Proceedings of the 9th U.S. National and 10th Canadian Conference on Earthquake Engineering
Compte Rendu de la 9ième Conférence Nationale Américaine et
10ième Conférence Canadienne de Génie Parasismique
July 25-29, 2010, Toronto, Ontario, Canada • Paper No 119

REGIONAL ESTIMATION OF SITE EFFECTS IN A COASTAL URBAN AREA USING A GIS FRAMEWORK

Chang-Guk Sun[1], Sung-Ho Chun[2], Jin-Soo Shin[3] and Hee-Il Lee[4]

ABSTRACT

Seismic disasters are often more severe over soft soils than over firm soils or rocks due to differences in local site effects. On a regional scale, such differences can be estimated by spatially predicting the subsurface soil thickness over the entire target area. Soil deposits are generally deeper in delta areas than in inland regions. Such variations in soil development have been frequently investigated in coastal areas. In this study, a highly urbanized coastal area, Busan, South Korea, was selected to assess site effects and provide information on seismic hazards. A geographic information system (GIS) was implemented for reliable spatial prediction of geotechnical layers over the entire study area. Approximately 3,000 existing borehole drilling data in the Busan area were gathered and archived into the GIS database. In addition, surface geo-knowledge data were acquired from a walkover survey. For practical application of the geo-knowledge database to site effect estimation in the study area, seismic zoning maps of geotechnical parameters, such as bedrock depth and site period, were created within the GIS environment and presented as information for use in a regional seismic strategy. The spatial distribution of seismic vulnerability potential was intuitively examined from the seismic zoning maps. Seismic zonation was also performed to determine site coefficients for seismic design over the entire target area. A case study of seismic zonation in the Busan area verified that the geo-knowledge based GIS was very useful for regional prediction of seismic site effects in an urbanized coastal area.

Introduction

Observations of recent destructive earthquakes have demonstrated that even at the same epicentral distances within an urban area, earthquake-induced hazard is often more severe over soft soils than over firm soils or rocks (Tsai and Huang 2000; Sun et al., 2005). Local geologic and soil conditions have a profound influence on the amplification of earthquake ground motions, which may result in serious damage and losses (Sun et al. 2005; 2008). The difference of seismic

[1]Senior Researcher, Earthquake Res. Center, Korea Inst. of Geoscience & Mineral Resources, Daejeon, Korea
[2]Assisstant Manager, Technology Res. Inst., Daelim Industrial Co., Seoul, Korea
[3]Principal Researcher, Earthquake Res. Center, Korea Inst. of Geoscience & Mineral Resources, Daejeon, Korea
[4]Principal Researcher, Earthquake Res. Center, Korea Inst. of Geoscience & Mineral Resources, Daejeon, Korea

amplification potential between sites in a region can be estimated by spatially predicting the subsurface soil thickness and the corresponding seismic response behavior in the entire area of interest. In general, soil deposits are deeper in delta areas where rivers join the sea than in inland areas. Thus, coastal urbanized areas built on deltaic plains may be at risk of extensive and severe hazards caused by amplification of earthquake ground motion. To spatially predict subsurface geotechnical conditions across an area of interest such as a wide metropolitan area, existing borehole drilling data in and near the area can be efficiently used as basic resources, and geotechnical expert knowledge can also be applied to enhance prediction reliability (Sun et al. 2008).

Geotechnical engineering data including borehole investigation data are distributed in the spatial domain (Kiremidjian 1997). To assess a geotechnical problem at regional scale, available geotechnical data referenced by geographic coordinates must be interpolated or extrapolated across the area of interest. An advanced computer-based expert system is required for management and estimation of geotechnical data over large spatial domains such as metropolitan area. With advances in computer technology in recent years, geographic information system (GIS) technology has emerged as a powerful computer-based tool that integrates spatial analysis, database management, and graphic visualization capabilities (Codermatiz et al. 2003). GIS-based expert systems have been increasingly developed and used to forecast and plan for natural hazards such as landslides and earthquakes (Holdstock 1998; Gangopadhyay et al. 1999; Sun et al. 2008). In geotechnical earthquake engineering, GIS technologies have been applied to produce seismic zonations for the prediction and mitigation of earthquake-induced hazards (Kolat et al. 2006; Sun et al. 2008). This study developed a spatial GIS-based geotechnical engineering system for reliable estimation of the geotechnical layers and earthquake-related hazard potential in the coastal metropolis of Busan in Korea.

