Spatial Information on Site-specific Seismic Response at Hongseong Damaged by 1978 Earthquake in Korea

CHANG-GUK SUN
Earthquake Research Center
Korea Institute of Geoscience and Mineral Resources (KIGAM)
92 Gwahangno, Yuseong-gu, Daejeon 305-350
KOREA
pungsun@kigam.re.kr

Abstract: - Site characterization on geologic and soil conditions was performed for evaluating the site effects relating to the site-specific seismic response characteristics at a small urbanized area, Hongseong, in Korea, where structural damages were recorded by an earthquake of magnitude 5.0 on October 7, 1978. In the field, various geotechnical site investigations composed of borehole drillings and seismic tests for determining shear wave velocity (V_S) profile were carried out at 16 sites. Based on the geotechnical data from site investigation and additional collection in and near Hongseong, an expert information system on geotechnical information was implemented with the spatial framework of GIS for regional geotechnical characterization across the entire study area. For practical application of the GIS-based geotechnical information system to estimate the site effects causing seismic hazards for the Hongseong area, spatial seismic zoning maps on geotechnical parameters, such as the bedrock depth and the site period, were created at the area of interest. Furthermore, seismic zonation of site classification according to the mean V_S to a depth of 30 m from ground surface was also performed for seismic design at any location in the area of interest. From the spatial geotechnical information and seismic zonations, the capability of seismic amplification was examined at plain and hill locations in Hongseong.

Key-Words: - Site effects, Geotechnical information, Seismic zonation, Site period, Geographic information system

1 Introduction

Seismic response characteristics at a site are strongly influenced by the local geologic and soil conditions such as soil thickness and dynamic soil properties. It has been recognized as the local site effects associated with the amplification of earthquake ground motion in earth science and geotechnical earthquake engineering fields [14]. The amplification capabilities depending on the local geologies at sites have been incorporated into current seismic design code provisions, because of their importance in earthquake-induced hazard prediction and preparedness [14, 16]. Actually, observations of recent destructive earthquakes have demonstrated that despite the same epicentral distances within a region, earthquake-induced hazard is often more severe over soft soils than over firm soils or rocks owing to the site effects [15, 17]. These recent observations indicate that the difference of seismic amplification potential between the sites in a region would be estimated by spatially predicting the subsurface geotechnical characteristics including the soil thickness and dynamic soil property in the entire area of interest.

As advances in the computer technology, geographic information system (GIS) in recent years has emerged to be a powerful computer-based technique that integrates spatial analysis, database management, and graphic visualization capabilities [2, 14]. For geotechnical purposes, GIS-based expert systems have been developed and used to forecast and plan for natural hazards such as landslides or earthquakes [9, 14, 19]. Especially, in geotechnical earthquake engineering, there have been several researches on GIS technology [1, 10]. And this technology will be widely used in increasing numbers of seismic zonations for the prediction of earthquake-induced hazards [18]. In this study, for the presentation and reliable estimation of the geotechnical information over the selected Hongseong area of Korea, a geotechnical information system (GTIS) was built within three-dimensional GIS framework. The constructed GTIS was applied to problems related to geotechnical earthquake engineering, particularly those dealing with site-specific amplification potentials that depend on local site effects.

2 Quantification of Seismic Site Response

Since a number of sites on recent alluvial deposits are prime locations for the development of urban areas, local seismic amplification is a major concern not only in earthquake-prone regions but also in weak or moderate seismicity regions like the Korean peninsula. The site effects that induce seismic amplification are mainly associated with geological site conditions.

2.1 Site period for seismic response characteristics

Site effects indicating site-specific seismic response is basically associated with the phenomenon of seismic waves travelling through soil layers [15, 18]. The phenomenon can be explained first by differences in the shear wave velocity (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. The largest amplification of earthquake ground motion at a nearly level site occurs at approximately the fundamental lowest natural frequency [15]. The period of vibration corresponding to the fundamental frequency is called the site period, T_G, and for multi-layered soil 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., the bedrock depth, $H = \Sigma D_i$), V_{Si} is the V_S of each soil layer, and n is the number of soil layers.

The site period is a useful indication of the period of vibration, at which the most significant amplification is expected. 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. Spatial data can be efficiently examined using GIS statistical techniques.

2.2 Site classes and site coefficients for quantifying site effects

For seismic design in accordance with site conditions in most of design guides, the local site effects are quantified by short- and mid-period site coefficients (or amplification factors), F_a and F_v, according to the mean V_S to a depth of 30 m (V_S30) and the corresponding site classes [6, 15]. Accordingly, in the current seismic codes, 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. For a profile consisting of n soil and/or rock layers, V_S30 (in units of m/s) can be given by:

