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Spatial zonations for regional assessment of seismic site effects in the Seoul metropolitan area

Chang-Guk Sun [a,*], Han-Saem Kim [b,1], Choong-Ki Chung [b,2], Heon-Cheol Chi [a,3]

[a] Earthquake Research Center, Korea Institute of Geoscience and Mineral Resources, 124 Gwahang-no, Yuseong-gu, Daejeon 305-350, South Korea
[b] Department of Civil and Environmental Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-742, South Korea

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ABSTRACT

Earthquake-induced hazards are profoundly affected by site effects related to the amplification of ground motions, which are strongly influenced by local geologic conditions such as soil thickness or bedrock depth and soil stiffness. In this study, an integrated geographic information system (GIS)-based system for geotechnical data, called the geotechnical information system (GTIS), was developed to establish a regional counterplan against earthquake ground motions in the Seoul metropolitan area. In particular, to reliably predict spatial geotechnical information, a procedural methodology for building the GTIS within a GIS framework was developed and applied to the Seoul area in Korea. To build the GTIS, pre-existing geotechnical data were collected in and around the study area, and then a walk-over site survey was conducted to acquire surface geo-knowledge data. In addition, the representative shear wave velocities for geotechnical layers were derived by statistically analyzing many seismic test data in Korea. The GTIS was used in a practical application to estimate site effects in the study area; seismic zoning maps of geotechnical earthquake parameters, such as the depth to bedrock and the site period, were created and presented as a regional synthetic strategy for earthquake risk assessment. Furthermore, seismic zonation of site classification was also performed to determine the site amplification coefficients for seismic design and seismic performance evaluation at any site and administrative sub-unit in the study area. The methodology and results of the case study of seismic zonations in the Seoul area verified that the GIS-based GTIS can be very useful for the regional estimation of seismic risk and also to support decisions regarding seismic hazard mitigation, particularly in the metropolitan area.

1. Introduction

Local site conditions are one of the most important influential factors on the amplification of earthquake ground motions. Current engineering seismic design code provisions have incorporated the amplification capabilities depending on local site geologic and soil conditions because of their importance in earthquake-induced hazard mitigation. Local site effects related to geologic conditions have been frequently observed in recent earthquake events such as the 1985 Mexico City, 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, 1999 Chi-Chi, 2005 Kashimir, 2008 Wenchuan, 2010 Haiti, and 2011 Tohoku earthquakes [1–8]. These earthquake events revealed that seismic damages tend to be concentrated in areas composed of sediments rather than firm rock [2,9]. This finding indicates that site effects are associated mainly with the spatial distribution and dynamic properties of the soils overlying a rock bed.

The Korean peninsula belongs to a region of moderate seismicity located inside the Eurasian plate [7,10], in contrast to high-seismicity regions located at the intersections of tectonic plates, such as the Western US, Japan, Taiwan, Chile, Mexico, Turkey, and Indonesia. Metropolitan areas in Korea have low absolute seismic risk relative to highly urbanized areas in interplate and have experienced few modern earthquake disasters. Nevertheless, over the long history of Seoul, the capital of Korea, numerous historical earthquake events and corresponding disasters have occurred [10,11]. Furthermore, while the absolute earthquake risk potential is lower in Seoul than in strong seismicity areas, the extent of damage may be much greater at soft soil sites in Seoul than at rock or firm soil sites in other areas because of ground motion amplification by site effects and the lack of earthquake preparedness [9,12].

The site effects have been quantified as a site classification system with the mean shear wave velocity of the top 30 m (V_S30) in many current earthquake-resistant design codes [7,13].

* Corresponding author. Tel.: +82 42 868 3176; fax: +82 42 861 1872.
E-mail addresses: pungsun@kigam.re.kr (C.-G. Sun), adoogen@snu.ac.kr (H.-S. Kim), geolabs@snu.ac.kr (C.-K. Chung), chi@kigam.re.kr (H.-C. Chi).
[1] Tel.: +82 2 880 7354; fax: +82 2 875 6933.
[2] Tel.: +82 2 880 7347; fax: +82 2 875 6933.
[3] Tel.: +82 42 868 3343; fax: +82 42 861 1872.

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Although the V_S30 is unambigus and practical criterion to classify the site conditions in seismic design, site-specific seismic response is a function of depth to bedrock (soil depth) which may be ignored in determining V_S30. Thus, several researchers [14–19] have demonstrated this limitation of using V_S30 and have presented (predominant) site period, as a better parameter than V_S30 for their research sites. In particular, Zhao and Xu [19] compared the site period and the V_S30 based on strong-motion records including KiK-net station data, and discussed quantitatively their variabilities with different terms. Sun [15] and Kim and Yoon [17] studied for Korea determined the site period by conducting in situ seismic tests and evaluated by means of numerical seismic response analyses, because of the lack of strong-motion records.