Site Period as an Index of Site Effects

The site effects inducing amplification of ground motion are directly related to geological site conditions and are basically associated with the travel of seismic waves through soil layers (Sun et al. 2008). The behavior of site-specific seismic response 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 (H). Site response analysis techniques have incorporated these concepts, particularly the phenomenon by which the largest amplification of earthquake ground motion at a nearly level site occurs at approximately the lowest natural frequency (Rodriguez-Marek et al. 2000). The period of vibration corresponding to the fundamental frequency is called the characteristic site period (T_G) and for multi-layered soil, it can be computed by:

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

where D_i is the thickness of each soil layer above the bedrock ($H=\Sigma D_i$), V_{Si} is the V_S of each soil layer, and n is the number of soil layers. The site period is a useful indicator of the period of vibration during which the most significant amplification is expected. In addition, the depth to bedrock geometrically indicates the local seismic response patterns by assuming similar stiffness in soil layers over the bedrock. 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 T_G can be readily established and used for regional earthquake hazard estimations.

To quantify site effects for use in structural design, correlations between site coefficients and several geotechnical characteristic parameters have been established based on empirical and numerical studies in many countries (Borcherdt 1994; Dobry et al. 1999; Rodriguez-Marek et al. 2000; Sun et al. 2005). Geotechnical parameters have been used as criteria for categorizing site conditions according to the extent of ground motion amplification quantified by site coefficients. Representative parameters include the mean V_S to a depth of 30 m (V_S30) and the site period (T_G). In most seismic design codes in Korea and the United States, local site effects are quantified by two site coefficients, F_a and F_v, for the short-period and mid-period (or long-period), respectively (Dobry et al. 1999; Sun et al. 2005). 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.

In most current seismic design codes, site conditions are classified into five categories (denoted by A to E) according to the V_S30 values and an exceptional special category (denoted by F) (Dobry et al. 1999; Sun et al. 2005). The site coefficients are used to estimate the design response spectra dependent on both the site classes 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 outcropping motions than for large rock motions because of geo-material nonlinearity (Dobry et al. 1999; Sun 2004).

Table 1. Site classification system using both V_S30 and T_G in Korea (modified from Sun 2004)

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
Deep Soft Soil	E		≤ 180	≥ 0.68	Need further study in Korea	

Current seismic design codes commonly use V_S30 as the sole criterion representing the geotechnical properties: however, this means that the depth to bedrock is disregarded in current site classification (Dobry et al. 1999; Sun et al. 2005). Recently, T_G has also been considered in seismic design in Korea to take both bedrock depth and geotechnical properties into account. Sun (2004) proposed a new site classification system based on T_G together with the current classification criterion, V_S30, although several Korean researchers have also recently suggested other seismic site classification systems (Kim and Yoon 2006; Kim et al. 2008). 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, with classes C and D each subdivided into four sub-classes.

Table 1 presents site classification system using both T_G and V_S30, especially for Korea. In this study, site class E in Table 1 was added to the original classification scheme developed by Sun (2004) for applying the scheme to soft or deep soil sites in coastal areas. This site classification scheme can be used by engineers for seismic design purposes as well as for seismic performance evaluation at a site. Furthermore, if the spatial distribution of geotechnical layers (soil layers), including the depth to bedrock and V_S values or V_S values for depth to 30 m or deeper, is known over the entire area of interest, the spatial distribution of T_G or V_S30 and the corresponding site classes for seismic design can be readily determined with the spatial GIS framework.

Geo-knowledge Based GIS

With rapid advancements of computer technology in recent decades, researchers can now use GIS to manage large data sets including those of composed of geotechnical data. To efficiently manage and use spatial geotechnical information for the ground surface and subsurface, geotechnical-purposed information systems have been developed based on GIS frameworks (Holdstock 1998). In this practical research, for highly urbanized area, an advanced methodology is applied to build spatial GIS to accommodate geotechnical information.

