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DEVELOPMENT AND VERIFICATION OF NEW SITE CLASSIFICATION AND SITE COEFFICIENTS FOR THE REGIONS OF SHALLOW BEDROCK IN KOREA

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ABSTRACT

Site response analyses were performed based on equivalent linear technique using the local geologic and dynamic site characteristics, which include the layer description and shear wave velocity (V_S) profiles for 125 sites collected in Korea peninsula. Based on the results of site response analyses, a novel two-parameters site classification system was developed and suggested. The proposed system incorporates the depth to bedrock (H) and mean shear wave velocity of soil above bedrock ($V_{S,Soil}$) separately, and is intended for use in regions of shallow bedrock like Korea. The corresponding site coefficients (F_a and F_v) and design response spectrum were also suggested for new seven site classes. As a further study, a series of centrifuge model tests using electro-hydraulic earthquake simulator were planned to conduct to study earthquake ground motions above shallow bedrock and the spectral analysis of the acceleration recorded at different depth and locations will be compared with the new design response spectrum.

Introduction

Korea is part of a region of low or moderate seismicity located inside the Eurasian plate, and few earthquakes with considerable magnitudes and intensities have been recorded in the area. The current Korean seismic codes use a site classification system and corresponding site coefficients that are similar to the NEHRP provisions which were revised based on data recorded during Loma Prieta (1989) and Northridge (1994) earthquakes in the western United States (BSSC 1997; MOCT 1997). However, site coefficients derived from earthquakes recorded under considerably different site and seismicity conditions cannot represent the actual motions of ground and structures in this region. According to Kim and Yoon (2006), the earthquake ground motions obtained from site response analyses of the geologic conditions in the inland area of the Korean peninsula differ significantly from the current Korean seismic codes. Therefore, suitable site coefficients based on local site conditions in the Korean peninsula are required to produce reliable estimates of earthquake ground motion.

The shear wave velocity (V_S) of the shallow subsurface at a site can exert a great influence on the site-specific seismic response (Joyner et al. 1981), so it is important to reliably

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investigate geotechnical dynamic properties of the shallow region. In general, 30 m is the typical depth for borings and detailed site characterization at a number of regions, including the western US. Therefore, many countries have adopted the soil parameter V_{S30}, which indicates the mean shear wave velocity for the top 30 m of soil, as a criterion for site classification (CEN 2003; ICBO 1997; ICC 2009; MOCT 1997). This kind of site classification system is acceptable for regions with relatively deep bedrock and soil sites with a gradual transition from soil to hard rock, both of which are common geologic conditions in the western US. However, the system may not be acceptable for regions with bedrock located at depths less than 30 m from ground level or with abrupt transitions from soil to much stiffer rock, both of which are common in Korea. Therefore, in Korea, V_{S30} values are fallaciously calculated by extrapolating the undesirable V_S of bedrock to 30 m thus, higher V_{S30} values are mistakenly assigned to soil sites with shallow bedrock. In regions of shallow bedrock, site investigations are often performed up to the bedrock, so the depth to bedrock is clearly defined, and V_S values can generally be determined for the soil layers and bedrock for the site response analysis. Therefore, in shallow bedrock areas it is possible to avoid averaging the V_S of soil and rock and to incorporate both depth to bedrock and V_S of soil layers as the parameters for site classification instead of using V_{S30}.

In this study, site response analyses were conducted using an one-dimensional equivalent linear analysis technique for 125 sites in the Korean peninsula. Based on results from site response analyses, a novel two-parameters site classification system was developed and suggested. The proposed system incorporates the depth to bedrock (H) and mean shear wave velocity of soil above bedrock ($V_{S,Soil}$) separately, and is intended for use in regions of shallow bedrock. The corresponding site coefficients and standard design response spectra were also proposed for new site classes. As a further study, to demonstrate the reliability of the new site coefficients, a series of centrifuge model tests were planned to conduct using electro-hydraulic earthquake simulator mounted on the KAIST geotechnical centrifuge to study earthquake ground motions above shallow bedrock and the spectral analysis of the acceleration recorded at different depth and locations will be compared with the new design response spectrum.

Site Response Analyses

Compiled Site Conditions in Korea

To conduct the site-specific seismic response analyses for local geologic conditions in Korea, subsurface geologic profiles and V_S profiles were compiled at 125 construction sites in various areas of the Korean peninsula. Of the 125 sites, 16, 57, 37, and 15 sites were classified as S_B, S_C, S_D and S_E respectively, according to current Korean seismic codes based on V_{S30}.