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

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

In order to quantify the site effects, correlations between the V_S30 and the site coefficients were established based on empirical and numerical studies [4, 15]. F_a and F_v are calculated by the average ratio of response spectra (RRS) or ratio of Fourier spectra (RFS) between a soil and a nearby firm to hard rock site, computed in period bands from 0.1 to 0.5 s and from 0.4 to 2.0 s, respectively. The period between 0.1 and 0.5 s indicates the short-period band, while the period between 0.4 and 2.0 s represents not only the mid- or intermediate-period band but also the long-period band [15]. In this study, the site coefficients, F_a and F_v, were based on the RRS and calculated by:

$$F_a(\mathrm{RRS}) = \frac{R_{\mathrm{soil}}}{R_{\mathrm{rock}}}\frac{1}{0.4}\int_{0.1}^{0.5}\frac{\mathrm{RS}_{\mathrm{soil}}(T)}{\mathrm{RS}_{\mathrm{rock}}(T)}\mathrm{d}T \tag{3}$$

$$F_v(\mathrm{RRS}) = \frac{R_{\mathrm{soil}}}{R_{\mathrm{rock}}}\frac{1}{1.6}\int_{0.4}^{2.0}\frac{\mathrm{RS}_{\mathrm{soil}}(T)}{\mathrm{RS}_{\mathrm{rock}}(T)}\mathrm{d}T \tag{4}$$

where $\mathrm{RS}_{\mathrm{soil}}$ and $\mathrm{RS}_{\mathrm{rock}}$ are the acceleration response spectra for a ground surface of soil and for rock-outcrop sites, respectively, in a given period (T), and $\mathrm{R}_{\mathrm{soil}}$ and $\mathrm{R}_{\mathrm{rock}}$ represent the hypocentral distances of the soil and rock sites, respectively.

As illustrated in Table 1, the site conditions can be classified into five categories (denoted by A to E or S_A to S_E) according to the V_S30 values, as suggested in current seismic codes, including Korean seismic design guides, the Uniform Building Code (UBC), and National Earthquake Hazard Reduction Program (NEHRP) provisions [6, 14, 15]. A sixth site category F (or S_F) is defined as requiring site-specific evaluation. In the current seismic design guides, site coefficients (F_a and F_v), quantifying the seismic amplification, are used to estimate the design response spectra dependent on both the site categories and the intensity of rock motions. Both F_a and F_v are unity for rock (site class B) and become greater as the soil becomes softer with decreasing V_S30 or as the site class evolves through C, D, and E. In addition, the site coefficients are generally higher for small rock motions than for large rock motions because of geo-material nonlinearity [15].

Table 1. Current site classification with the mean V_S to a depth of 30 m (V_S30) for seismic design [15]

Site Class (Soil Profile Type)	Generic Description	V_S30 (m/s)
A (S_A)	Hard Rock	$1500 < V_S30$
B (S_B)	Rock	$760 < V_S30 \leq 1500$
C (S_C)	Very Dense Soil and Soft Rock	$360 < V_S30 \leq 760$
D (S_D)	Stiff Soil	$180 < V_S30 \leq 360$
E (S_E)	Soft Soil	$V_S30 \leq 180$
F (S_F)	Requires site-specific evaluation	

In spite of common use of the V_S30 as sole criterion considering the representative geotechnical property in the current seismic design codes, the depth to bedrock is disregarded in the current site classification system [15]. Recently, in order to use the T_G taking account of both the bedrock depth and the geotechnical property particularly for seismic design in Korea, Sun [13] proposed a new site classification system based on the T_G together with the current classification criterion, V_S30. In the proposed site classification scheme for seismic design, the local site effects are also quantified by F_a and F_v according to the site classes but the site classes C and D are subdivided into four sub-classes, respectively. Table 2 illustrates the site classification system according to both of the T_G and the V_S30 especially for the inland region in Korea developed by Sun [13]. This site classification scheme (Table 2) can be used by engineers to conduct the seismic design as well as the seismic performance evaluation at a site. Furthermore, if the spatial distribution of the geotechnical layers (geo-layers or soil layers) including the depth to bedrock and their V_S values or the V_S values for depth to 30 m or deeper is known over the entire area of interest, the spatial distribution of the T_G or the V_S30 and the corresponding site classes for seismic design can be readily determined with the three-dimensional GIS framework.

Table 2. Site classes and site coefficients based on site period for the inland region of Korea [13]

Generic Description	Site Class		Criteria		Site Coefficients	
			V_S30 (m/s)	T_G (s)	F_a	F_v
Rock	B		> 760	< 0.06	1.00	1.00
Weathered Rock and Very Stiff Soil	C	C1	> 620	< 0.10	1.20	1.03
		C2	> 520	< 0.14	1.40	1.07
Intermediate Stiff Soil		C3	> 440	< 0.19	1.60	1.12
		C4	> 360	< 0.27	1.80	1.17
Deep Stiff Soil	D	D1	> 320	< 0.34	2.00	1.22
		D2	> 280	< 0.43	2.20	1.27
		D3	> 240	< 0.55	2.40	1.32
		D4	> 180	< 0.68	2.60	1.37

3 GIS Framework for Geotechnical Information

When GIS was introduced in the 1950s, it was initially used by limited groups of researchers, mainly in the fields of transportation and botany, and for small data sets [8]. However, due to rapid advancements of computer technology in recent decades, researchers can now use GIS to manage large data sets [19]. To efficiently manage and use spatial geotechnical information for the ground surface and subsurface, information systems for geotechnical data have been developed based on GIS technology.