Framework of the Geo-knowledge Based GIS

The geo-knowledge based GIS developed in this study incorporates geo-knowledge data and a geostatistical kriging interpolation technique adopted for reliable spatial prediction of geotechnical values. The geo-knowledge based GIS is implemented for Busan, a coastal metropolitan area. As presented in Figure 1, the GIS implementation has four functional components: the geo-knowledge database, spatial analysis, geotechnical analysis, and visualization components (Sun et al. 2008). Arrows in the figure indicate the direction of data flows, which occur between the database component and geotechnical analysis component for assessing seismic hazards.

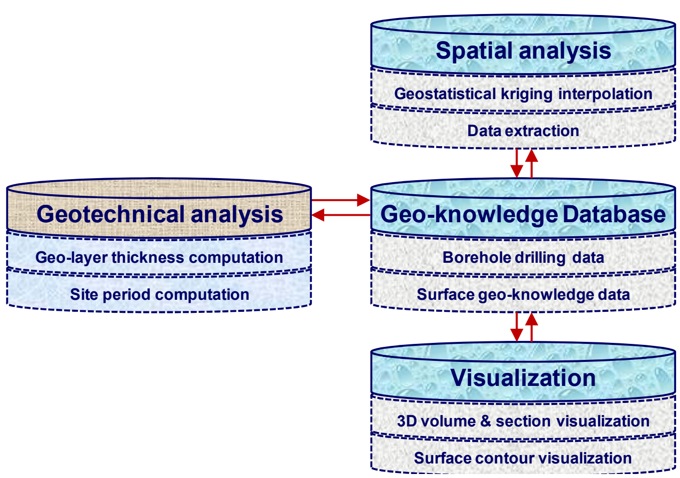

Figure 1. Components of the geo-knowledge based GIS.

To build a database for the GIS (Sun et al. 2008), we first collected existing data obtained from boreholes in and near the area of interest. In addition, to more reliably predict spatial geotechnical information in the area of interest (Sun 2004), we applied the new concept of the use of geo-knowledge to acquire additional surface geotechnical data. Geo-knowledge refers to information spanning the fields of geotechnical engineering, geology, and geomorphology; this information was acquired from topographic maps, satellite images, and surface geologies. We also conducted a walkover survey to acquire data related to the ground surface, mostly in areas where existing borehole data were lacking.

The geo-knowledge based GIS was implemented for a representative coastal metropolis, Busan, and applied to assess site characteristics, especially the thickness of geotechnical layers or the depth to bedrock. Busan is the second largest urban area in Korea and is located on the southeastern edge of the Korean peninsula. In this study, subsurface geotechnical layers revealed by borehole data and surface geotechnical materials from the site visits were classified into five categories: fill, alluvial soil, weathered soil, weathered rock, and bedrock (Sun 2004).

Building the Geo-knowledge Database

To manage and update the geotechnical data, a database (DB) management system for the geo-knowledge data was developed using the ESRI ArcGIS Engine. The system is composed of the Microsoft SQL DB server supported by an FTP server and the DB management program for clients. The system allows for data input and renewal by communication between the server and client's program through the TCP/IP network and export for general-purpose application into text or spread-sheet formats.

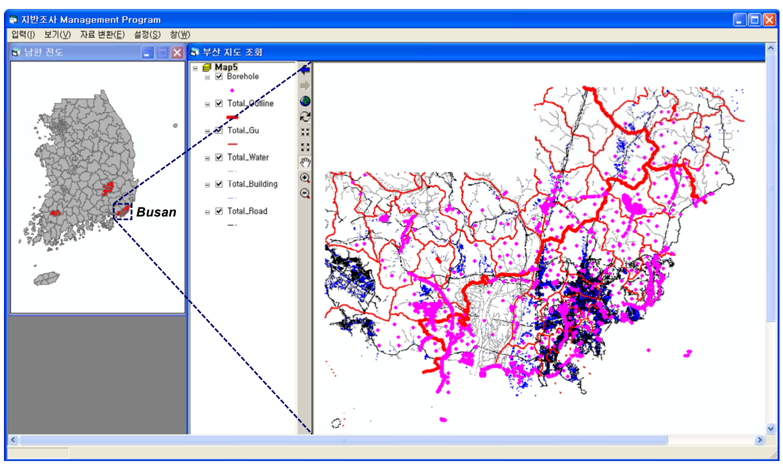

Figure 2. An interface of the client's database management program.