The two-parameters site classification system divided the 125 sites into three site class categories: H_1, H_2, and H_3, based on H with boundaries of 10 and 20 m. H was determined as the depth from the surface to the depth where V_S values increase to more than 760 m/s in V_S profiles. No S_E sites were included in site classes H_1 and H_2 due to the shallow bedrock, and no S_B sites were included in site class H_3 due to the relatively deep bedrock. Fig. 1 presents the V_S profiles of all sites classified as H_1, H_2, and H_3. It also shows the average and average $\pm 1\sigma$ V_S profiles up to the soil layer for site classes H_2 (Fig. 1(b)) and H_3 (Fig. 1(c)). Based on V_S profiles, V_{S30}, $V_{S,Soil}$, and T_G of all sites for each class were calculated using the Eqs. 1, 2, and 3 respectively, and Table 1 presents the minimum, maximum and average values. Average values of T_G increased with the increase of H, and the differences between average values of V_{S30} and $V_{S,Soil}$ for site classes H_1 and H_2 were comparatively greater than that for site class H_3 due to the influence of the undesirable V_S values from bedrock to 30 m during computation of V_{S30}. Therefore, it is necessary to use $V_{S,Soil}$, rather than V_{S30}, as the parameter for site classification in the regions of shallow bedrock to reflect local geologic conditions better and to ensure that projected earthquake ground motion is closer to field measurements.

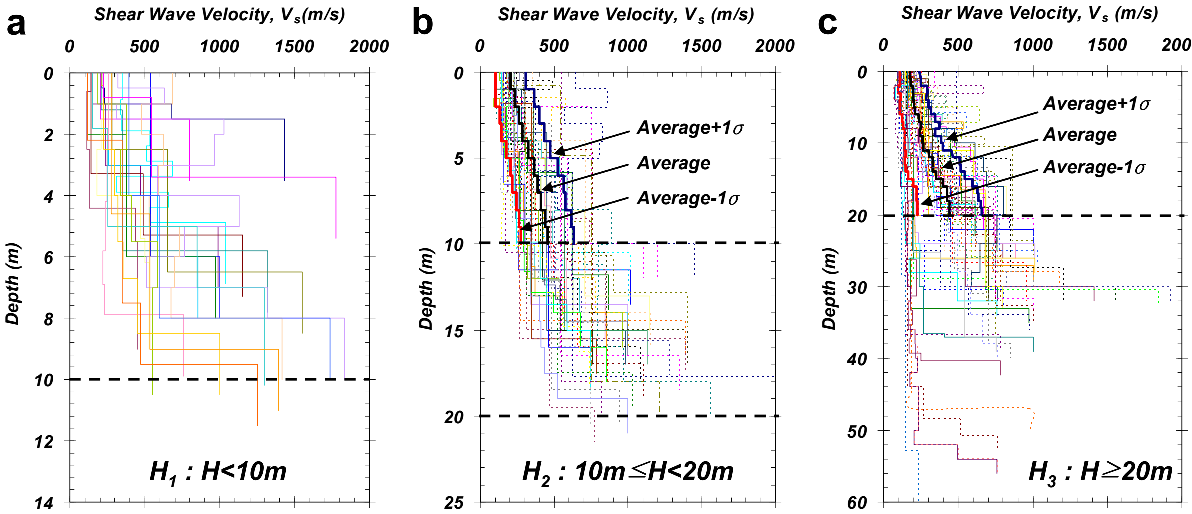

Figure 1. V_S profiles of site classes: (a) site class H_1, (b) site class H_2, and (c) site class H_3.

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

$$V_{S,Soil} = \left(\sum_{i=1}^{n} D_i \right) / \left(\sum_{i=1}^{n} \frac{D_i}{V_{Si}} \right) \tag{2}$$

$$T_G = 4 \times \sum_{i=1}^{n} \frac{D_i}{V_{Si}} \tag{3}$$

where d_i and D_i are the thickness for each soil layer to a depth of 30m and above bedrock, respectively, and V_{Si} is the V_S of each soil layer.

