GIS-Based Assessment of Geotechnical Characteristics Related to Earthquake Motion in a Small Urban Area

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Abstract— Site characterization on geological and geotechnical conditions was performed for evaluating the earthquake ground motions associated with seismic site effects at a small urbanized area, Hongseong, in Korea, where structural damages were recorded by an earthquake of magnitude 5.0 on October 7, 1978 and severe damages were also recorded in many historical documents. In the field, various geotechnical site investigations composed of borehole drillings and seismic tests for determining shear wave velocity 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 over an entire area of interest. For practical application of the GIS-based geotechnical information system to assess the earthquake motions in a small urban area, spatial seismic zoning maps on geotechnical parameters, such as the bedrock depth and the site period (T_G), were created over the entire administrative urban area of Hongseong, and the spatial distributions of seismic vulnerability potentials were intuitively examined. Seismic zonation was also performed to determine site coefficients for seismic design by adopting a site classification system based on T_G. A case study of seismic zonation in the Hongseong area verified that the site investigation based GIS was very useful for regional prediction of site effects related to seismic response characteristics in a small urbanized inland area.

Keywords—Geotechnical information, Geographic information system, Geotechnical condition, Seismic zonation, Earthquake ground motion.

I. INTRODUCTION

RECENT destructive earthquakes demonstrated that earthquake-induced geotechnical hazard and corresponding structural disasters are generally more severe over soft soils than over firm soils or rocks in urban areas [21], [23]. That is, the local geologic and soil conditions have a profound influence on the amplification of earthquake ground motions, which may result in the serious seismic hazards [18], [24]. The difference of seismic amplification potential between the sites in a region would be estimated by spatially predicting the subsurface soil thickness and the corresponding seismic response behaviour in the entire area of interest. In the spatial prediction of the subsurface geotechnical conditions across the area of interest, in-situ site investigation data in and near the area can be efficiently used as the basic resources and geotechnical expert knowledge can be also applied for enhancing the prediction reliability [18].

Geotechnical engineering data including geological borehole investigation data and seismic survey data are distributed in the spatial domain [12]. To assess geotechnical or geological problem with regional scale, the geotechnical data referenced by spatial geographic coordinate should be interpolated or extrapolated across the area of interest based on the existing and/or obtained known geotechnical data. Advanced computer-based expert system is required for the management and estimation of geotechnical data in spatial domain. 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 [18].

For geotechnical purposes, GIS-based expert systems have been developed and used to forecast and plan for natural hazards such as landslides or earthquakes [16], [18], [25]. Especially, in geotechnical earthquake engineering, there have been several researches on GIS technology [1], [12]. And this technology will be widely used in increasing numbers of seismic zonations for the prediction of earthquake-induced hazards [18]. In this study, a spatial GIS-based tool, geotechnical information system (GTIS), was built for the presentation and reliable estimation of the geotechnical information over the selected small urban area, Hongseong, of Korea. Particularly, to assess more systematically in the Hongseong area comparing with the prior case study [17], the GIS-based GTIS was here implemented for enlarged study area of the entire administrative region. 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.

II. EARTHQUAKE GROUND MOTION

Earthquake ground motion inducing a variety of hazards on and near the ground surface is influenced by several factors such as the seismic source, ray path, and local site effects. Among these factors, the geotechnical earthquake engineering

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has been mainly concentrated on the development of quantitative methods for evaluating the influence of local site conditions on the amplification of earthquake motion [6].

A. Characteristic Site Period

It is commonly recognized in the discipline of earthquake engineering that the ground motion from earthquake base excitation can be significantly modified by the local site effects [6], [21]. The site effects indicating site-specific seismic response is basically associated with the phenomenon of seismic waves travelling through soil layers. 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 [17], [18]. 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

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

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.

B. Site Classification System for Site Coefficients

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], [7], [21]. 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

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

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], [21]. 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 [21]. In this study, the site coefficients, F_a and F_v, were based on the RRS and calculated by

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

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

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 [10], [18], [21]. 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. The site coefficients with site classes in the Hongseong are presented in Table 2, for rock-outcropping acceleration level of 0.11g. 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 [21].

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

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

To use the T_G taking account of both the bedrock depth and the geotechnical property particularly for seismic design in Korea, Sun [16] 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. 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 [16]. Applications of this system are restricted into site classes B, C and D, which are common for the inland regions in Korea.

