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Site-Specific Zonation of Seismic Site Effects by Optimization of the Expert GIS-Based Geotechnical Information System for Western Coastal Urban Areas in South Korea

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Abstract Earthquake-induced disasters are often more severe over soft soils than over firm soils or rocks owing to the seismic site effects related to the amplification of ground motion. On a regional scale, such differences can be estimated by spatially predicting the subsurface soil thickness over the entire target area. Generally, soil deposits are deeper in coastal or riverside areas than in inland regions. In this study, the seismic site effects in the coastal metropolitan areas of Incheon and Bucheon, South Korea, were assessed to provide information on seismic hazards. Spatial prediction of geotechnical layers was performed for the entire study area within an advanced GIS framework. Approximately 7500 existing borehole records in the Incheon and Bucheon areas were gathered and archived into a GIS database. Surface geotechnical data were acquired from a walk-over survey. Based on the optimized geo-data, spatial zoning maps of site-specific seismic response parameters, based on multiscale geospatial modeling, were created and presented for use in a regional seismic mitigation strategy. Seismic zonation was also performed to determine site coefficients for seismic design over the entire target area and to compare them with each other. We verified that the geotechnical data based spatial zonation would be useful for seismic hazard mitigation.

Keywords Coastal urban areas · Geo-data · Geostatistical spatial zonation · Seismic site effects · Site classification · South Korea

1 Introduction

Frequent earthquakes in recent years, and the subsequent significant human and property damages, have triggered acute awareness not only in countries with strong earthquakes but also in countries with small to medium-level earthquakes, such as South Korea (Green et al. 2011; Lee et al. 2012; Sun et al. 2014; Kim et al. 2018). The temporal and spatial uncertainties of earthquakes have become the basis for establishing basic countermeasures, even in countries that have not recently experienced large-scale earthquakes, including South Korea. Countermeasures against earthquakes may include various approaches such as seismic alerts, recovery, and design (Sun et al. 2010). Among them, seismic design, considered a proactive concept, is an engineering approach that reflects economic feasibility. Seismic design is intended to be applied directly to new facilities, but may include assessing the seismic performance of existing facilities and reinforcing them in general.

Seismic design considers different performance levels from an economic standpoint, according to the importance of the target facility (MPSS 2017), and determines the earthquake ground motions for design by considering the region-specific earthquake occurrence environment or geotechnical characteristics. Currently, in South Korea, the seismic design criteria for major facilities are created and applied by management agencies or related organizations. The guiding concept for most of these criteria was the result of a study related to seismic design that was

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published in 1997 (MOCT 1997). This concept suggests a decision method for ground motion and directly applies the 1997 Uniform Building Code (ICBO 1997), which corresponds to the criteria applied in the United States, except for the seismic hazard map (recently modified to the seismic risk map) that corresponds to the reference motion.

Applying overseas seismic criteria can result in wrong determination of the actual ground motion because regional differences in geotechnical characteristics are not reflected (Kim et al. 2002). Recently, major study results (Lee et al. 2012) have presented differences in the seismic response characteristics owing to differences in regional and geological ground conditions in Korea. In particular, the Uniform Building Code and the subsequent International Building Code (IBC) have been derived from empirical seismic measurements and damage data primarily from the western region of the United States, along with the corresponding numerical analyses (Dobry et al. 2000; ICC 2000, 2006). This US region has deeper bedrock and higher soil stiffness compared to regions in South Korea (Sun et al. 2005). Such geotechnical characteristics are also related to the terrain and geological conditions (Wills et al. 2000; Wald and Allen 2007). In the western region of the United States, major sites are geographically composed of wide plains and have simple geological conditions. In South Korea, hills and mountains are more developed than plains, and structures have been actively constructed by embankment or excavation.