Table 1. V_{S30}, $V_{S,Soil}$, and T_G for each site class

Soil Parameters	H_1: $H < 10$ m			H_2: $10\text{ m} \leq H < 20$ m			H3: $H \geq 20$ m		
	Min	Max	Ave	Min	Max	Ave	Min	Max	Ave
V_{S30}	322.7	1244.8	799.4	313.5	993.8	517.0	114.3	591.3	298.8
$V_{S,Soil}$	168.3	661.1	347.2	184.6	610.1	338.6	118.2	486.7	283.1
T_G	0.02	0.17	0.08	0.07	0.31	0.19	0.20	1.86	0.52

Input Parameters for site response analysis

Site response analyses were performed using the SHAKE 91 program (Idriss and Sun 1992) to estimate site-specific earthquake ground motions at all 125 sites. Because of the lack of strong-motion earthquake records for seismic designs in Korea, site response analyses incorporated a variety of seven earthquake accelerograms as input rock outcrop motion to consider the various frequency contents of earthquake motion. These consisted of six real earthquake motions (El Centro, Hachinohe, Kobe, Ofunato, Chi Chi, and Kocaeli) that had been recorded in strong seismic regions and one artificial synthetic earthquake motion. The peak acceleration of each earthquake motion was adjusted to the three acceleration levels (0.110, 0.154, and 0.220 g). Nonlinear deformation characteristics of soils (G/G_{max} and D) with shear strain were determined from laboratory tests using soil samples acquired at site locations or based on the database compiled for the representative types of soils in Korea unless the test results were available (Sun et al. 2005).

Two-parameters Site Classification System based on H and $V_{S,Soil}$

New Site Classes and Corresponding Site Coefficients

A total of 2625 SHAKE runs (125 sites, three rock outcrop accelerations and seven earthquake motions) were conducted in this study and short- and long-period site coefficients (F_a, F_v) were calculated from each SHAKE output according to Dobry et al. (1999). Fig. 2 plots the calculated F_a and F_v values with $V_{S,Soil}$ for the three site classes classified based on H for the rock outcrop acceleration of 0.154 g. Site coefficients for the other rock outcrop accelerations exhibited similar trends.

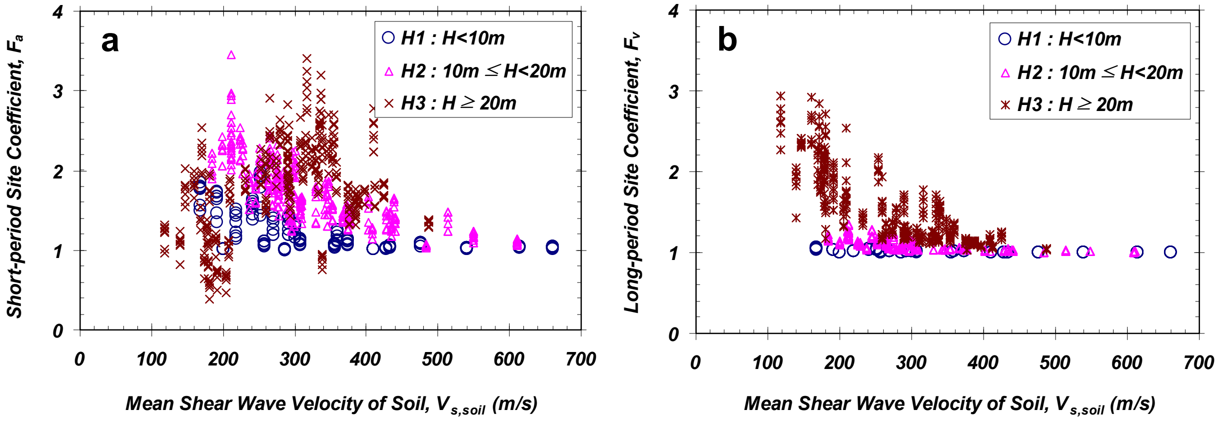

Figure 2. Site coefficients from the results of site response analyses and correlation with $V_{S,Soil}$: (a) Short-period site coefficients (F_a), (b) Long-period site coefficients (F_v).

