SYSTEMATIC PREDICTION OF EARTHQUAKE-INDUCED HAZARDS FOR AN URBAN AREA BASED ON SPATIAL GIS FRAMEWORK

Chang-Guk Sun[1], Jin-Soo Shin[2], Heon-Cheol Chi[3]

Earthquake Research Center, Korea Institute of Geoscience and Mineral Resources, South Korea

Keywords

GIS, earthquake-induced hazard, seismic zonation, site effects, site period

Abstract

Most of earthquake-induced geotechnical hazards have been caused by the site effects relating to the amplification of ground motion, which are strongly influenced by the local geologic conditions such as soil thickness or bedrock depth and soil stiffness. In this study, an integrated GIS-based information system for geotechnical data, called geotechnical information system (GTIS), was constructed to establish a regional counterplan against earthquake-induced hazards at an urban area, Daejeon, which is represented as a hub of research and development in Korea. Particularly, in order to predict reliably spatial geotechnical information, a procedural methodology for building GTIS within GIS framework was developed by devising new concepts of an extended area including entire study area and geo-knowledge. To build the GTIS for the area of interesting, pre-existing geotechnical data collections were performed across the extended area and a walk-over site survey was additionally carried out to acquire surface geo-knowledge data in accordance with the procedure developed to build the GTIS. For practical application of the GTIS used to estimate the site effects at the area of interesting, seismic microzoning map of the characteristic site period was created and presented as regional synthetic strategy for earthquake-induced hazards prediction. In addition, seismic zonation of site classification according to the spatial distribution of the site period was also performed to determine the site amplification coefficients for seismic design and seismic performance evaluation at any site in the area of interesting. Based on the case study on seismic zonations at Daejeon, it was verified that the GIS-based GTIS was very useful for the regional prediction of seismic hazards and also the decision support for seismic hazard mitigation.

Introduction

The local geologic and soil conditions have a profound influence on the amplification of earthquake ground motions. 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 mitigation (Dobry et al., 1999). Moreover, the local site effects related with geologic conditions have been frequently observed in recent

[1] 92 Gwahangno, Yuseong-gu, Daejeon 305-350, South Korea
T: +82 42 868 3176, E: pungsun@kigam.re.kr
[2] T: +82 42 868 3266, E: jinsoo@kigam.re.kr
[3] T: +82 42 868 3343, E: chi@kigam.re.kr

earthquake events such as the 1967 Caracas, 1985 Mexico City, 1989 Loma Prieta, 1994 Northridge, 1995 Kobe, and 1999 Chi-Chi earthquake (Sun et al., 2005). These earthquake events revealed that seismic damages were concentrated at areas which were composed of sediments rather than firm rock. This finding indicates that site effects are associated mainly with the spatial distribution and dynamic properties of the soils overlying a rock bed.

Geographic information system (GIS) in recent years has emerged to be a powerful computer-based technique, with the integrated capabilities of spatial analysis, database management and graphic visualization. For geotechnical purposes, the GIS-based information systems have been developed and utilized to forecast and reduce natural hazards such as landslides or earthquakes. Particularly, in geotechnical earthquake engineering, there have been several researches on GIS technology (Kiremidjian, 1997; Anastasiadis et al., 2001). And this technology will be widely used in increasing number of seismic zonations for the prediction and mitigation of earthquake-induced hazards.

In this study, for the presentation and reliable estimation of the geotechnical sub-layers and dynamic properties information over the selected Daejeon area, which is represented as a hub of research and development in Korea, Geotechnical Information System (GTIS) was built within three-dimensional GIS framework. The constructed GTIS was applied to geotechnical earthquake engineering related problems, particularly, to those dealing with site-specific amplification potentials that depend on the local site effects over the study area.

Site effects

Site effects are basically associated with the phenomenon of seismic waves traveling 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 (Rodriguez-Marek et al., 2000). The period of vibration corresponding to the fundamental frequency is called the characteristic (or predominant) 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 shear wave velocity 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. Thus, if the spatial variations in the thickness and V_S values of soil layers are known for an entire study area, the spatial variation of the T_G can be readily established and used for regional earthquake hazard estimations.