Table 2. Site classes and site coefficients based on site period for the inland region of Korea [16]

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
Very Dense Soil and Soft Rock	C	> 360	< 0.27	1.50	1.10
Stiff Soil	D	> 180	< 0.68	2.30	1.30

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.

III. FRAMEWORK OF GIS-BASED GEOTECHNICAL INFORMATION SYSTEM

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 [25]. The geotechnical information system (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 [15].

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

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

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. As presented in Fig. 1, the GTIS has four functional components: database, spatial analysis, geotechnical analysis, and visualization components.

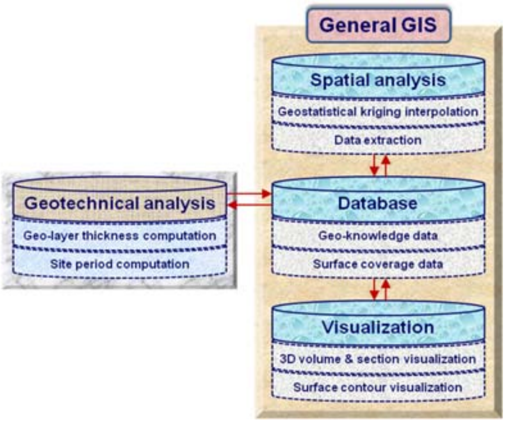

Fig. 1 Components for GIS-based geotechnical information system

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 [18], [22]. 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). 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 [8], [9]. In this study, GTIS was implemented based on several expert GIS tools [3], [5], [18], in combination with various specified expert techniques. 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.

IV. SPATIAL GEOLOGICAL AND GEOTECHNICAL CONDITIONS IN THE STUDY AREA

The GTIS was implemented 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 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.

A. Geological Setting and Site Investigation Locations of Study Area

To build a GIS-based GTIS, the Hongseong area, where earthquake-induced structural damages were caused by magnitude 5.0 earthquake on October 7, 1978, was selected in this study [17], [21]. Particularly, a number of historical seismic activities present severe seismic hazards [21]. In view of geomorphology and geology, Hongseong shows a typical topography of old age with gentle relief of the inland region in Korea [17], [20], [21]. Fig. 2 shows the geographic location on the distribution of granitic rocks in South Korea and detailed geological setting of central area in Hongseong [20]. 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 [21]. The granitic rock series are biotite granite and schistose granite, and rocks are mostly weathered in most cases [20], [21].

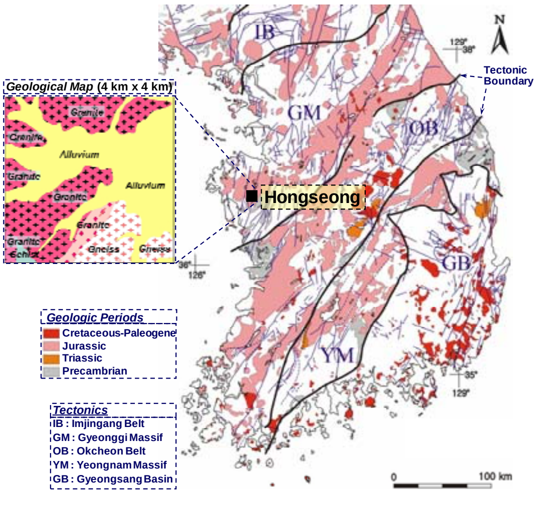

Fig. 2 Distribution of granitic rocks in South Korea and geological setting of central area in Hongseong

For the site characterization of the entire administrative area for Hongseong, first, we collected approximately 100 existing borehole drilling data over an extended area including the study area. The study area indicates the administrative district for the Hongseong-yeob (town) in this study. Then, usually in central downtown area, we conducted a variety of geotechnical site investigations: 9 boring investigations, 3 crosshole tests, 6 downhole tests and 15 SASW tests at total 16 sites. Geotechnical subsurface materials observed during the site investigation were classified into five categories: fill, soil deposits composed of alluvium and colluvium, weathered or residual soil, weathered rock, and bedrock of soft rock or harder, which are typical compositions in the inland areas of Korea [20], [21].

Fig. 3 shows the spatial distribution of existing and investigated data in the extended area of Hongseong created within the spatial GIS-based system. In this paper, the vertical scales in three-dimensional figures were exaggerated three times and surface coverage data such as waterways, buildings and/or roads were overlain on ground surface for better visual depiction of surface and subsurface features. The spatial information was built with the unit of meter on the local TM (Transverse Mercator) projected coordinate system of local origin, on which X and Y represent the directions from west (W) to east (E) and south (S) to north (N), respectively, and Z represents the elevation. The rectangular dimension of the extended area in Fig. 3 measures 8.0 km on WE and 8.0 km on NS.