The F_a values for site class H_2 are obviously greater than those for site class H_1 for all ranges of $V_{S,Soil}$. In contrast, F_a values for site class H_3 increase as $V_{S,Soil}$ values increase to about 360m/s, but decrease above 360m/s; F_a values for both site classes H_1 and H_2 decrease consistently toward 1.0 as $V_{S,Soil}$ values increase. In site class H_3, F_a values are relatively low, even less than 1.0 at $V_{S,Soil}$ values below 200m/s. This finding can be explained by the difference in period ranges: soil sites with relatively high T_G values above 0.5sec due to relatively deep and soft soil deposits are little amplified at short-period ranges of 0.1－0.5 s when calculating F_a. In addition, soft soils are significantly affected by nonlinear soil characteristics, where stiffness decreases and damping ratio increases as the shear strain of soil increases during earthquake shaking.

For all three site classes, F_v values decrease toward 1.0 as $V_{S,Soil}$ values increase. The F_v values for site class H_3 are significantly higher than those for site classes H_1 and H_2. Those for site class H_2 are slightly higher than those for H_1 at $V_{S,Soil}$ values ranging up to about 300 m/s, but for values greater than 300 m/s, F_v values for H_1 and H_2 are almost identical to 1.0. This finding can also be explained by the fact that shallow and medium to stiff soil deposits, which have low T_G values, are only minimally amplified at period ranges of $0.4-2.0$ s when calculating F_v.

To subdivide site categories based on $V_{S,Soil}$, site coefficients F_a and F_v for each site class (H_1, H_2, and H_3) were plotted with $V_{S,Soil}$ for an rock outcrop acceleration of 0.154 g. Figs. 3, 4, and 5 plot the values with regression curves and mean values of site coefficients for subclasses. Based on the spread of data, site classes H_1 and H_2 were subdivided into two subclasses with the boundary of $V_{S,Soil}$=300 m/s. Site class H_3 was subdivided into three subclasses with $V_{S,Soil}$ boundaries of 200 and 360 m/s. These boundary values were selected because they are easy to remember and minimize standard deviations in the mean values of site coefficients for each subclass. The regression curves can be evaluated using a power equation considering the decreasing trend of site coefficients with increasing $V_{S,Soil}$. However, the second-order polynomial was used to reflect the uncommon trend in F_a values for site class H_3. Regression curves are useful for site classes in which site coefficients decrease obviously as $V_{S,Soil}$ values increase, such as F_a values for site class H_2 and F_v values for site class H_3, as shown in Figs 4(a) and 5(b).

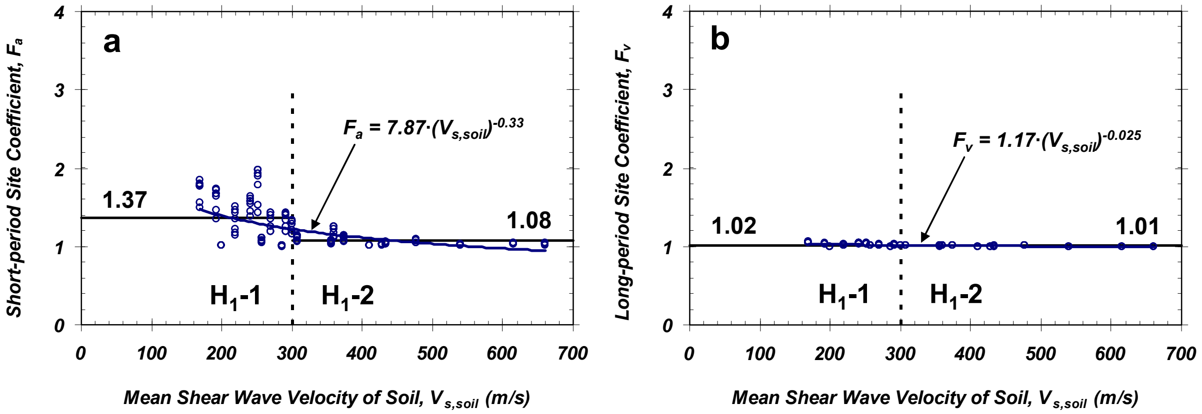

Figure 3. Subdivision of site class H_1 based on $V_{S,Soil}$: (a) F_a, (b) F_v.