For seismic design in accordance with site conditions, correlations between mean V_S of the upper 30 m (V_S30) and site coefficients (or amplification factors) in specific earthquakes, including the 1989 Loma Prieta earthquake, were established based on empirical and numerical studies (Sun et al., 2005). Accordingly, in the current seismic codes, the site characterization for a site class is based only on the top 30 m of the ground. Recently, in order to use the T_G particularly for seismic design in Korea, Sun (2004) proposed a new site classification system based on the T_G instead of the current classification criterion, V_S30. In most recent site classification scheme for seismic design, the local site effects are quantified by short-period (0.1 to 0.5 s) and mid-period (0.4 to 2.0 s) site coefficients, F_a and F_v, according to the site classes. Table 1 illustrates the site classification system according to the T_G especially for the inland region in Korea developed by Sun (2004). This site classification scheme (Table 1) can be used by engineers to conduct the seismic design as well as the seismic performance evaluation at a site.

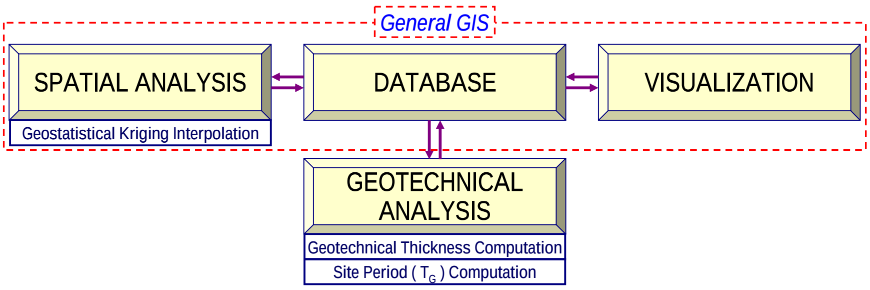
Table 1. Site classes and corresponding site coefficients based on site period (Sun, 2004).

Generic Description	Site Class		Criteria	Site Coefficients	
			Site period, T_G (s)	F_a (for short-period)	F_v (for mid-period)
Rock	B		< 0.06	1.00	1.00
Weathered Rock and Very Stiff Soil	C	C1	< 0.10	1.20	1.03
		C2	< 0.14	1.40	1.07
Intermediate Stiff Soil		C3	< 0.19	1.60	1.12
		C4	< 0.27	1.80	1.17
Deep Stiff Soil	D	D1	< 0.34	2.00	1.22
		D2	< 0.43	2.20	1.27
		D3	< 0.55	2.40	1.32
		D4	< 0.68	2.60	1.37

Construction of the GTIS based on GIS framework

To efficiently manage and use spatial geotechnical information for the ground surface and subsurface, geotechnical information systems 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 (Oliver and Webster, 1990). In this study, a procedure for building a GTIS is proposed and then a GTIS is constructed for the Daejeon area of Korea. As presented in Figure 1, the developed GTIS has four functional components: database, spatial analysis, geotechnical analysis, and visualization components. Arrows in the figure indicate the direction of data flows.

Figure 1. Architecture of the GTIS based on GIS.



The database component contains information on the geotechnical sub-layers and 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 computation was performed in the geotechnical analysis component. The geotechnical analysis component contains computation modules on the thickness of geotechnical layers and site period (T_G). Particularly, the T_G 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 (Gangopadhyay et al., 1999). In this study, GTIS was developed based on GIS tools, in combination with various specified expert techniques.

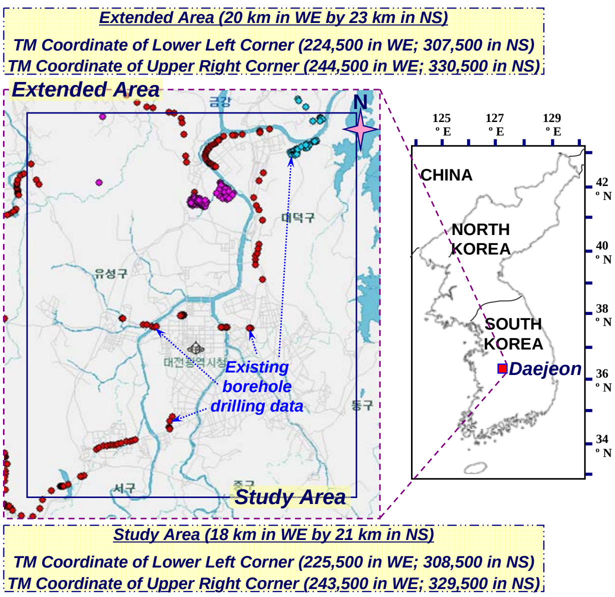
In developing the GTIS, we applied new concepts, such as the use of an extended area encompassing the main study site and the use of geo-knowledge to acquire additional surface geotechnical data. Table 2 shows the procedure developed to build the GTIS. Geo-knowledge refers to information spanning the fields of geotechnical engineering, geology, and geomorphology and was acquired from topographic maps, remote sensing images, and surface geologies (mainly using geological maps). We also conducted a field observation study to acquire data related to the ground surface. These observation sites were referenced by spatial coordinates determined by a Global Positioning System (GPS). Because interpolation was expected to produce more reliable spatial predictions than extrapolation, we applied the kriging technique to the extended area (20 km in WE × 23 km in NS) encompassing the study area (18 km in WE × 21 km in NS). Geotechnical information for the study area was then extracted from that of the extended area using a GIS tool.