Amplification of ground motion and changes in the surface or underground terrain owing to surface geological conditions are deeply related to region-specific geotechnical characteristics and are considered as additional amplification factors. Such additional amplification phenomena have also been reported in cases of major earthquake damages (Green et al. 2011). Therefore, in the case of seismic response owing to amplifications related to the intrinsic characteristics of regions and sites, the quantitative assessment of the geotechnical characteristics that reflect the environmental characteristics must be prioritized. Considering the geoseismic response data or results as spatial information of the wide target area (Sun 2004; Sun et al. 2008, 2014), efficient information should be derived and produced using advanced geographic information system (GIS) methods (Ge et al. 2010; Hashemi and Alesheikh 2011). This study assessed the quantitative regional seismic response characteristics of the coastal cities of Incheon and Bucheon on the Korean Peninsula, and constructed the geotechnical seismic hazard spatial information. To predict the regional earthquake risk of the target area, the expert GIS-based seismic response information system was optimized with advanced geostatistical modeling and geotechnical analysis. A seismic response spatial information system was separately developed and

utilized to construct systematic geospatial information based on the GIS database for the expanded Incheon and Bucheon areas. Based on the constructed geospatial database, a spatial zoning map for each site-specific seismic response parameter was developed. The spatial heterogeneities of the seismic response parameters, according to the site classification criteria of western coastal areas in South Korea, were compared and analyzed. Subsequently, the optimal site classification information that can be used for conservative seismic response and the determination of seismic design site coefficients was compiled.

2 Optimization of the Expert GIS-Based Geotechnical Information System

To develop reasonable site-specific seismic zonation using noncorrelated and irregularly distributed geospatial data, the geotechnical information system based on GIS is essential. Appropriate spatial modeling and empirical seismic response estimation that considers the spatial uncertainty of geospatial datasets should be conducted prior to the seismic design or performance evaluation of the target area. Thus, the expert GIS-based geotechnical information system was established through the optimization of the GIS-based framework for the geostatistical zonation of site-specific seismic site effects proposed by Sun et al. (2010, 2014) and Sun and Kim (2017). In these studies, however, insufficient borehole records—which are disproportionately distributed in specific areas such as inner cities or river banks—were utilized to construct isotropic spatial grids, without any geo-knowledge-based information for areas with partially insufficient data and outliers. This approach resulted in the uneven zonation of the seismic site classification, with earthquake-engineering-based decisions focusing only on the urban areas.

Moreover, site-specific nonlinear geotechnical dynamic properties (shear wave velocity and shear strain) should be derived and applied for each geo-layer, rather than the representative shear wave velocity, to compute the reliable site response parameters. Not only administrative area-based zonation but also vulnerable building blocks and lot-based zonation should be visualized to identify site-specific seismic fragility depending on the spatial coincidence of the seismic site effect (for example, site period) and seismic performance (for example, natural period). In this study, the optimized framework was composed of five sequential components: construction of geo-data; optimization of the borehole dataset (containing coordinate information, geo-layers, and standard penetration test results); geospatial modeling to construct a multiscale geospatial grid; geotechnical analysis; and zonation of the seismic site classification (Fig. 1).

Fig. 1 Advanced GIS-based framework for the optimum estimation of local site effects

2.1 Construction and Optimization of Geo-Data

The multisource geospatial information such as borehole records, geographic coverage data (digital numerical maps, digital elevation models, and so on), administrative boundaries, and facility data are collected with the same spatial coordinate system. Borehole records are probe information (containing strata information, standard penetration test results, and rock quality information along geo-layer profiles), and provide direct and reliable specific strata boundaries. However, outliers indicate borehole records that appear to be inconsistent with the remainder of the data and can be determined using the cross-validation-based outlier analysis method proposed by Kim et al. (2016). Accordingly, the possible outliers among the collected borehole records are regarded as reexaminable references for the reconstruction of geological strata and should be preferentially replaced by a new borehole. Specifically, unknown geo-layers, where borehole records were not collected, should be supplemented with walk-over site visits to acquire surface geo-knowledge data that consider the geographic coverage data. Thus, the procedures for outlier analysis and geo-knowledge-based site survey were proposed to construct the geo-layer and shear wave velocity (V_s) profiles (Fig. 2). First, the target area was overlaid and divided into a rectangular grid array to develop the geospatial information based on the optimized site-specific borehole and geo-knowledge point records.

Kim et al. (2017) proposed a framework to detect outlier data using statistical analysis, a cross-validation-based method. Borehole records that include the soil depth distribution in regions of central Seoul, South Korea, were assessed to validate the aforementioned methods through a comparison between distribution-based methods and the Moran scatterplot method (Anselin et al. 2006). The results

indicate that outlier methods that consider spatial correlations facilitated obtaining more reliable spatial distributions, and with a quantitative evaluation of local reliability. These outlier methods are closely related to clustering methods. Quantitative methods provide tests to distinguish such spatial outliers from the remaining data in a sub-cluster. Therefore, conventional outlier analysis and spatial interpolation methodologies should be integrated and optimized while considering outlier locations (Yu et al. 2002). The outlier threshold was defined as 10% of the borehole record total according to Kim et al. (2017).