The GTIS described here incorporates a geostatistical kriging interpolation technique, adopted for reliable prediction of geotechnical data values. Kriging is considered 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 having minimum variance [12]. The basic premise of kriging interpolation is that every unknown point can be estimated by the weighted sum of the known points. The estimated value, $Z^*(x_i, y_j)$, at coordinates (x_i, y_j), can be calculated by:

$$Z^*(x_i, y_j) = \sum_{\alpha=1}^{n} w_{ij\alpha} \times Z_\alpha \tag{5}$$

where n is the number of the known values, Z_α. A set of weights, $w_{ij\alpha}$, is calculated for every point. These weights are computed to place greater emphasis on the known points close to the unknown points and less emphasis on known points far from unknown points. This process is performed by calculating a variogram that characterizes the spatial continuity or roughness of a point data set with the distance between each pair of points.

Table 3. Procedure for reliably estimating spatial geotechnical information within GTIS [14]

Step	Working Details at Each Step
1st	Select the extended area including the study area
2nd	Compile all available documentary information for geo-knowledge in the
3rd	Determine local landform characteristics based on terrain analysis
4th	Zone the extended area with the geologic and geomorphic characteristics
5th	Select locations for the site investigations including drilling
6th	Perform the site investigations such as drilling and other tests
7th	Visit the extended area to collect additional nearby surface geo-knowledge data in field
8th	Build a database based on site investigations data and surface geo-knowledge data
9th	Interpolate geotechnical information for the extended area
10th	Extract geotechnical spatial information for the study area from the extended area

In this study, a procedure for building a GTIS was introduced from the prior case study for an inland area by Sun et al. [14], as illustrated in Table 3. To reliably predict the spatial geotechnical information in the entire study area, Sun et al. [14] applied new concept of the use of geo-knowledge to acquire additional surface geotechnical data. Geo-knowledge refers to information spanning the fields of geotechnology, geology, and geomorphology and was acquired from topographic maps, remote sensing images, and surface geologies. Sun et al. [14] also conducted a walk-over survey to acquire data related to the ground surface mostly in areas where existing borehole data were lacking. In this study, the procedure and architecture for the GTIS proposed by Sun et al. [14] was also applied for the target area, Hongseong.

As presented in Fig. 1, the GTIS has four functional components: database, spatial analysis, geotechnical analysis, and visualization components. Arrows in the figure indicate the direction of data flows, which occur between the database component and complementary (geotechnical analysis) component for assessing geotechnical characteristics [14, 16].

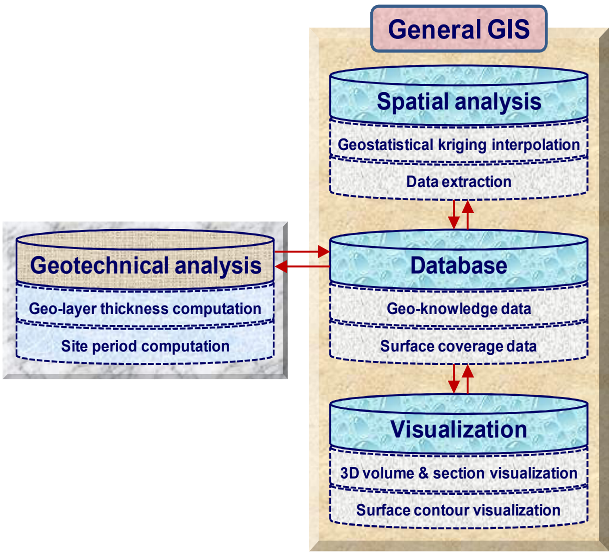


Fig. 1. Components for GIS-based GTIS [16].

The database component contains information on the geotechnical layers, as well as the spatial coverage of waterways, buildings, and roads. Data from the database component are provided to the spatial analysis component, in which the point data are interpolated or extrapolated over the area of interest by the geostatistical kriging method. To evaluate additional geotechnical and earthquake engineering information based on estimated data from the spatial analysis component, geotechnical analysis was performed. The geotechnical analysis component contains computation modules on the thickness of geotechnical layers, depth to bedrock (H), and site period (T_G). In general, these values can be used to assess the seismic sensitivity of the ground without any numerical analysis procedure. The computed geotechnical data were then interpolated over the study area within the spatial analysis components. Finally, the interpolated data were displayed in three dimensions or two dimensions, together with the spatial coverage data, within the visualization component.

In geotechnical and earthquake engineering, a GIS can be used either alone or in conjunction with specified model-analysis techniques [7]. In this study, GTIS was implemented based on GIS tools, EVS-Pro from CTech [5] and AutoCAD LDDT from Autodesk [3], in combination with various specified expert techniques. EVS-Pro was used mainly for the advanced spatial visualization, and AutoCAD LDDT was applied to manipulate the digital topographic maps. Moreover, for better spatial estimation of geotechnical information using an optimum variogram model for each geotechnical sub-layer, a sophisticated kriging interpolation program based on Visual BASIC code was developed and adopted in the spatial analysis component, although EVS-Pro provides ordinary kriging estimation.