Table 2. Procedure for reliably estimating spatial geotechnical information within GTIS.

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 extended area
3rd	Determine local landform characteristics based on terrain analysis
4th	Zone the extended area with the geologic and geomorphic characteristics
5th	Collect the existing site investigation data including borehole data for the extended area
6th	Visit the extended area to collect additional nearby surface geo-knowledge data in field
7th	Build a database based on site investigations data and surface geo-knowledge data
8th	Interpolate geotechnical information for the extended area
9th	Extract geotechnical spatial information for the study area from the extended area

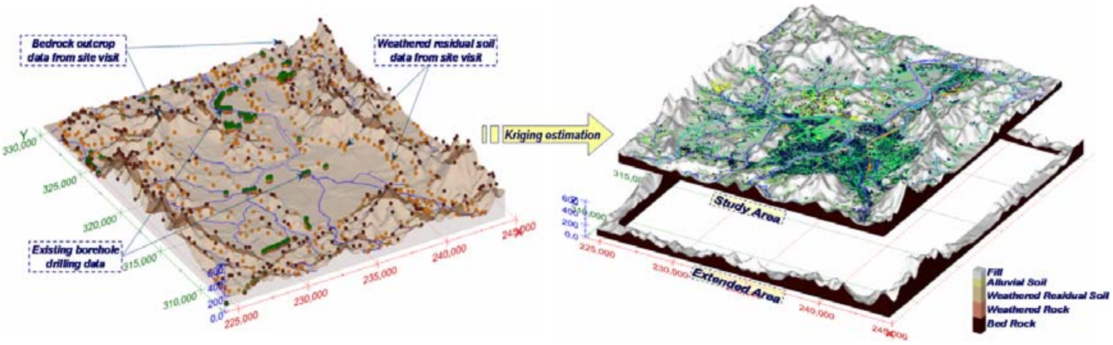
The GTIS was constructed for a typical inland basin area, Deajeon, and applied to assess site characteristics, specifically the thicknesses of geotechnical layers or depth to bedrock. Deajeon is one of the largest metropolitan areas in Korea and particularly a hub of technical research and development in Korea. To build a GTIS for the Deajeon area, we collected existing borehole data and additionally acquired surface geo-knowledge data from a walk-over site visit across the extended area including the study area. Subsurface geotechnical layers from the borehole data and surface geotechnical materials from the site visits were classified into five categories: fill, alluvial soil, weathered residual soil, weathered rock, and bedrock (Sun, 2004). Figure 2 shows the geographic information of Deajeon and corresponding selected areas (extended area and study area). Locations of existing borehole data complied for this study are also presented in Figure 2. The utilization of only existing borehole data is inadequate to cover the study area because of the biased distribution of the data. Accordingly, site visits for data observation and acquisition are conducted mostly in areas where borehole data were lacking.

Figure 2. Geographic information of selected areas and existing borehole data for Deajeon.