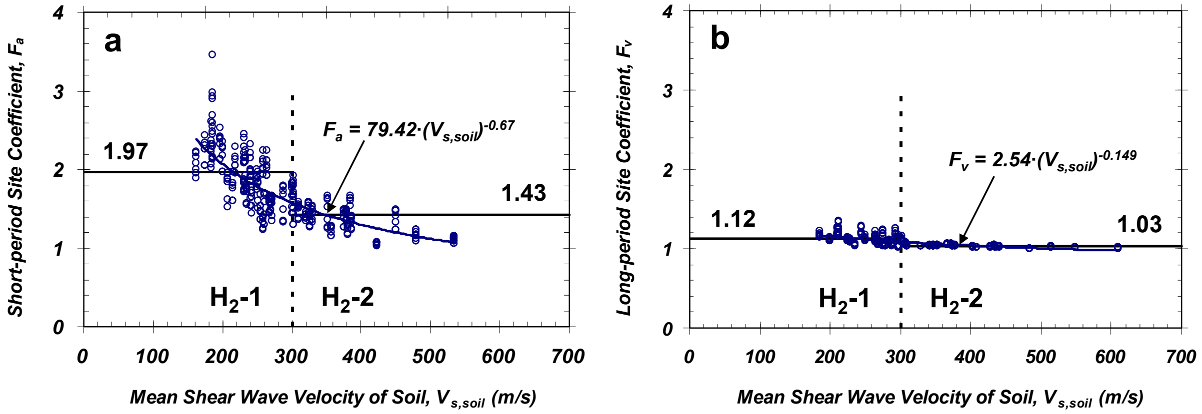

Figure 4. Subdivision of site class H_2 based on $V_{S,Soil}$: (a) F_a, (b) F_v.

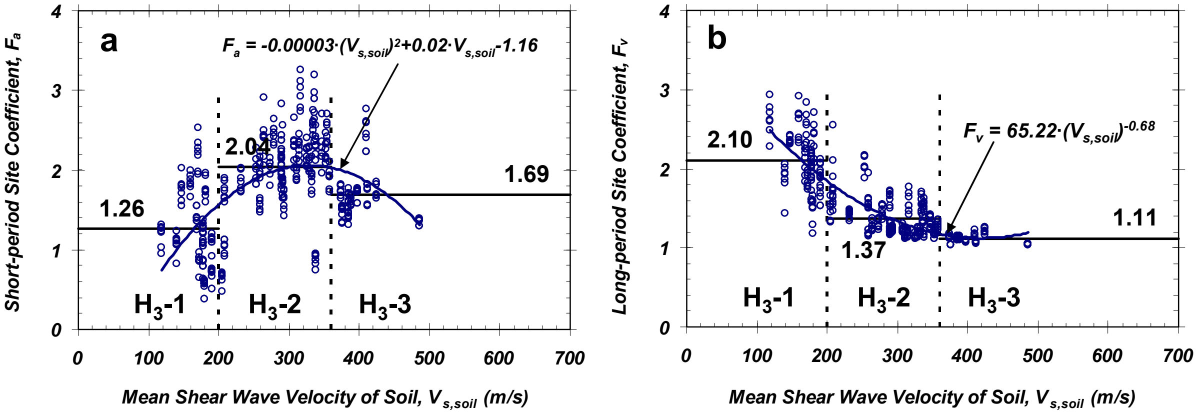

Figure 5. Subdivision of site class H_3 based on $V_{S,Soil}$: (a) F_a, (b) F_v.

Based on the two-parameters approach, site classes are divided into a total seven groups. Table 2 lists the corresponding site coefficients, F_a and F_v, for the new site classes and as well as the standard deviation (σ), regression curves, and coefficients of determination (R^2). Dobry et al. (1999) obtained the F_a values specified in the NEHRP Provision using the mean values of various data and determined F_v values from mean+1σ values. F_v values are highly variable depending on site conditions and input motions, and the use of mean+1σ provides better protection for long period structures. In the same manner, the F_a and F_v values represent mean and mean+1σ values of site coefficients, respectively, based on the results of site response analyses.

Table 2. Site coefficients based on the two-parameters approach (0.154 g).