4 Spatial Geotechnical Information for Hongseong

The GTIS was constructed for an inland small urban area, Hongseong, and applied to assess site characteristics, specifically the thickness of geotechnical layers or depth to bedrock and the value of the dynamic property, V_S. To build a GTIS for the study area, we compiled various geo-knowledge resources, including existing borehole logs and topographic and geological maps, and carried out site investigations such as geological borehole drillings and seismic tests. Seismic tests to obtain the V_S profile included crosshole, downhole, and spectral analysis of surface waves (SASW) tests. For site characterization, spatial geotechnical layers and V_S values were predicted according to the developed procedure for building GTIS.

4.1 Selection of study area and testing sites

To build a GIS-based GTIS, the Hongseong area, where earthquake-induced structural damages were caused by magnitude 5.0 earthuqkae on October 7, 1978, was selected in this study [9]. Particularly, a number of historical seismic activities present severe seismic hazards [15]. In view of geomorphology and geology, Hongseong shows a typical topography of old age with gentle relief of the inland region in Korea [15]. Fig. 2 shows the geographic location and geological setting of Hongseong. As illustrated in Fig. 2, Hongseong lies within the mid-western region of South Korea. Mountains and hills in Hongseong are formed with granitic rocks, which intruded the Pre-Cambrian formations during the Jurassic period, and plains are covered by thin alluvium underlying bedrock of Daebo granite [15]. The granitic rock series are biotite granite and schistose granite, and rocks are mostly weathered in most cases [15].

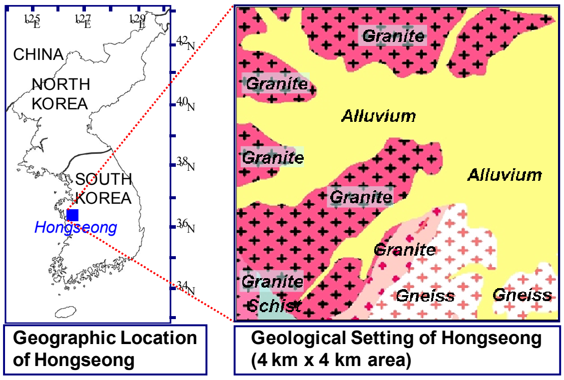


Fig. 2. Geographic location and geological setting of Hongseong.

For the site characterization of the 4 km × 4 km area in Hongseong, 9 boring investigations, 3 crosshole tests, 6 downhole tests and 15 SASW tests were conducted at total 16 sites, as depicted in Fig. 3. And several pre-existing boring data around the study area were collected. The site visit to acquire the surface geotechnical data for geo-knowledge was conducted, and it was specially concentrated at locations where the investigated and collected borehole data were deficient. Geotechnical surface and subsurface materials observed during the site investigation and site visit were classified into five categories consisting of fill, soil deposits of alluvium and colluvium, weathered residual soil, weathered rock, and bedrock of soft rock or harder, which are typical compositions in the inland areas of Korea.

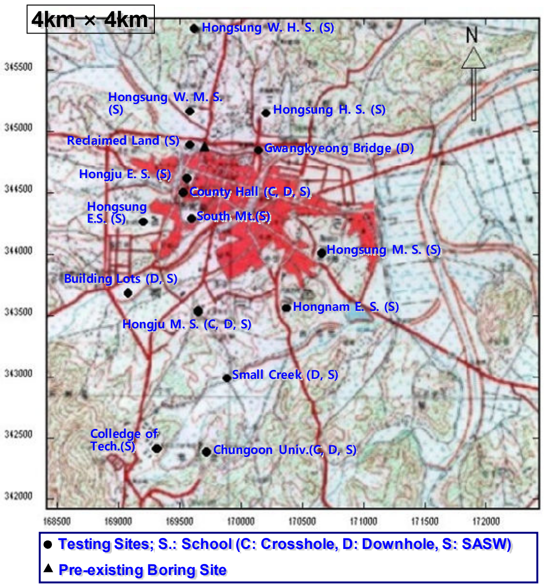


Fig. 3. Contents of site investigations in Hongseong.

The subsurface geologic conditions in the study areas were investigated based on the results of either boring investigations or SASW tests, and were classified as five geotechnical material categories: fill, deposited soil, weathered residual soil, weathered rock, and bedrock. Most of locations of Hongseong are composed of 10 to 45 m thick weathered residual soils and weathered rocks beneath thin alluvial soils. These weathered layers consisting weathered residual soil and weathered rock were formed from erosion and extensive weathering. These thick weathered layers in Hongseong were developed in ancient topography with hills and plains, which is one of the most common geomorphologies in Korea.

4.2 Spatial Site Characterization at Hongseong within GTIS

For site characterization at the entire study area, the spatial variations of geotechnical layers and V_S values over the study area for Hongseong were estimated based on the investigated and collected geotechnical data as well as on the geo-knowledge data obtained from site visit within the GTIS. As the illustration of GIS-based regional site characterization, Fig. 4 shows the spatial variation of geotechnical layers for the study area of Hongseong predicted by applying the kriging estimation method based on both the site investigation data and the surface geo-knowledge data.