To estimate the cross-validated residuals based on the kriging and variogram model, an experimental semivariogram was computed and a plausible model was fitted. After excluding the measured target values at a given point, the sequential value at each sampling point was estimated using a candidate kriging. The difference between the estimated and measured values at each sampling point was subsequently calculated. For comparison, the root mean square error (RMSE) from the cross-validation result was the square root of the average squared distance of a data point from the fitted line, as calculated with the following equation:

$$\text{RMSE} = \sqrt{\frac{1}{n} \sum_{i=1}^n (\hat{y}_i - y_i)^2}, \quad (1)$$

where y_i and $\hat{y}_i$ are the measured and estimated values of the i th data point, respectively, and n is the total number of data points. As the RMSE approaches zero, the estimation becomes more accurate. The coefficient of variation is the ratio of the RMSE to the mean of the dependent variable (Öztürk and Nasuf 2002). The spatial distribution of the standard deviation of depth to the bedrock was also

Fig. 2 Conceptual procedure for outlier analysis and geo-knowledge-based site survey to construct geo-layer and V_s profiles. *USCS* Unified Soil Classification System; *SPT-N* standard penetration test N -value

constructed based on the four spatial interpolation methods to estimate the spatial grid information residuals ($\hat{y}_i - y_i$).

After excluding the outliers, site visits were conducted to acquire surface geo-knowledge information, primarily in areas where borehole data were lacking. The surface geo-knowledge information (representatively, bedrock outcrop data) were determined by a geotechnical ground survey (using a simple cone test, GPS, and so on) with grid-type locations and by cross-checking with the geotechnical layers from the neighboring borehole data based on geotechnical engineering judgments. Consequently, the geo-layer strata identified from borehole and site visits were classified into five categories: fill, alluvial soil, weathered soil, weathered rock, and bedrock. For the borehole records, the detailed multi-geotechnical profiles with a depth of 1 m are classified according to the widely used Unified Soil Classification System (USCS) to

correlate nonlinear geotechnical dynamic characteristics, such as the standard penetration test (SPT) N -value with each geo-layer. The shear wave velocity with each geo-layer (USCS-based strata), which is used to predict the seismic response parameters, is computed based on an empirical correlation ($V_s = 65.64N^{0.407}$) (Sun et al. 2014). Thus, the average value of V_s is determined for the geo-layer strata.

Regarding representative geotechnical dynamic characteristics by geo-knowledge-based geo-layer, the quantitative values of V_s have been presented by Sun et al. (2014): 190 m/s for fill, 280 m/s for alluvial soil, 350 m/s for weathered soil, and 650 m/s for weathered rock (Fig. 2). Although the hardness and stiffness of the bedrock significantly increased as the depth increases, the representative shear wave velocity of the bedrock, derived from the

Fig. 3 Conceptual procedure for geostatistical spatial modeling

data in which soft rock and normal rock are dominant, is 1300 m/s.

2.2 Geospatial Modeling

One of the key issues is in applying a method that can continuously and reliably interpolate unknown data distributed in space using the constructed geo-data. Grid-based geotechnical spatial information is constructed according to the proposed sequential geospatial modeling procedures: spatial density estimation, geostatistical interpolation, multiscale spatial grid development, and data extraction (Fig. 3). Constructing geotechnical spatial grid information, which was divided into a multiscale spatial grid of different sizes, depends on the spatial density and correlations; geostatistical modeling was applied based on the Esri ArcGIS platform.