The DB management program serves as the interface, as shown in Figure 2, after accessing the DB server. The left and right windows present the administrative units of South Korea and the data locations (indicated with points in the right window) in the target Busan area referenced by topographic features and administrative borders, respectively. In the DB management program, the client can input new data according to the standardized format by opening another interface option. More than 3,000 data, including about 2,900 from borehole drilling and 200 surface geotechnical data, were archived into the geo-knowledge database for the Busan metropolitan area. The database was then exported for analysis and display within the GIS framework.

Implementation of the Geo-knowledge Based GIS for Spatial Geotechnical Layers

In geotechnical and earthquake engineering, a GIS can be used either alone or in conjunction with specified model-analysis techniques (Gangopadhyay et al. 1999). In this study, the geo-knowledge based GIS was developed based on several GIS tools (ESRI ArcGIS Desktop, CTech EVS-Pro, and Autodesk AutoCAD) in combination with various expert techniques (Sun et al. 2008). Furthermore, for better spatial estimation of geotechnical information using an optimum variogram model for each subsurface geotechnical layer, a sophisticated kriging interpolation program based on Visual BASIC code was developed and adopted in the spatial analysis component, although GIS tools usually provide ordinary kriging estimation.

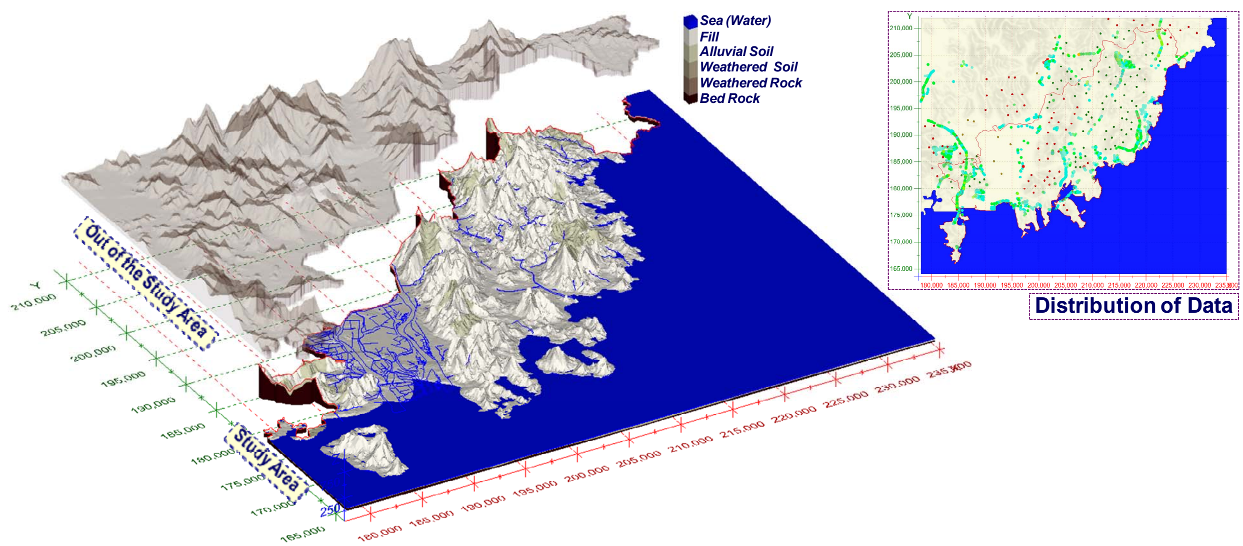

Figure 3. Spatial geotechnical layers predicted by building the geo-knowledge based GIS for Busan.