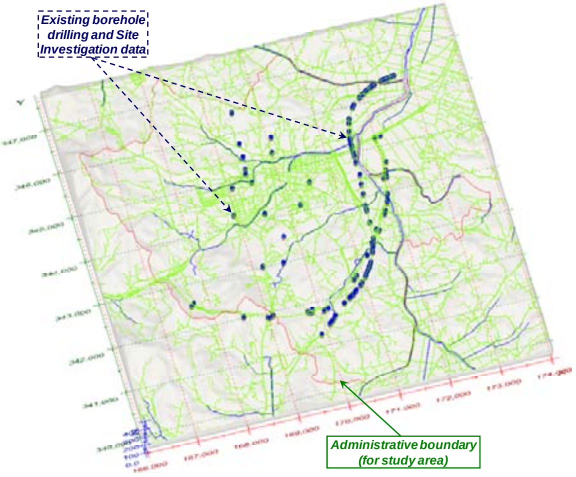

Fig. 3 Distribution of performed and collected geotechnical data in the extended area of Hongseong

B. Geotechnical Information using Spatial GIS Framework

To demonstrate the building of GIS-based system, the study and extended areas were selected for target area, Hongseong. The study area consists of the whole administrative region for Hongseong town. For reliably estimating the spatial geotechnical layers in area of interest, the kriging prediction method was applied to the extended area. From these estimated values, the geotechnical information for the study area was extracted using a specified GIS cut function. The conceptual steps involved in this extraction are depicted in Fig. 4.

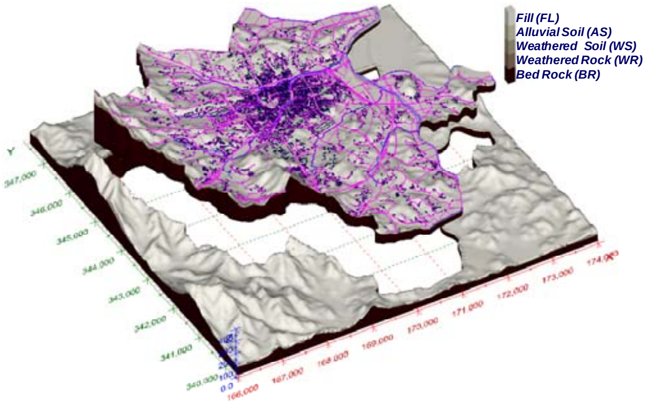

Fig. 4 Spatial geotechnical layers predicted within GIS-based geotechnical information system for Hongseong

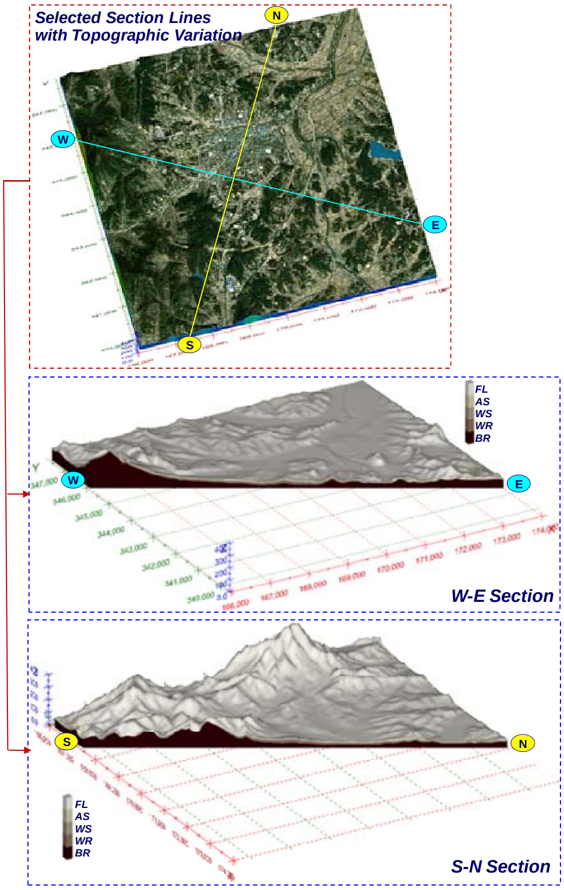

Fig. 5 Sections examined for subsurface geological structures with topographic feature in Hongseong

The variation of geotechnical information at any section in the area of interest can be examined by using the expert GIS tools, which were adopted in this study. Fig. 5 shows two sections of predicted spatial geotechnical layers for several slices of the study area together with the topographic variation illustrated by superposing the satellite image. Particularly, thick soil layers were observed in plain areas while shallow bedrock underlying thin soil deposits were observed at mountainous areas of the outskirts of Hongseong, as shown in Fig. 5. In particular, most areas in Hongseong are composed of thick weathered residual soils and weathered rocks beneath thin alluvial sands and silts. These soils and rocks were formed from erosion and extensive weathering [20], [21]. 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.