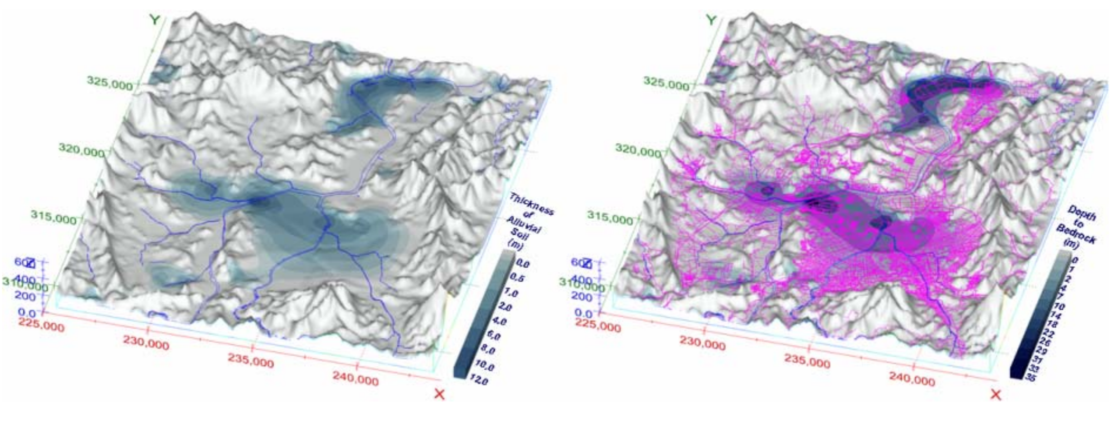
For site characterization at the entire study area, the variations of geotechnical layers over the extended area were estimated based on the collected existing borehole data as well as on the geo-knowledge data obtained from site visit within the GTIS. To estimate the spatial geotechnical layers across the extended area, we used both of 187 existing borehole data and 930 surface geo-knowledge data composed of 378 bedrock outcrop data and 552 surface weathered residual soil data. Based on these results, the spatial information for the smaller study area was extracted using the GIS shape-cut technique. Figure 3 shows the spatial distribution of existing borehole data and surface geo-knowledge data (bedrock outcrop and weathered residual soil data) in the extended area of Deajeon. Also, the geotechnical layers predicted by adopting the kriging estimation are also presented in Figure 3. In this paper, the vertical scales in three-dimensional figures were exaggerated five times and surface coverage data such as waterways, buildings and 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 TM (Transverse Mercator) coordinate system. Particularly the right figure shows geotechnical layers for the study area, extracted from the extended area.

Figure 3. Spatial geotechnical layers predicted based on both existing borehole data and geo-knowledge data in Deajeon.



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. 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. Figure 4 presents representatively two spatial zoning maps showing the distribution of the thickness of alluvial soil (left figure) and the depth to bedrock (right figure) in the study area, which were computed in the geotechnical analysis component of the GTIS.

Figure 4. Distribution of the thickness of alluvial soil and the depth to bedrock in Daejeon.



In particular, the depth to bedrock is one of the most important geotechnical parameters. The rocks beneath or harder than weathered rock are commonly designated as bedrock; the V_S

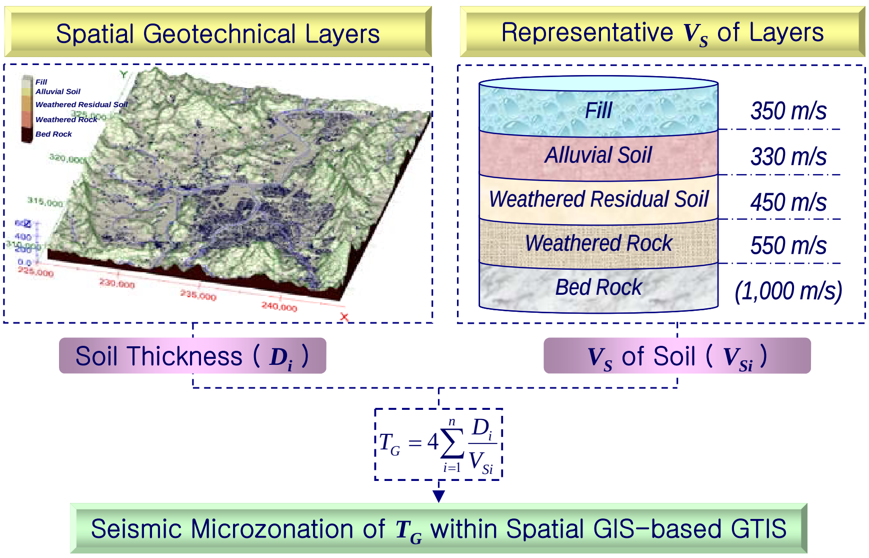
values (V_S > 750 m/s) of these rocks in the study area fall within the category of engineering rock (Sun et al., 2005). In the evaluation of the seismic ground amplification and corresponding seismic hazards, the depth to bedrock is particularly important (Olsen, 2000). On central and northern plains including rivers and creeks, the thickness of alluvial soil is thicker and the depth to bedrock is deeper than that in surrounding mountain areas. Soil development in the central and northern plain zones in the basin occurs mainly by fluvial landform processes. Such zones of thick soil or deep depth to bedrock are susceptible to ground motion amplification due to site effects during earthquakes.