Because interpolation is expected to produce more reliable predictions of unknown geotechnical data from known geotechnical data than extrapolation in the spatial domain, we introduced a concept of the extended area encompassing the study area (Sun 2004; Sun et al. 2008). Specifically, the target study area was chosen to the entire territory surrounded by the administrative boundary of Busan metropolitan city (the administrative region). To estimate geotechnical layers spatially for the target Busan area, we applied the kriging prediction method (Oliver and Webster 1990) to the extended area (56.8 km west to east × 47.8 km north to south). Then, the geotechnical layer information for the study area was extracted from that for the extended area using the GIS area-cut function. Figure 3 shows the process for extracting the spatial geotechnical layers for the administrative region of the target study area by removing the inland region from the target area in the rectangular extended area. Distribution of data in DB for the extended area of Busan is also shown in the subset of Figure 3.

In this paper, the vertical scales in three-dimensional figures were exaggerated five times, and surface coverage data such as administrative borders, waterways, and buildings were overlaid on the ground surface for better visual depiction of surface and subsurface features. The spatial information was built in the unit of meters on the Transverse Mercator (TM) coordinate system, on which X and Y represent the directions from west to east and south to north, respectively, and Z is the elevation.

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 a plane (Kim et al. 2002; Kolat et al. 2006). The thickness of geotechnical layers and the depth to bedrock are expressed as zoning contour maps and can be overlain with spatial topographic surfaces of the study area to better reflect reality. Figure 4 presents a spatial zoning map showing the distribution of bedrock depth (with a maximum value of about 80 m in the study area), computed in the geotechnical analysis component of the geo-knowledge based GIS.

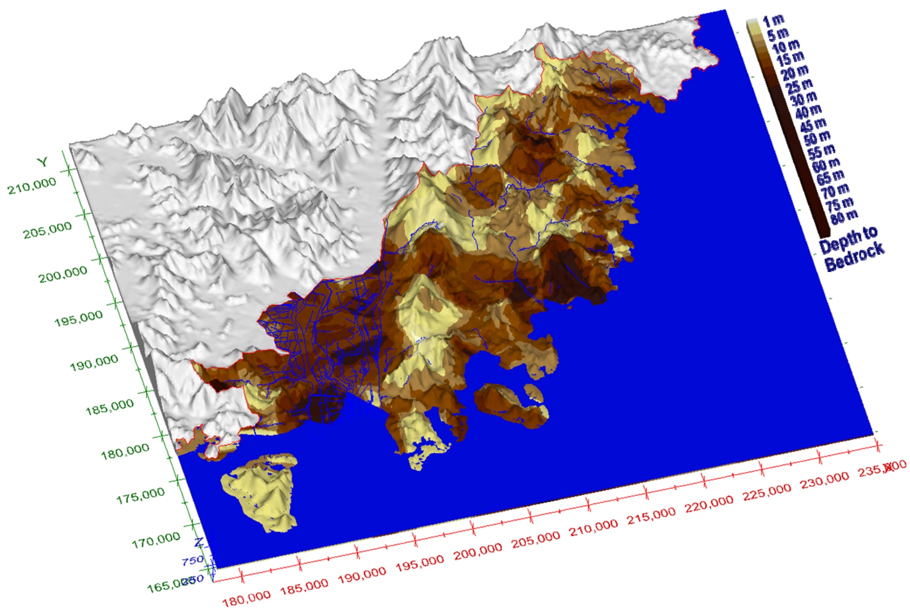

Figure 4. Spatial distribution of depth to bedrock in Busan.

Estimation of Site Effects within the Spatial GIS

Local site effects play an important role in seismic damage to structures. Empirical relationships or simple site classification schemes have been used to evaluate site-specific seismic responses at a regional scale for convenience and effectiveness (Kim et al. 2002; Sun and Chung 2008). In this study, the sole parameter of the site period (T_G) was used to estimate the site effects for the entire administrative area of Busan. The resulting site effects shown by the GIS are presented on zoning maps identifying locations or zones of varying seismic hazard potential.