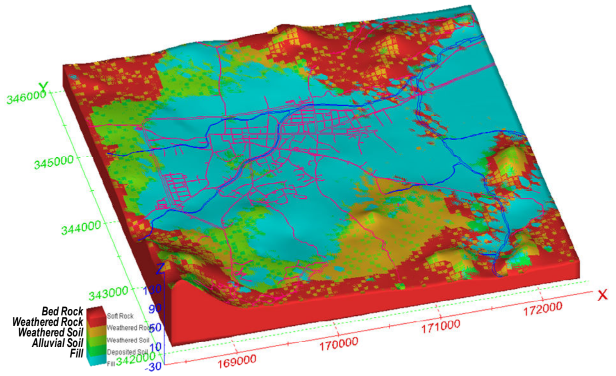


Fig. 4. Spatial geotechnical layers at Hongseong.

The variation of geotechnical layers was utilized as the basic data to compute the site period (T_G) for the study area of Hongseong. In this paper, the vertical scales in three-dimensional figures were exaggerated three times and surface coverage data such as waterways, roads, buildings and elevation contour lines for better visual depiction of surface and subsurface features. The spatial information for this study is the unit of meter on TM (Transverse Mercator) coordinate system, on which X and Y represent the directions of west to east and south to north, respectively, and Z means the elevation. Also, the predicted variation of V_S value within the GTIS for the Hongseong is presented in Fig. 5. The spatial V_S variation is a valuable fundamental parameter for estimating earthquake phenomena and was used in this study to evaluate T_G and the mean V_S to a depth of 30 m (V_S30).

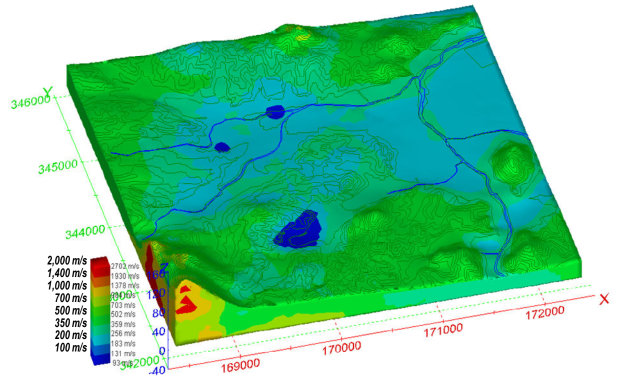
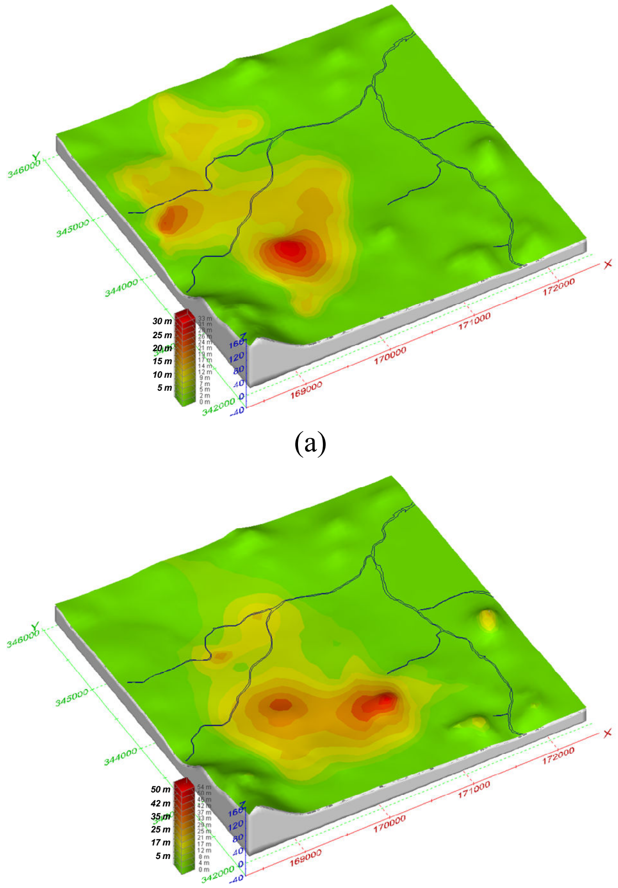


Fig. 5. Spatial shear wave velocity (V_S) variation at Hongseong.



(a)

(b)

Fig. 6. Distribution of (a) the thickness of weathered residual soil and (b) the thickness of weathered rock in Hongseong.

Spatial geotechnical data and their three-dimensional visualizations are generally quite informative. However, a solid three-dimensional ground volume cannot be directly applied in engineering projects because subsurface geological structures will not be clear to most users. Thus, visualizations within GIS usually present two-dimensional contour maps on the plane [9]. The thickness of geotechnical layers and the depth to bedrock are also expressed as contours on corresponding contour maps and can be overlain with three-dimensional topographic surfaces of the study area to better reflect reality [9]. Fig. 6 presents representatively two spatial zoning maps within the GTIS at Hongseong showing the distributions of thicknesses of weathered residual soil and weathered rock among four geotechnical layers over bedrock. It is observed that thick weathered soils of 10 to 33 m thickness are distributed in western plain zone (Fig. 6(a)) and weathered rock of 10 to 50 m thickness are distributed in southern plain zone (Fig. 6(b)). These characteristics in soil formation represent the general inland topography of old age in Korea. They resulted from the weathering process for a long time.