Spatial density estimation is a particularly useful method because it helps to identify precisely the location, spatial extent, and intensity of site-specific geotechnical or geological clustering zones (Borruso 2005, 2008). Accordingly, deviations in spatial interpolation exist depending on the density of the specific cluster in the target area. To identify the spatial pattern of the geo-data with respect to the site effect parameters, the spatial density was evaluated based on kernel density. Kernel density calculates the magnitude per unit area from the point or polyline features using a kernel function to fit a smoothly tapered surface to each point (Borruso and Schoier 2004). Therefore, this

method can compensate for a paucity of data. A general density estimation function is as follows:

$$f(x) = \frac{1}{nh} \sum_{i=1}^n \frac{K(x - x_i)}{h} \quad (2)$$

where x_i is the value of the variable x at location i ; n signifies the total number of locations; h denotes the bandwidth or smoothing parameter; and K represents the kernel function, as presented in an earlier report (Borruso and Schoier 2004). The multiscale spatial grid was sectionalized depending on the kernel density and was utilized as the base kriging grid to extract the interpolated geotechnical information (geo-layer thickness, SPT- N value, and V_s) for each unit spatial grid. The small-scale spatial grid was classified based on the density zone. Additionally, the large-scale spatial grid was categorized for the lower density zone.

In constructing a GIS-based geotechnical information system, the geo-layer thicknesses are first interpolated using the kriging method to predict the spatial layer information for the target area. The geo-layers are arranged in the order below the surface extracted from the digital topographic map, the spatial coordinates of each interface between the layers are provided, and the spatial geo-layer information is visualized. In particular, in target areas where surface and underground terrain changes are severe, or data are insufficient, the method of geostatistical interpolating and predicting the thickness data for each layer is more accurate for the layer thickness prediction on two-

dimensional (2D) coordinates, compared with linear interpolation of layer thickness based on elevation (Chun et al. 2005). After the 2D geo-layers are constructed, the SPT- N , and correlated and representative V_S are interpolated for each unit spatial grid. This is more efficient owing to the absence of an additional conversion process compared to interpolating and predicting altitude data, such as interface, and converting them to layer thicknesses.

Kriging, a representative geostatistical interpolation method, interpolates the geo-data of the target area by quantifying and analyzing the variation characteristics of all the known data within the target area, according to distance, using a variogram. The variogram is a mathematical description of the relationship (or structure) between the variance of pairs of observations (or data points) and the distance separating these observations (h) (Olea 1991). The fitted curve minimizes the variance of the errors. The variogram model is used to define the weights of the kriging function (Webster and Oliver 2001; Sun and Kim 2016) and the semivariance is an autocorrelation statistic defined as:

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} \{Z(x_i) - Z(x_i + h)\}^2 \quad (3)$$

where $\gamma(h)$ is the semivariance for the interval distance class or lag interval h ; $N(h)$ is the total number of sample couples or pairs of observations separated by a distance h ; $Z(x_i)$ is the measured sample value at point i ; $Z(x_i + h)$ is the measured sample value at point $i + h$ (Isaaks and Srivastava 1989).

To obtain reliable geotechnical spatial grid information that considers local site effects, an optimized geostatistical method is needed. Sun and Kim (2017) investigated four representative interpolation methods (inverse distance method, simple kriging, ordinary kriging, and empirical Bayesian kriging) in a cross-validation-based verification test for borehole records in South Korea and found that ordinary kriging had the lowest RMSE, indicating that the technique was the most accurate geostatistical interpolation method among the conventional kriging methods. In this study, ordinary kriging was selected as the geostatistical interpolation method to construct the geotechnical spatial grid information. Thus, the interpolated geo-layer and the correlated geotechnical properties based on ordinary kriging were extracted with a multiscale spatial grid.

2.3 Geotechnical Analysis

Combined with spatial grid information including the geo-layer and V_S values, the seismic site response parameters were derived and suggested for establishing the local strategies for a seismic mitigation plan based on the site-

specific zonation map. This study first examined various geotechnical engineering parameters that can quantify the amplification characteristics of ground motion, which is the site-specific geotechnical response.

Site classification systems use seismic response parameters related to the geotechnical characteristics of the study area as the classification criteria. The current site classification systems in South Korea and the United States suggest V_{S30} , the average V_S up to 30 m underground. This criterion uses only the dynamic characteristics of the site without considering its geometric distribution characteristics (Sun 2009). Conversely, bedrock depth (H), which has also been considered as an empirical indicator, reflects only the geometric characteristics of the site without considering V_S , which is the soil stiffness. Additionally, the site period (T_G) has been recently considered by many researchers (Rodriguez-Marek et al. 2001; Sun 2010), and is presented as a reference indicator that reflects both the geotechnical dynamic and geometric characteristics of the target site. In this study, spatial zonation was performed for each of the three parameters (V_{S30} , H , and T_G) presented as expert-knowledge techniques.