Seismic zonation of site period for predicting earthquake-induced hazards

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 (Kiremidjian, 1997). In this study, among the various quantified parameters of seismic responses, sole parameter of the site period (T_G) was used to estimate the site effects for the entire study area. The resulting site effects shown by the GTIS are presented on zoning maps identifying locations or zones of varying seismic hazard potential. The scale of seismic zonation for Deajeon area in this study is the micro scale (called microzonation), which is the most detailed among three scale levels: general, macro and micro scale (ISSMGE, 1999).

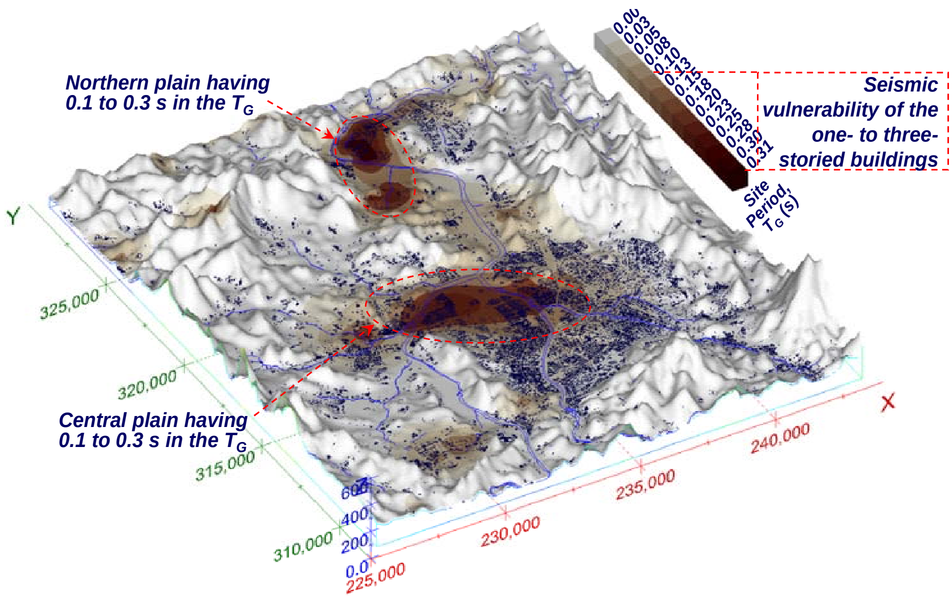
The T_G is computed using both the thickness and shear wave velocity (V_S) of soil layers over the bedrock. The thickness of soil layers were already estimated across the study area within the spatial GTIS. On the other hand, the V_S was not determined for the Deajeon area. Thus, the representative V_S values of geotechnical layers for Deajeon were determined by compiling the results of the previous in-situ seismic tests for obtaining V_S profiles in the Korean land areas (Sun, 2004; Sun et al., 2005). Figure 5 describes the conceptual flow for building the seismic microzoning map on the T_G within the GTIS. As indicated in Figure 5, the V_S was determined representatively 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, from the prior seismic testing results in Korea.

Figure 5. Conceptual flow for seismic microzonation on the site period (T_G).