Fig. 7 shows the distribution of the depth to bedrock in the study area, which was computed using the thickness of the geotechnical layers in the geotechnical analysis component of the GTIS. The depth to bedrock is one of the most important geotechnical parameters for various geotechnical problems. The rocks beneath or harder than weathered rock are commonly designated as bedrock; the V_S values ($V_S > 750$ m/s) of these rocks in the study area fall within the category of engineering rock [14, 15].

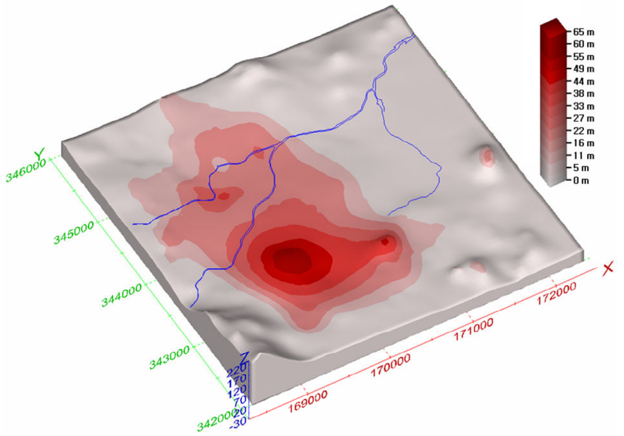


Fig. 7. Distribution of the depth to bedrock (H) in Hongseong.

In the evaluation of the seismic ground amplification and corresponding seismic hazards, the depth to bedrock is particularly important [15]. The depth to bedrock in the western plain ranging to about 65 m in maximum is deeper than that in the southwestern mountain and eastern plain. This distribution pattern of the depth to bedrock is generally similar to that of the weathered soil shown in Fig. 6. Soil development in the western plain zone occurs mainly by weathering landform processes, as mentioned above. Such zones of deep depth to bedrock are susceptible to ground motion amplification due to site effects during earthquakes.

5 Spatial Seismic Site Responses at Hongseong

Local site effects play an important role in seismic damage to structures. Although a GTIS for assessing the local site effects can be constructed based on instrument-measured or analyzed ground motions, empirical relationships or simple site classification schemes have also been used to evaluate site-specific seismic responses at a regional scale because of their convenience and effectiveness [10]. In this study, among the various quantified parameters of seismic responses, two parameters (i.e., the site period (T_G) and the mean V_S to 30 m depth (V_S30)) were used to build the GTIS for the entire study area. The resulting site effects shown by the GTIS are mostly presented on zoning maps identifying locations or zones of varying seismic hazard potential. Fig. 8 describes the conceptual flow for building the seismic zoning map on the T_G and the V_S30 within the GTIS. As illustrated in Fig. 8, the zonation of T_G is established based on both data of geotechnical layers and V_S, on the other hand the zonation of V_S30 is created using only V_S information.

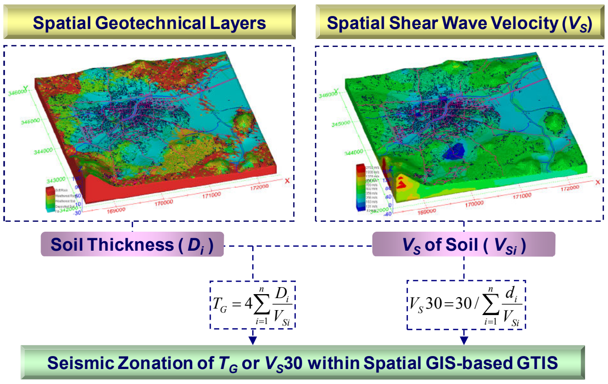


Fig. 8. Conceptual flow for seismic zonations on the site period (T_G) and the mean shear wave velocity to a depth of 30 m (V_S30).

To synthetically predict the spatial variation of seismic disasters in urban areas [9, 14], seismic microzonation studies have been conducted using GTIS. Various seismic zoning maps involving both site period and V_S30 values have been constructed without numerical analyses considering the time requirements and work efficiency [10]. In this study, for efficient microzonation based on the site period over the study area, interpolated spatial data representing each soil layer and V_S values were imported into the geotechnical analysis component of the GTIS. The imported spatial V_S data were assigned, with reference coordinates, to each layer. The average layer thickness and V_S value for each layer were then calculated at 10 m intervals, and the site period at each grid point was computed based on Equation (1). The calculated site periods were spatially modelled, resulting in the seismic microzoning map presented in Fig. 9.