Site Class	H (m)	$V_{S,Soil}$ (m/s)	Short-period				Long-period			
			F_a	σ	Regression curve	R^2	F_v	σ	Regression curve	R^2
H_1-1	<10m	<300	1.37	0.29	$7.87(V_{S,Soil})^{-0.33}$	0.41	1.04	0.02	$1.27(V_{S,Soil})^{-0.038}$	0.60
H_1-2		≥300	1.08	0.08			1.01	0.00		
H_2-1	10~20m	<300	1.97	0.36	$79.42(V_{S,Soil})^{-0.67}$	0.71	1.20	0.07	$3.58(V_{S,Soil})^{-0.201}$	0.64
H_2-2		≥300	1.43	0.24			1.06	0.02		
H_3-1	≥ 20m	<200	1.26	0.48	$-0.00003(V_{S,Soil})^2$ $+0.02(V_{S,Soil})$ -1.16	0.33	2.48	0.37	$108.9(V_{S,Soil})^{-0.75}$	0.70
H_3-2		200~360	2.04	0.50			1.61	0.24		
H_3-3		≥360	1.69	0.21			1.17	0.04		

Local site conditions such as subsurface geologic profiles and V_S profiles were greatly various because they were compiled in various areas of the Korean peninsula. The frequency contents of the input earthquake motions are also wide, so σ values for some site classes listed in Table 2 are relatively large compared with the corresponding site coefficients, especially for the short-period site coefficient, F_a. However, in F_a values for site class H_2 and F_v values for site class H_3, site coefficients decrease obviously as $V_{S,Soil}$ values increase, so the σ values could be undesirably large even though site coefficients are not widely scattered. In these cases, regression curves showing good correlation, with R^2 values exceeding about 0.7, are better able to estimate earthquake ground motion reliably.

Compared to the results published by Kim and Yoon (2006) based on T_G, both proposed site coefficients, F_a and F_v, are generally superior with regard to σ values. Dobry et al. (1999) also proposed site coefficients for site classes S_C and S_D based on V_{S30} values using various numerical methods and the 1994 Northridge earthquake records. The σ values for F_a ranged from

0.53 to 0.92 and 0.48 to 0.58 for site classes S_C and S_D, respectively. Those for F_v ranged from 0.72 to 0.89 and 0.65 to 0.88 for site classes S_C and S_D, respectively. Borcherdt (2002) conducted a similar study using the 1994 Northridge earthquake records and also reported large σ values for the site coefficients. Therefore, σ values computed in this study are within reasonable bounds when compared with previously published results. Theses findings indicate that the proposed two-parameters site classification system and the corresponding site coefficients are suitable for site conditions with shallow bedrock in Korea.

Standard Design Response Spectrum in Two-parameters approach

For each site class based on the two-parameters site classification system, average response spectra from site response analyses were compared with new standard design response spectra for the rock outcrop acceleration of 0.154 g as shown in Fig. 6. Standard design response spectra were determined based on the Korean seismic design guide (MOCT 1997) and the site coefficients listed in Table 2.