Three-dimensional visualization of geotechnical layers in space is generally quite informative. However, a solid spatial ground volume model cannot be directly applied to engineering projects because from this model subsurface geological structures will not be clear to most users. Therefore, visualizations within GIS tools usually present two-dimensional contour maps [13]. The thickness of geotechnical layers and the depth to bedrock are depicted as zoning contour maps on spatial topographic features of the study area [19].

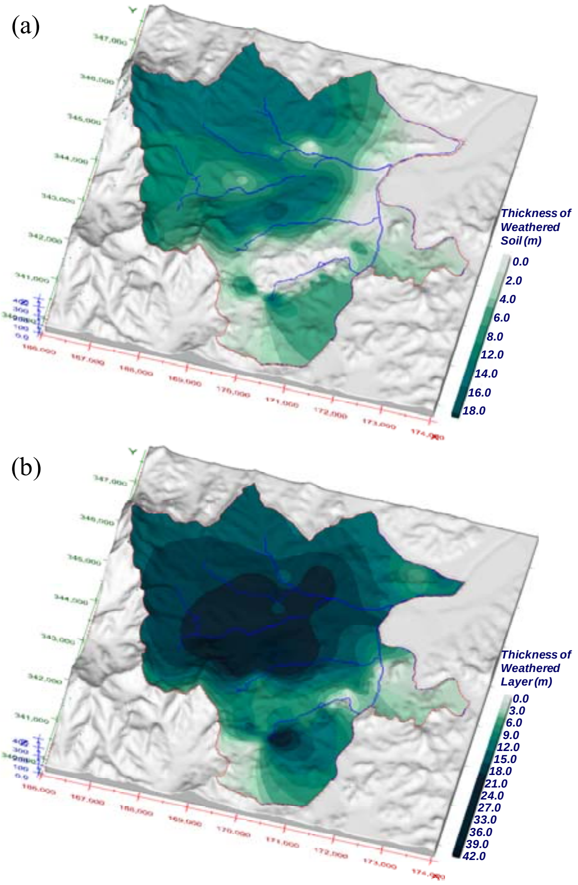

Fig. 6 Distribution of (a) the thickness of weathered soil and (b) the thickness of weathered layer in Hongseong

Fig. 6 presents representatively two spatial zoning maps within the GTIS at Hongseong showing the distributions of thicknesses of weathered soil and weathered layer among four geotechnical layers over bedrock. The weathered layer means the layer containing weathered soil and rock. It is observed that thick weathered soils of 10 to 18 m thickness are distributed in central plain and western hilly zones (Fig. 6(a)) and weathered layer of 10 to 42 m thickness are distributed in central plain zone (Fig. 6(b)).

Fig. 7 presents representative spatial zoning maps showing the distribution of the depth to bedrock at Hongseong, which were computed in the geotechnical analysis component of the GIS-based geotechnical information system. From Fig. 7, it is observed that the 20 to 46 m thick soil layers are distributed in the plains. Especially, the soil layers consist mainly of weathered layers from the parent rock than alluvial soils from the outside. These characteristics in soil formation generally represent an inland topography of old age with gentle relief, and they could have resulted from weathering processes for long time. The depth to bedrock is one of the most important geotechnical parameters for addressing various geotechnical problems [16], particularly for evaluating seismic site amplification and corresponding hazards [2, 18]. As shown in Fig. 7, the depth to bedrock in the plains is more than that in surrounding mountain areas. Such zones of deep bedrock are susceptible to ground motion amplification owing to the site effects.