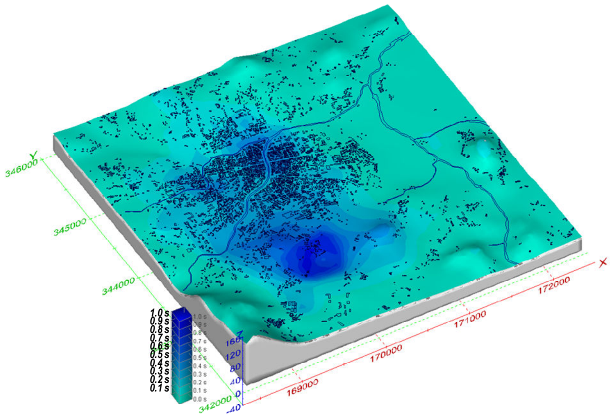


Fig. 9. Spatial distribution of the site period (T_G) in Hongseong.

The site periods for western plains were generally longer than those for other plains and mountainous and hilly areas, ranging mainly between about 0.3 and 1.0 s in the Hongseong area. The spatial distribution of site periods is particularly consistent with the distribution of bedrock depths depicted in Fig. 7. In Fig. 9, the spatial building coverage data are overlain on the site period distribution to examine the seismic vulnerability of buildings. These rigorous zonations including building coverage can serve as a fundamental resource for predicting seismically induced structural damage. All objects or structures have their own natural periods. Tall multi-storied buildings with long natural periods tend to react very differently than small buildings with short natural periods. The natural period of a building is generally accepted to be 0.1 times its number of stories [11]. Most buildings in downtown located at western plain of the study area of Hongseong have more than three stories and would therefore be vulnerable to seismic damage caused by earthquake resonance. Microzoning information based on the site period can contribute to earthquake-related strategies and also to rational land use and city planning or development in the entire study area.

The site class for seismic design in the current seismic design guides is determined solely and unambiguously by one parameter, V_S30 [15]. Thus, if the spatial variations of V_S values are known over the entire study area, the site coefficients according to these site classes can be readily determined for any site in the study area by the GTIS. Using the spatially interpolated V_S values, which were imported into the geotechnical analysis component, V_S30 was computed at each grid point based on Equation (2). Fig. 10 presents a map of the V_S30 distribution created by the GTIS for site classification in the Hongseong area.

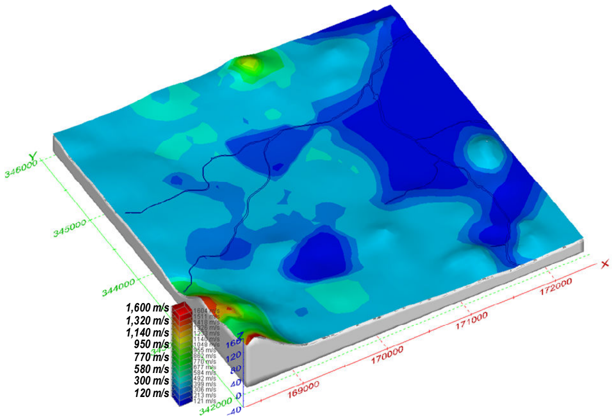


Fig. 10. Spatial distribution of the mean shear wave velocity to a depth of 30 m (V_S30) in Hongseong.

Most of the plains have lower V_S30 distributions than mountainous and hilly areas, differing from the case of T_G. Precisely, for the eastern plain, the distribution trend of V_S30 is definitely differently from that of T_G, because of the lack of geotechnical site investigation data. Thus, intensive site investigations including the borehole drillings and seismic tests are required at the eastern plains in the study area of Hongseong, for more reliable estimation of the site effects based on the V_S30 over the entire area of interest. The spatial variation of the V_S30 presented in Fig. 10 allows for easy preliminary classification of all locations in the study area (see Tables 1 and 2) prior to adding site-based classifications. In the study area, most locations (with the exception of mountainous areas) fall into site classes B, C or D. Most plain zones are site classes C or D, with site coefficients larger than unity. This spatial seismic zoning map of V_S30 can be directly used for preliminary earthquake-resistant design in any location of the study area. Furthermore, besides the prediction of earthquake-induced hazard potential, the T_G can be also applied in seismic design and seismic performance evaluation in the area of interest by adopting the site classification system according to the T_G (Table 2).

The spatial seismic microzonation maps on T_G and V_S30 produced by the GTIS can be used to predict spatial site-specific seismic responses associated with the site effects causing earthquake hazards particularly in Hongseong. Also, the zonations on the T_G and V_S30 can be applied in both preliminary seismic design and seismic performance evaluation of structure at any site in the entire study area. The GIS-based GTIS developed in this study successfully revealed the seismic microzonation for estimating systematically the local site effects in an inland urban area of Korea.

6 Conclusion

A methodology was proposed and used in GIS-based GTIS to manage a variety of geotechnical data and to reliably estimate spatial geotechnical information. The GTIS was applied in the geotechnical site characterization to assess local site effects and corresponding earthquake-induced hazards in Hongseong, a typical inland area of Korea.

A GIS-based tool, the GTIS, was implemented based on new concept of geo-knowledge by adopting a prior building procedure. The spatial geotechnical layers and V_S values were reliably predicted over the 4 km × 4 km area Hongseong study area using a sophisticated geostatistical interpolation technique. Based on the spatially interpolated geotechnical layers, distribution map of the depth to bedrock, which is an important parameter for geotechnical and earthquake engineering problems, were constructed. The map shows that the western plain zones in the study area are potentially susceptible to seismic amplification.