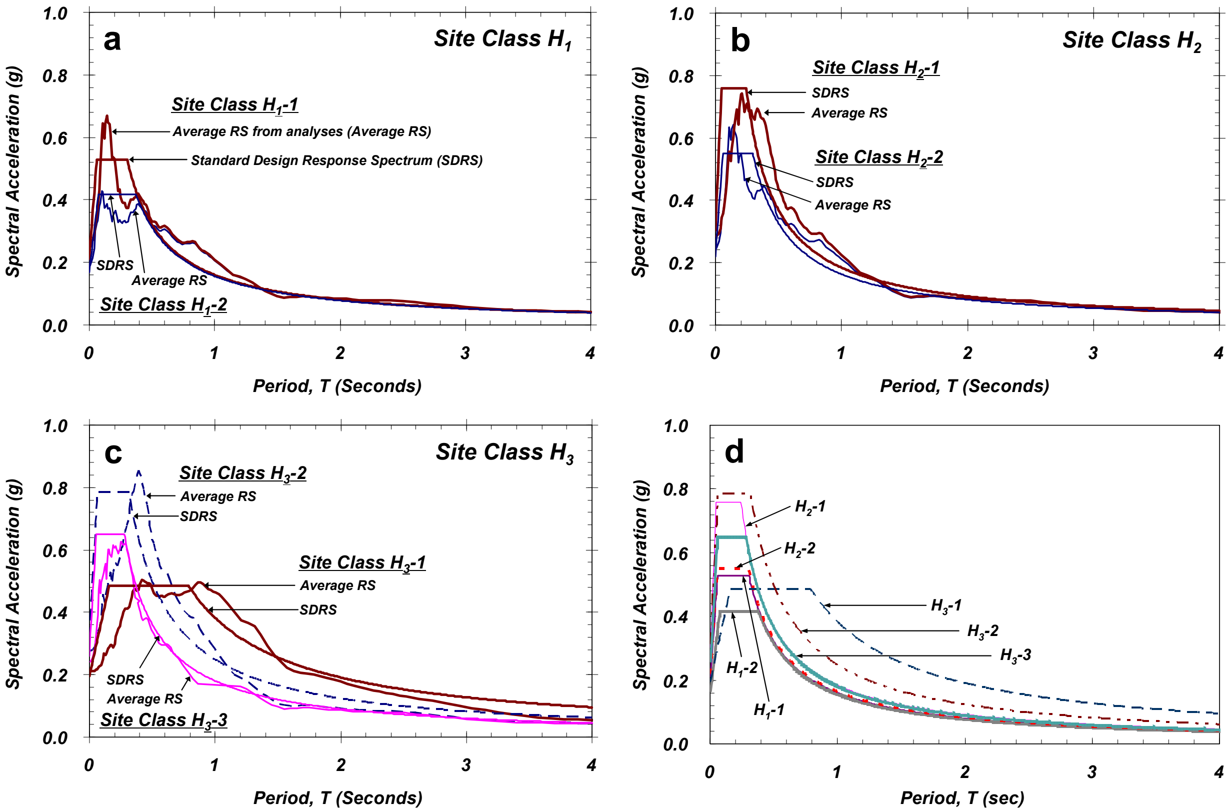

Figure 6. Response spectra in two-parameters approach (0.154 g): (a) Site class H_1, (b) Site class H_2, (c) Site Class H_3, (d) Collection of standard design response spectrum.

For site classes H_1-1, H_1-2, H_2-2, and H_3-3, the new standard design response spectra matched well with the average spectral acceleration over the whole period ranges due to the low σ values ranged from 0.08 to 0.29 and 0 to 0.04 for site coefficients F_a and F_v, respectively. In contrast, for site classes H_2-1, H_3-1, and H_3-2, the new standard design response spectra do not match well with average spectral accelerations for the short-period range of 0.1 − 0.5 s, which includes the average T_G ranges for site classes H_2 and H_3 as indicated in Table 1. The σ values ranged from 0.36 to 0.50 and 0.07 to 0.37 for site coefficients F_a and F_v, respectively. Even though the σ values are relatively high, for both site coefficients, they are superior to those reported by Kim and Yoon [13] based on T_G, especially for the long-period site coefficient, F_v. Fig. 6(d) plots the new standard design response spectra for seven site classes.

Plan of Future Centrifuge Modeling

Recently, lots of research on geotechnical earthquake engineering using centrifuges has been undertaken throughout the world. In this study, a series of centrifuge model tests for demonstrating the reliability of newly proposed site coefficients, will be conducted using electro-hydraulic shaking table mounted on the KOCED 5.0 m radius beam centrifuge at KAIST in Korea. The in-flight shaking table at KAIST (Fig. 7) is two-horizontal biaxial type and it has been designed based on dynamic balancing principle (Perdriat et al. 2002). There are two counterweights with similar mass of the experimental model at the shaking table, and dynamic balancing is achieved by reciprocal actuation of the model and the balancing counterweight. In this system, the X and Y axis dynamically balanced motion is obtained by close loop control of its two parallel pairs of actuators. The dynamic balancing is important not only for simulating accurate input motion but for reducing the risk of damaging mechanical part of the centrifuge itself. At present, the installation of KAIST shaking table is ongoing.

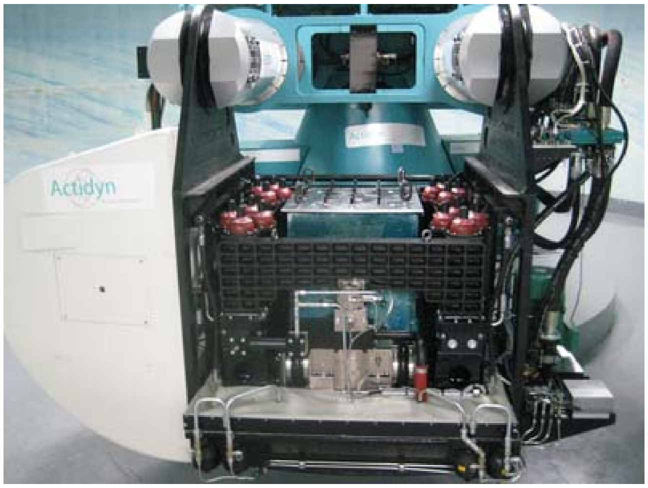

Figure 7. KAIST in-flight biaxial shaking table.