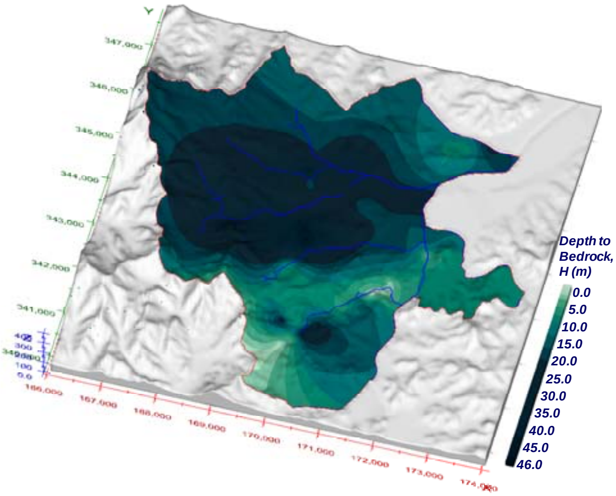

Fig. 7 Spatial distribution of depth to bedrock in the study area of Hongseong

V. SPATIAL ZONATIONS ON EARTHQUAKE GROUND MOTION

Site-specific seismic response characteristics, represented as the site effects, play an important role in evaluating earthquake disasters. Empirical relationships or simple site classification schemes have also been used to evaluate site-specific seismic responses on a regional scale because of their convenience and effectiveness [18], [26]. In this study, only the geotechnical parameter of the site period (T_G) was used to evaluate the site effects for the Hongseong area. The results obtained by using the GIS technique are presented on zoning maps showing the locations or zones of earthquake ground motion-induced disaster potential.

The T_G was computed using both the thickness and V_S of soil layers over the bedrock. The thicknesses of soil layers were already estimated across the study area using the GIS-based geotechnical information system. And the representative V_S values of geotechnical layers for Hongseong were determined based on the results of the in-situ seismic tests for this study in Hongseong and from the previous studies in several inland areas of Korea [16], [21]. In particular, the representative V_S values of weathered layers were determined basically from the results in this study for Hongseong. Fig. 8 shows the V_S profiles in terms of average with standard deviation (SD) for weathered soil and weathered rock and the general ranges of V_S values for weathered layers. From these results, the V_S was determined representatively to be 350 m/s for fill, 300 m/s for alluvial soil, 350 m/s for weathered residual soil, 450 m/s for weathered rock, and 1,000 m/s for bedrock.

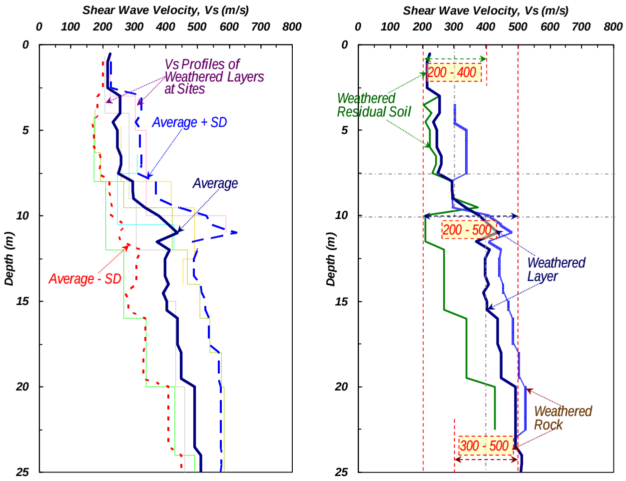

Fig. 8 Average profiles and ranges of shear wave velocity of weathered layers obtained from in-situ seismic tests in Hongseong

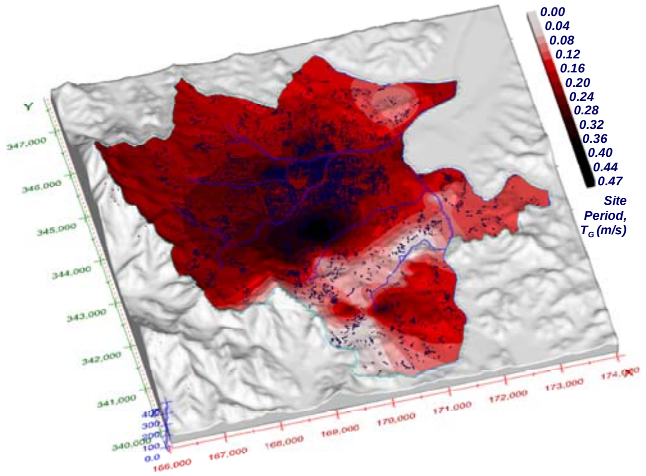

Fig. 9 Spatial zonation of site period for potential of earthquake ground motion in Hongseong

For efficient geotechnical zonation based on the T_G values over the study area, the geotechnical thickness data interpolated in the spatial analysis of the GIS-based tool and the representative V_S values were imported into the geotechnical analysis component. Then, the T_G was calculated at 50 m intervals based on (1). The T_G values calculated for the target small urban area were spatially modelled, and the results are presented as spatial zoning map in Fig. 9.