To assess the site effects leading different site-specific seismic responses without numerical seismic response analyses and to apply in preliminary seismic design in the entire study area, distributions of both the site period and V_S30 were efficiently created in the form of microzonation maps based on the spatial geotechnical layers and V_S value. The site period map suggests that buildings higher than three-stories in Hongseong are vulnerable to seismic activity. The V_S30 map indicates that most of the plain areas fall into site classes C and D. Moreover, the site classification based on the zonation of T_G would be applicable in the entire study area. These seismic zonation case studies using GIS technology verify the usefulness of the GTIS as a regional synthetic tool for spatially estimating the site-specific seismic responses with regional scale.

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References

[1] Anastasiadis, A., Raptakis, D. and Pitilakis, K., Thessaloniki's detailed microzoning: subsurface structure as basis for site response analysis, *Pure and Applied Geophysics*, Vol.158, No.12, 2001, pp. 2597-2633.

[2] Arshad, N.H., Mohamed, A. and Mansor, R., Organizational structural strategies in risk management implementation: best practice and benefits, *WSEAS Transactions on Information Science and Applications*, Vol.6, No.6, 2009, pp. 885-894.

[3] Autodesk, *AutoCAD land development desktop 2i manuals and application books*, Autodesk, Inc., 2001.

[4] Borcherdt, R.D., Estimates of site-dependent response spectra for design (methodology and justification), *Earthquake Spectra*, Vol. 10, No. 4, 1994, pp. 617-654.

[5] CTech, *EVS/MVS manuals version 9.12: main helps and visualization fundamentals, module libraries, workbooks and sample applications*, CTech Development Corporation, 2001.

[6] Dobry, R., Ramos, R. and Power, M.S., *Site Factors and Site Categories in Seismic Codes*, Technical Report MCEER-99-0010, Multidisciplinary Center for Earthquake Engineering Research, 1999.

[7] Gangopadhyay, S., Gautam, T.R. and Gupta, A.D., Subsurface characterization using artificial neural network and GIS, *Journal of Computing in Civil Engineering*, ASCE, Vol.13, No.3, 1999, pp. 153-161.

[8] Holdstock, D.A., Editorial: Basics of geographic information systems (GIS), *Journal of Computing in Civil Engineering*, ASCE, Vol. 13, No. 1, 1998, pp. 1-4.

[9] Kim, D.S., Chung, C.K., Sun, C.G. and Bang, E.S., Site assessment and evaluation of spatial

earthquake ground motion of Kyeongju, *Soil Dynamics and Earthquake Engineering*, Vol.22, No.5, 2002, pp. 371-387.

[10] Kiremidjian, A.S., Spatial analysis in geotechnical earthquake engineering, *Special Analysis Soil Dynamics and Earthquake Engineering*, Geotechnical Special Publication No. 67, ASCE, 1997, pp.1-14.

[11] Kramer, S.L., *Geotechnical Earthquake Engineering*, New Jersey: Prentice-Hall, 1996, pp. 309-323.

[12] Oliver, M.A. and Webster, R., Kriging: a method of interpolation for geographical information systems, *International Journal of Geographical Information Science*, Vol.4, No.3, 1990, pp. 313-332.

[13] Sun, C.G., *Geotechnical Information System and Site Amplification Characteristics for Earthquake Ground Motions at Inland of the Korean Peninsula*, Ph.D. Dissertation, Seoul National University, Korea, 2004.

[14] Sun, C.G., Chun, S.H., Ha, T.G., Chung C.K. and Kim D.S., Development and application of GIS-based tool for earthquake-induced hazard prediction, *Computers and Geotechnics*, Vol.35, No.3, 2008, pp. 436-449.

[15] Sun, C.G., Kim, D.S. and Chung, C.K., Geologic site conditions and site coefficients for estimating earthquake ground motions in the inland areas of Korea, *Engineering Geology*, Vol.81, No.4, 2005, pp. 446-469.

[16] Sun, C.G., Shin, J.S. and Chi, H.C., Regional estimation of site-specific seismic response by spatial zoning at an inland urban area, Daegu, in Korea, *WSEAS Transactions on Environment and Development*, Vol.5, No.2, 2009, pp. 168-177.

[17] Tsai, Y.B. and Huang, M.W., Strong ground motion characteristics of the Chi-Chi, Taiwan earthquake of September 21, 1999, *Earthquake Engineering and Engineering Seismology*, Vol. 2, 2000, pp. 1-21.

[18] Tsang, H.H., Lam, N.T.K., Asten, M.W. and Lo, S.H., Generic theoretical formulae for estimating site effects, *WSEAS Transactions on Environment and Development*, Vol.3, No.1, 2007, pp. 1-7.

[19] Vargues, P. and Loures, L., Using geographic information systems in visual and aesthetic analysis: the case study of a golf course in Algarve, *WSEAS Transactions on Environment and Development*, Vol.4, No.9, 2008, pp. 774-783.