Recently, the geographic information system (GIS) has emerged as a powerful computer-based technique that can integrate the capabilities of spatial analysis, database management, and graphic visualization. GIS-based information systems have been developed and applied for geotechnical purposes to forecast and reduce natural hazards such as landslides and earthquakes [9,20–22]. Several studies of GIS technology have focused on geotechnical earthquake engineering, and this technology will be increasingly and widely used for seismic zonations to help to predict and mitigate earthquake-induced hazards [23–26]. In this study, a geotechnical information system (GTIS) was built within a three-dimensional GIS framework to present and reliably estimate the geotechnical profiles and dynamic properties of a selected area around Seoul, South Korea. The constructed GTIS was applied to geotechnical earthquake engineering-related problems, particularly those dealing with site-specific amplification potentials that depend on the local site effects in the study area.

2. Methods for spatial zonation of site effects

2.1. Quantification of site effects inducing earthquake hazards

Site effects are basically associated with the phenomenon of seismic waves traveling through soil layers, and result in serious earthquake hazards in the site [3,26]. The phenomenon can be explained first by differences in the shear wave velocity (V_S) between the soil layers and the underlying rock, representing an impedance contrast, and second by the thickness of the soil layers or the depth to bedrock, H [9]. The largest amplification of earthquake ground motion at a nearly level site occurs at approximately the fundamental lowest natural frequency [14]. The period of vibration corresponding to the fundamental frequency is called the characteristic (or predominant) site period, T_G, and for multi-layered soil site can be computed as

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

where D_i is the thickness of each soil layer above the bedrock (i.e., bedrock depth, $H=\sum D_i$), V_{Si} is the shear wave velocity of each soil layer, and n is the number of soil layers. The site period is a useful indicator of the vibration period [27], during which the most significant amplification is expected. Thus, if the spatial variations in the thickness and V_S values of soil layers are known for an entire study area, the spatial variation of the T_G can be readily established and used for regional earthquake hazard estimations [9,28].

For seismic design in accordance with site conditions, correlations have been established between the mean V_S of the upper 30 m (V_S30) and site coefficients (or amplification factors) based on empirical and numerical studies of specific earthquakes, including the 1989 Loma Prieta earthquake [29–31]. Accordingly, current seismic codes apply site characterization for a site class based only on the top 30 m of the ground [7,13]. The site class is determined solely and unambiguously by one parameter: V_S30. For a profile consisting of n soil and/or rock layers, V_S30 (in units of m/s) can be given by

$$V_S30 = 30\Big/\sum_{i=1}^{n}\frac{d_i}{V_{Si}} \tag{2}$$

where d_i is the thickness of each soil and/or rock layer to a depth of 30 m (30 m$=\Sigma d_i$)

Recently, Sun [15,32] and Kim and Yoon [17] proposed new site classification systems based on T_G instead of the current classification criterion, V_S30, in order to use T_G for seismic design, particularly considering the regional geotechnical characteristics in Korea. To quantify the site-specific seismic response characteristics and establish correspondently the site classification system for the Korean peninsula, they conducted extensive seismic response analyses for a variety of sites based on intensive site investigation data [7,25]. In most recent site classification schemes for seismic design including the new classification system for Korea [32], local site effects are quantified by short-period (0.1–0.5 s) and mid-period (0.4–2.0 s) site coefficients, F_a and F_v, respectively, according to the site class. Table 1 illustrates the new Korean site classification system [32] based on T_G. Engineers can use this site classification scheme to conduct seismic design as well as to evaluate seismic performance at a site.

2.2. Development and application of GIS-based geotechnical information system

Geotechnical information systems have been developed based on GIS technology to manage and utilize spatial geotechnical information about the ground surface and subsurface efficiently [9,33,34]. Williams et al. [33] referred to this sort of system as a geotechnical GIS (GEOGIS). Based on the concepts and methodologies from previous studies [9,33,34], the geotechnical information system (GTIS) constructed in the current study incorporates a geostatistical kriging interpolation technique [9,34], which is adopted to enable reliable spatial prediction of geotechnical data values [35].

Kriging may be the best linear unbiased estimate and optimal interpolation method for geological and geotechnical predictions in space because it is a linear combination of weighted sample values with minimal variance [8,36]. The basic premise of kriging interpolation is that every unknown point can be estimated using the weighted sum of the known points [8]. The estimated value,

Table 1
Recent site classification with T_G for seismic design [32].

Generic description	Site class		Criterion	Site coefficients	
			T_G (m/s)	F_a	F_v
Rock	B		< 0.06	1.00	1.00
Weathered rock and very stiff soil	C	C1	< 0.10	1.28	1.04
		C2	< 0.14	1.45	1.09
Intermediate stiff soil		C3	< 0.20	1.65	1.13
		C4	< 0.29	1.90	1.19
Deep stiff soil	D	D1	< 0.38	2.08	1.23
		D2	< 0.46	2.26	1.29
		D3	< 0.54	2.48	1.36
		D4	< 0.62	2.86	1.43
Deep soft soil	E		≥ 0.62	1.50	2.00