The T_G was computed using both the thickness and V_S of soil layers over the bedrock. The thickness of soil layers had already been estimated across the study area within the geo-knowledge based GIS. However, V_S had not been determined for the Busan area owing to insufficient seismic testing. Thus, representative V_S values for geotechnical layers in Busan were determined by compiling and averaging the results of previous in-situ seismic tests that obtained V_S profiles at a number of sites in South Korean (Sun 2004; Sun et al. 2005). On the basis of such prior seismic testing results, representative V_S values were determined to be 350 m/s for fill, 330 m/s for alluvial soil, 450 m/s for weathered residual soil, 550 m/s for weathered rock, and 1,000 m/s for bedrock (Sun and Chung 2008). However, to reduce the uncertainty of T_G estimation for

Busan, systematic seismic site characterization is required by performing in-situ seismic tests at various sites in and near the study area.

For efficient zonation based on T_G over the study area, the geotechnical thickness data interpolated by spatial analysis in the GIS and the representative V_S values were imported into the geotechnical analysis component of the GIS. Then, T_G was calculated at 100 m intervals based on Eq. 1. The calculated T_G values were spatially modeled, resulting in the seismic zoning map presented in Figure 5. Generally, T_G was longer in the western deltaic plains and parts of eastern coastal slopes than for mountainous and hilly areas, ranging mainly between about 0.5 and 1.0 s in the Busan area. The spatial distribution of T_G is particularly consistent with the distribution of bedrock depth depicted in Figure 4. In Figure 5, the spatial data on main building coverage are overlain on the T_G distribution to examine the seismic vulnerability of buildings. These spatial 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. The natural period of a building is generally accepted to be 0.1 times its number of stories (Sun et al. 2008). Particularly, in western deltaic areas of Busan, buildings higher than five stories would be vulnerable to seismic damage caused by earthquake resonance. Zoning information based on T_G can contribute to earthquake-related strategies and also to rational land use, city planning, and development in the study area.

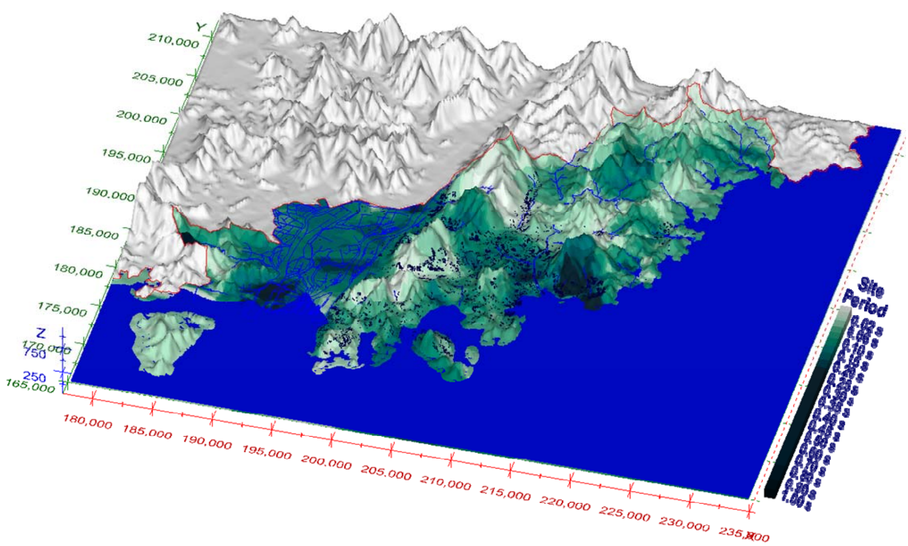

Figure 5. Spatial seismic zonation of T_G indicating seismic hazard potential in Busan.

In addition to prediction of earthquake-induced hazards, seismic design and seismic performance evaluation can also be conducted using the seismic zoning map based on T_G by using a site classification system according to T_G. In this study, the site classification scheme for Korea (Table 1) was adopted to demonstrate site classification based on the T_G zoning map. Figure 6 presents a spatial zoning map of site classes in the Busan area, created within the geo-knowledge based spatial GIS. The short- and mid-period site coefficients (F_a and F_v) according to T_G for the seismic design of structures, described in the site classification system of Table 1, are presented in the legend of Figure 6. As shown in Figure 6, the western deltaic plains and several coastal slope zones in Busan fall within site classes D (D1 to D4) and E, representing site conditions of significant ground motion amplification. These areas also correspond to seismically vulnerable areas identified by T_G, as indicated in Figure 5. On the other hand, most mountainous and hilly areas in Busan fall into site class B, having a value of 1.0 for both F_a and F_v, or site classes C1 and C2, with slightly amplified ground motion. This spatial zonation map of site classes can provide information for preliminary seismic design before practical seismic design of structures or buildings at a site. As shown in Figure 6, the site class for seismic design and seismic performance evaluation can be determined solely and unambiguously by one parameter, T_G. Thus, if the spatial variations of T_G 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 spatial seismic zonation.

