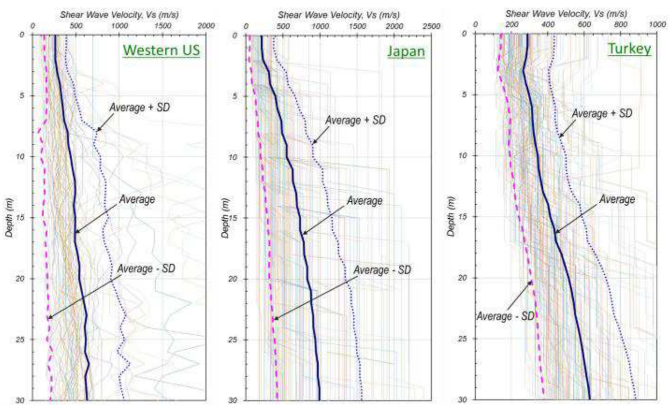

Figure 7. Average V_S profile to 30 m depth based on V_S profiles at sites in strong seismicity regions.

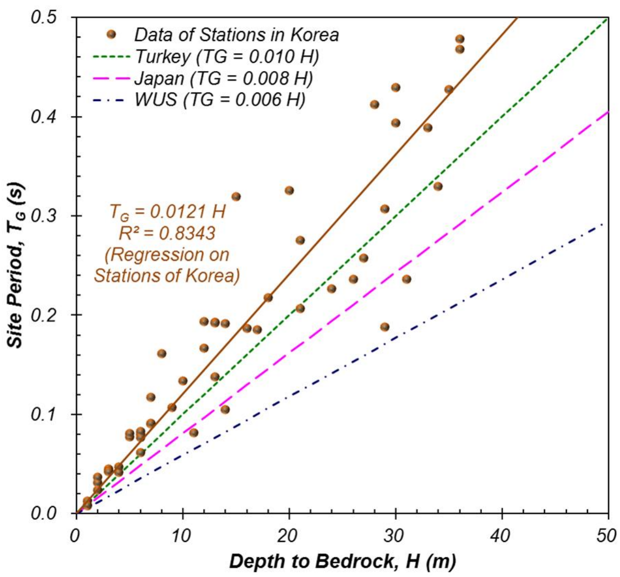

Figure 8. Comparison of the correlations between T_G and H for seismic stations in Korea and strong seismicity regions.

Regional differences in site conditions can be identified by comparing the probability distributions of the site response parameters and their correlations. We investigated the correlations between T_G

and H in Korea and other regions of strong seismicity (western US, Japan, and Turkey), as presented in Figure 8. The slope of the regression reflects the stiffness of the soils above bedrock, and decreases for softer soils. Examining the slopes of the regressions shows that the soil layers at the seismic stations in Korea are stiffer than those in the other three strong seismicity regions.

Of the various site parameters, the probabilistic distributions of T_G for site classes C and D in Korea were compared with those in the other three regions, as shown in Figures 9 and 10, respectively. For Korea, T_G is generally smaller than for strong seismicity regions, regardless of site class, owing to the shallow bedrock in Korea. For Japan and western US, T_G is distributed across a wide range compared with T_G for Korea and Turkey. These differences in geotechnical site conditions, such as the soil stiffness and the depth to bedrock, between the strong seismicity regions and Korea would result in different site responses at the seismic monitoring stations.

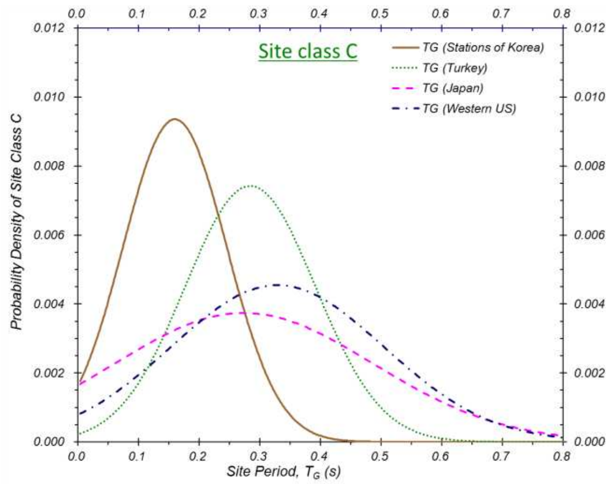

Figure 9. Comparisons of the probability distributions of T_G for seismic stations of site class C in Korea and strong seismicity regions.

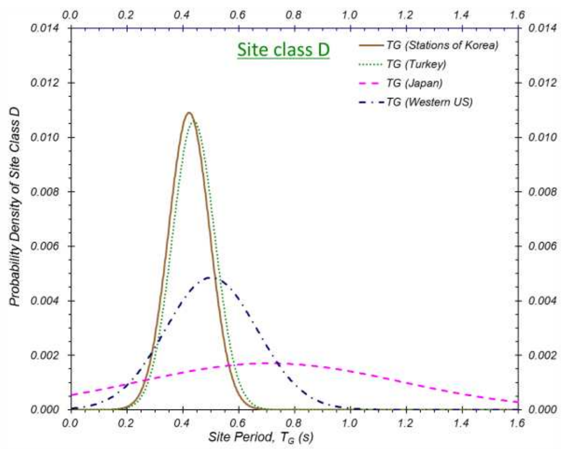

Figure 10. Comparisons of the probability distributions of T_G for seismic stations of site class D in Korea and strong seismicity regions.

5 CONCLUSIONS

Site characterization was performed at 53 seismic monitoring stations in Korea using in situ investigations up to at least 30 m depth and including downhole seismic tests. Most of the stations were categorized into site class C according to V_{S30}. The average values of the site parameters at the stations in Korea were 550 m/s for V_{S30}, 340 m/s for $V_{S,soil}$, and 0.18 s for T_G. Comparing the site conditions at seismic stations in Korea with other strong seismicity regions, the depth to bedrock in Korea is shallower, and the soils are stiffer, comparing to those in western US, Japan and Turkey.

6 ACKNOWLEDGEMENTS

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