Although several parts of mountainous zones show the T_G values higher than other parts, the T_G values for plains are generally higher than those for mountainous and hilly locations, and range mainly between about 0.20 and 0.47 s in the Hongseong area. The distribution of T_G values in space is particularly consistent with the distribution of bedrock depth depicted in Fig. 7. In Fig. 9, the spatial main building coverage data are shown as an overlay on the T_G distribution data 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. The natural period of a building is generally accepted to be 0.1 times the number of its stories [11], [14]. Buildings having two to five stories would therefore be vulnerable to seismic damage caused by earthquake resonance. Zoning information based on the T_G values can contribute to formulating earthquake-related strategies, rational land-use plans, and developmental plans for inland urban areas.

Seismic design and seismic performance evaluation can also be carried out by adopting the site classification system based on the T_G values available from the seismic zoning maps. In this study, a site classification scheme (see Table 2) for the inland region in Korea was adopted. Fig. 10 shows the spatial zoning map with the main road coverage data in respect of seismic site classification in the study area, built within the GIS-based geotechnical information system. The site coefficients, F_a and F_v, according to T_G values for the seismic design of structures are presented as legend to the figure.

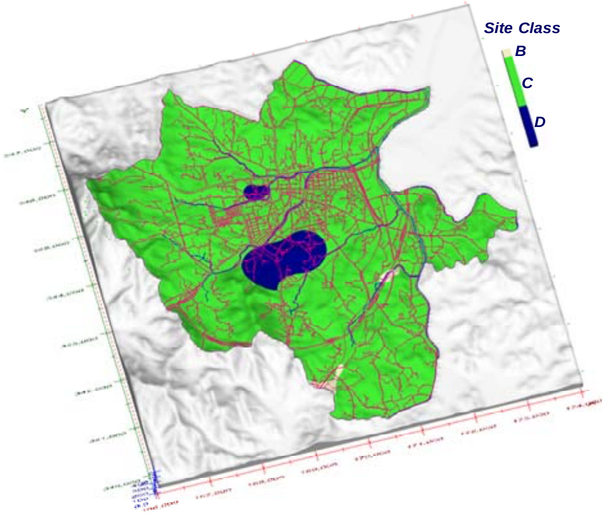

Fig. 10 Spatial zonation on site classes for preliminary seismic design in Hongseong

The plains in the area of interest fall within the site classes C and D, which represent the amplifying earthquake ground motions of the sites, and match with the seismically vulnerable areas inferred from T_G values indicated in Fig. 8. This spatial zonation map of site class provides the information needed for preliminary seismic design of the structure or building. Further, the site classification maps indicate whether the buildings or structures located on the plains need evaluation of their seismic performances. As depicted in Fig. 9, the site class can be determined solely and unambiguously by one parameter, T_G. Therefore, if the spatial variations of T_G are known for the entire study area, the site classes and from them the site coefficients can be readily determined for any location in the study area by spatial seismic zonation.

VI. CONCLUSION

This study presented GIS-assisted information on earthquake ground motion-related hazards in terms of site effects for a small urban area, Hongseong, Korea. In particular, intensive site investigations such as borehole drilling and seismic tests were performed to reliably assess the geological and geotechnical conditions, and existing borehole data were utilized. Based on the investigation data and acquired existing borehole data, the information on spatial geotechnical layers was reliably predicted by building a spatial GIS-based tool, geotechnical information system, for the target urban area.

Based on the spatially interpolated geotechnical layers for the extended area, the map showing the distribution of the depth to bedrock was prepared for the study area composed of the whole administrative region for Hongseong town. To assess the seismic site effects on a regional scale, the distribution of the T_G was created in the form of spatial zonation map based on the geotechnical layers estimated within the GIS-based system and V_S determined representatively from the in-situ investigations for the study area and prior researches. The T_G map suggests that the buildings having two to four stories are vulnerable to seismic activity. Based on the distribution of T_G values in the area of interest, seismic zoning map for site classification was also created to determine the short- and mid-period site coefficients for preliminary seismic design. These site classification maps show that the plains in the study areas fall within the site classes C and D in terms of amplifying earthquake ground motion, implying thereby that the structures or buildings on the plains may need seismic performance evaluation.

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