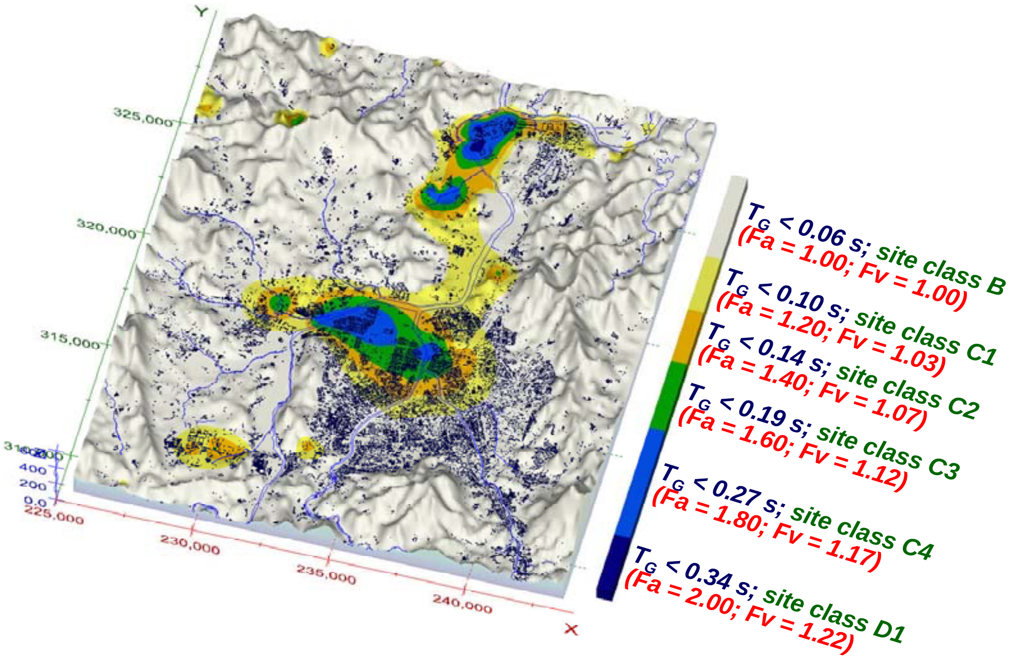
For efficient microzonation based on the T_G over the study area, the geotechnical thickness data interpolated in the spatial analysis of the GTIS and the representative V_S values determined from the prior researches were imported into the geotechnical analysis component of the GTIS. Then, the T_G was calculated at 20 m intervals based on Equation (1). The calculated T_G's were spatially modeled, resulting in the seismic microzoning map presented in Figure 6. The T_G's for central and northern plains with many buildings were generally longer than those for mountainous and hilly areas, ranging mainly between about 0.1 and 0.3 s in the Daejeon area. The spatial distribution of T_G is particularly consistent with the distribution of bedrock depth depicted in Figure 4. In Figure 6, the spatial building coverage data are overlain on the T_G 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. The natural period of a building is generally accepted to be 0.1 times its number of stories (Kramer, 1996). The buildings lower than three or four stories would therefore be vulnerable to seismic damage caused by earthquake resonance. Microzoning information based on the T_G can contribute to earthquake-related strategies and also to rational land use and city planning or development in the entire study area.

Figure 6. Spatial distribution of site period (T_G) and buildings in Deajeon.



Besides the prediction of earthquake-induced hazards, seismic design and seismic performance evaluation in the area of interesting can be carried out based on the seismic microzoning map of the T_G, by adopting the site classification system according to the T_G. In this study, the site classification scheme for the inland region in Korea developed by Sun (2004) (see Table 1) was adopted to demonstrate the spatial seismic microzonation on site classification based on the T_G zoning map. Figure 7 is the spatial microzoning map on seismic site classification in the study area, Daejeon, built within the GTIS. The building coverage overlain on ground surface was also presented in Figure 7. The short- and mid-period site coefficients (F_a and F_v) according to the T_G for the seismic design of structures, which are illustrated in the site classification system of Table 1, are presented as the legend in Figure 7. As shown in Figure 7, the plain areas in Daejeon fall within site classes C (C1 to C4) and D (D1), which represent the site conditions amplifying earthquake ground motions, and match with the seismic vulnerable areas based on the T_G indicated in Figure 6. On the other hand, most of mountainous and hilly areas in Daejeon fall into site class B having 1.0 in both short- and mid-period site coefficients. This spatial microzonation map on site class provides the information for preliminary seismic design before practical seismic design of the structure or building at a site. Furthermore, the site classification map indicates that the buildings or structures located on the central and northern plains may need evaluating their seismic performances. As described from Figure 6 to Figure 7, 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 the GTIS.

Figure 7. Spatial distribution of site classes and corresponding site coefficients for seismic design in Daejeon.



The spatial seismic microzonation maps on T_G produced by the GTIS can be used to predict earthquake hazards. Also, the spatial site classification map based on the T_G can be applied in both preliminary seismic design and seismic performance evaluation of structure at any site in the entire study area. The GTIS developed in this study successfully revealed the seismic microzonation for estimating systematically the local site effects in an inland urban area of Korea. The fundamental seismic information provided should prove useful to earthquake engineers, regional agencies, and insurance companies. The microzoning map with site classes, which provide short- and mid-period site coefficients referenced by spatial coordinates across the entire study area, can also be used to develop earthquake preparedness plans and strategies for the Daejeon area.