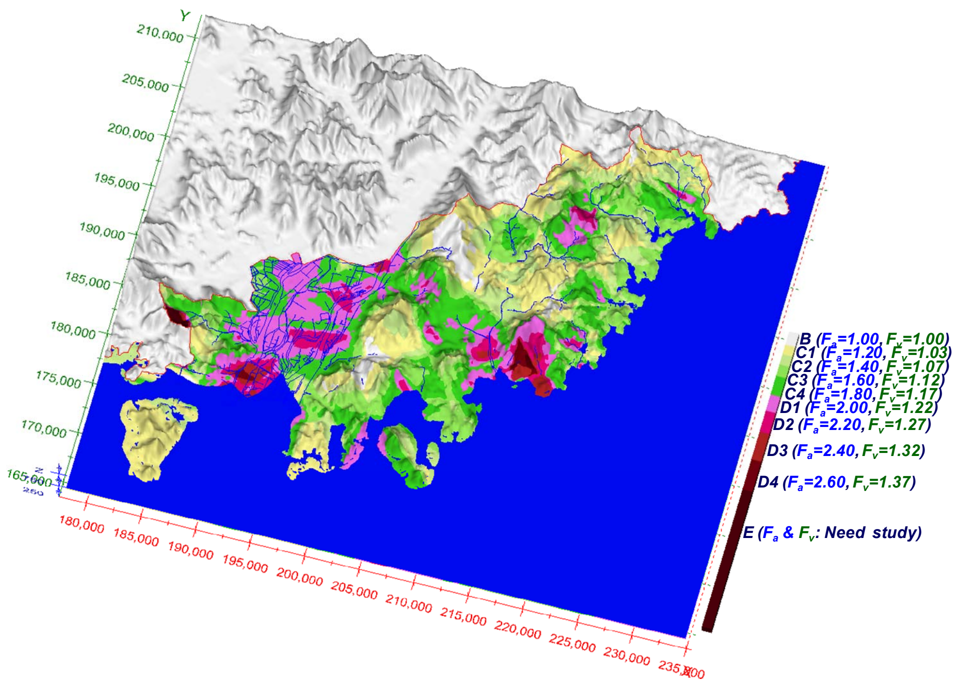

Figure 6. Spatial distribution of site classes based on T_G for seismic design in Busan.

Conclusions

On the basis of a geo-knowledge database for Busan, a representative coastal metropolis, in South Korea, a spatial GIS was implemented for geotechnical site characterization across the entire area of interest in terms of geotechnical layers. In addition, a distribution map of bedrock depth was established for practical use. To predict earthquake-induced hazard potential associated with site effects and provide information for preliminary seismic design in the entire administrative region of Busan, the distribution of T_G was efficiently created in the form of zonation maps within the geo-knowledge based GIS. The T_G map suggests seismic vulnerability in parts of Busan, particularly for buildings higher than five stories in the western deltaic plains. Based on the T_G distribution, a seismic zoning map for site classification was also created to determine the site coefficients F_a and F_v for preliminary seismic design according to the previously established site classification system for Korea. This site classification map shows that the deltaic plains and some coastal slopes in Busan fall within site classes D and E, in which earthquake ground motions become amplified. This seismic zonation case study verifies the usefulness of the geo-knowledge based GIS as a regional seismic countermeasure.

Acknowledgments

The authors wish to express their deepest gratitude for the support from the Basic Research Project of the Korea Institute of Geoscience and Mineral Resources (KIGAM) funded by the Ministry of Knowledge Economy of Korea.

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