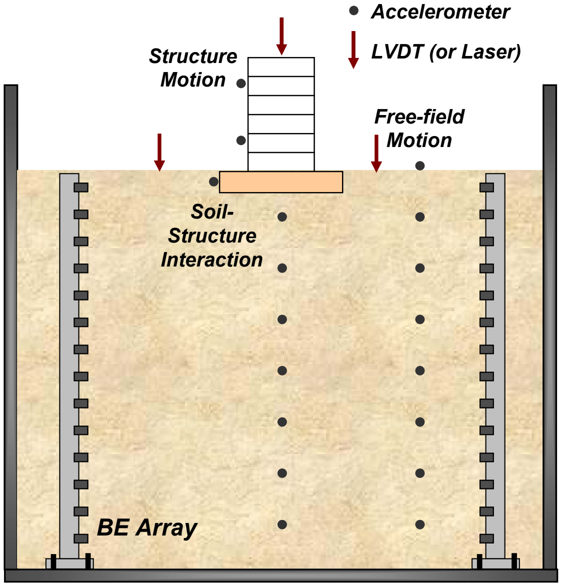

Figure 8. centrifuge model configuration

Fig. 8 shows configuration of projected soil model. This model consists of sand, a SDOF structure and a foundation model slightly embedded in the soil. The thickness of the soil model (depth to bedrock) 200, 400, and 600 mm, simulating 12, 24, and 36 m on prototype at 20, 40, and 60 g. More than ten accelerometers are placed within the soil model in order to evaluate free-field motion as well as soil-structure interaction, as shown in Fig. 8, by raining the sand to the required level, placing the accelerometers in the desired position and then adding more soil to the required level. Some accelerometers are attached to wall of the structure and foundation. LVDT or laser sensors are used to measure the settlement of the soil surface and the vertical displacement of the model structure.

Table 3 summarizes the projected centrifuge model testing conditions. Total three tests are planned immediately after installation process. Each test will be conducted in sequence at three g-levels of 20, 40, and 60 g in order to simulate widely ranged H, $V_{s,soil}$, and T_G. And also, several earthquake events and sinusoidal input motions will be applied to the model in order to consider the various frequency contents and horizontal loading g-level. The testing results will be intensively discussed with respect to accelerations recorded at various depths and locations. Finally, the site coefficients and standard design response spectra will be compared with the spectral analysis results of the acceleration records to verify the reliability and superiority in region of shallow bedrock.

Table 3. Projected centrifuge model testing condition

Test Number	G-level	H (m): Model/Prototype	Expected $V_{S,Soil}$ (m/s)	T_G (sec)
1	20 g	0.2 / 4	160	0.10
	40 g	0.2 / 8	180	0.18
	60 g	0.2 / 12	200	0.24
2	20 g	0.4 / 8	180	0.18
	40 g	0.4 / 16	200	0.32
	60 g	0.4 / 24	220	0.44
3	20 g	0.6 / 12	200	0.24
	40 g	0.6 / 24	220	0.44
	60 g	0.6 / 36	260	0.55

Conclusions

In order to evaluate the earthquake ground motions in regions of shallow bedrock in Korea, site response analyses were performed based on the Vs-profiles for 125 sites collected in Korean peninsula. Based on the results of site response analyses, a novel two-parameters site classification system was developed and suggested. The proposed system incorporates the depth to bedrock (H) and mean shear wave velocity of soil above bedrock ($V_{S,Soil}$) separately, and is intended for use in regions of shallow bedrock. First, as the boundaries of H for site classification were determined as 10 m and 20 m, the soil sites were divided into 3 site classes as H_1, H_2 and H_3. And then, the 3 site classes were divided into 7 subclasses based on $V_{S,Soil}$. The corresponding site coefficients (F_a and F_v) and design response spectrum were developed by analyzing uniform trend and dispersion of site coefficients for each site category. As a further study, to demonstrate the reliability of the new site coefficients, a series of centrifuge model tests were planned to conduct using electro-hydraulic earthquake simulator mounted on the KAIST geotechnical centrifuge to study earthquake ground motions above shallow bedrock and the spectral analysis of the acceleration recorded at different depth and locations will be compared with the new design response spectrum.

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