Conclusions

In this paper, a methodology was proposed and used in GTIS to manage a variety of geotechnical data and to reliably estimate spatial geotechnical information based on both existing borehole drilling data and additionally acquired surface geo-knowledge data. The developed GTIS was applied in the geotechnical site characterization to assess local site effects and corresponding earthquake-induced hazards for the Daejeon area, which is a hub of technical research and development and a typical inland urban area of Korea.

A GIS-based tool, the GTIS, was developed based on new concepts of an extended area and geo-knowledge and combined with established procedure. The spatial geotechnical layers were reliably predicted over the 18 km in WE × 21 km in NS area, Daejeon study area, using a 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 central and northern plain zones in the study area are potentially susceptible to seismic amplification.

To apply to the seismic hazard prediction associated with the site effects and preliminary seismic design in the entire study area, distribution of the site period (T_G) was efficiently created in the form of microzonation maps based on the spatial geotechnical layers estimated within the GTIS and shear wave velocity (V_S) determined representatively from the prior researches. The T_G map suggests that one- to three-storied buildings in Daejeon are vulnerable to seismic activity. Based on the T_G in Daejeon area, seismic microzoning map for site classification was also created to determine the short- and mid-period site coefficients for preliminary seismic design according to the previous site classification system for the Korean inland region. This site classification map shows that the central and northern plains in Daejeon fall within site classes C and D amplifying earthquake ground motion and that the structures or buildings on the central and northern plains may need their seismic performance evaluation. This seismic zonation case study using GIS technology verifies the usefulness of the GTIS as a regional systematic tool for use in seismic hazards planning.

References

Anastasiadis, A., Raptakis, D., and Pitilakis K. (2001). Thessaloniki's detailed microzoning: subsurface structure as basis for site response analysis. *Pure and Applied Geophysics*, Vol. 158, pp. 2597-2633.

Dobry, R., Ramos, R., and Power, M.S. (1999). *Site factors and site categories in seismic codes*. Technical Report MCEER-99-0010.

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

ISSMGE (1999). *Manual for zonation on seismic geotechnical hazards (revised version)*. TC4, International Society for Soil Mechanics and Geotechnical Engineering.

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

Oliver, M.A., and Webster, R. (1990). Kriging: a method of interpolation for geographical information systems. *International Journal of Geographic Information Systems*, Vol. 4, No. 3, pp. 313-332.

Olsen, K.B. (2000). Site amplification in the Los Angeles basin from three-dimensional modeling of ground motion. *Bulletin of the Seismological Society of America*, Vol. 90, No. 6B, pp. 77-94.

Rodriguez-Marek, A., Bray, J.D., and Abrahamson, N. (2000). A geotechnical seismic site response evaluation procedure. *Proceedings of the 12th World Conference on Earthquake Engineering*, Oakland, New Zealand, CD-ROM, Paper No. 1590.

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

Acknowledgements

This work was supported by the Basic Research Project of the Korea Institute of Geoscience and Mineral Resources (KIGAM).

Author Biographies

Chang-Guk Sun holds a PhD in Geotechnical and Earthquake Engineering. He is working as researcher on developing synthetic strategies for earthquake-induced hazards prediction and reduction in Earthquake Research Center at Korea Institute of Geoscience and Mineral Resources (KIGAM). Particularly, he has various experiences in the design of GIS-based expert system for seismic hazard assessment, the seismic design and seismic performance evaluation of geotechnical structures, and the development and application of geotechnical site investigation technologies.

Jin-Soo Shin holds a PhD in Seismology and is researcher at Korea Institute of Geoscience and Mineral Resources (KIGIM). He has experience in the field of earthquake hazard evaluation. As a researcher, the carries out several projects related on estimation of earthquake risk. From 2006 he has been director of Earthquake Research Center at KIGAM.

Heon-Cheol Chi holds a PhD in Geophysics and is working as researcher in Earthquake Researcher at Korea Institute of Geoscience and Mineral Resources (KIGAM). He has experience in the field of seismic hazard analysis and seismic counterplan establishment.