The calculation equations for the site effect parameters can be summarized as follows. First, V_{S30} , which is primarily applied in the current site classification system, can be calculated as:

$$V_{s30} = \frac{30}{\sum_{i=1}^n \frac{d_i}{V_{Si}}} \quad (4)$$

where d_i and V_{Si} represent the thickness and average V_S of the i th layer up to 30 m underground, respectively. In this case, the sum of d_i is 30 m. In addition to the existing V_{S30} , various site response parameters are examined and identified, including T_G , $V_{S,Ds}$ (DS; thickness of soil deposit < 30 m) and $V_{S,soil}$. T_G rises as the bedrock depth ($H = \sum D_i$) increases. Whereas $V_{S,Ds}$ and $V_{S,soil}$ decrease as the bedrock depth increases. T_G is a useful indicator of the period of vibration, during which the most significant amplification is expected. T_G can be calculated as:

$$T_G = 4 \sum_{i=1}^n \frac{d_i}{V_{Si}} \quad (5)$$

To predict the ground motion caused by earthquakes and subsequent seismic hazards, and to generate a more reasonable ground motion in the seismic design and seismic performance assessment process that considers site effects, site (or geotechnical) classification systems are presented in the current seismic design criteria. Such site classification systems can be used as fundamental indicators in early warning and prompt response guidance for minimizing earthquake damages. Therefore, significantly different site effects can be expressed

Table 1 Site classification system with H , V_{S30} , and T_G in South Korea. *Source* Sun (2010)

Generic description	Site class		Criteria			Site coefficients	
			H (m)	V_{S30} (m/s)	T_G (s)	F_a	F_v
Rock	B		< 6	≥ 760	< 0.06	1.00	1.00
Weathered rock and very stiff soil	C	C1	< 10	< 760	< 0.10	1.28	1.04
		C2	< 14	< 620	< 0.14	1.45	1.09
Intermediate stiff soil		C3	< 20	< 520	< 0.20	1.65	1.13
		C4	< 29	< 440	< 0.29	1.90	1.19
Deep stiff soil	D	D1	< 38	< 360	< 0.38	2.08	1.23
		D2	< 46	< 320	< 0.46	2.26	1.29
		D3	< 54	< 280	< 0.54	2.48	1.36
		D4	< 62	< 240	< 0.62	2.86	1.43
Deep soft soil	E		≥ 62	< 180	≥ 0.62	1.50	2.00

depending on regional ground and geological conditions. Previous studies have improved and rationalized the geotechnical classification systems that reflect regional geotechnical characteristics (Rodriguez-Marek et al. 2001; Sun et al. 2005, 2010; Lee et al. 2012). In this study, to secure the practical seismic utilization of the site period, a classification system according to the site period is introduced (Table 1) from the results of the previous studies on the improvement methods of the geotechnical classification system (Sun 2010). It was applied to provide the regional seismic hazard information. As presented in Table 1, site classification can be performed using seismic response parameters, and the short-term site coefficient (F_a) and long-term site coefficient (F_v) can be determined accordingly.

3 GIS-Based Spatial Geotechnical Information System for Predicting Geotechnical Spatial Layers in Western Coastal Areas of South Korea

To support the decision making for reliable determination of the seismic vulnerable zone in macroscale regions, the management program should be developed based on the optimized GIS-based geotechnical information system. Accordingly, the proposed site-specific geostatistical modeling and estimation of seismic site response parameters were conducted by inputting geo-data from western coastal areas in South Korea. The geotechnical spatial grid information was also computed using the multiscale grid-based geospatial modeling to compare this approach with conventional interpolation methods.

3.1 Management Program with Geo-Data

In this study, Incheon and Bucheon, the major areas of interest in terms of earthquake engineering and administrative areas with a complicated polygonal shape, were selected as the study areas. These areas are composed of a wide range of plane areas because they comprise the Incheon and Bucheon administrative areas, including islands. For the processing and extraction of plane area data with arbitrary shape, the conventional masking and interpolation techniques for square or circular plane areas must be significantly improved. After introducing and improving the technique that can process and extract the data of an area with an arbitrarily closed shape, the proposed geospatial modeling method was applied to this study. The databases for the study areas and their surrounding areas were examined and reconstructed considering their earthquake engineering utilization purpose.

The submodules—geo-data input module, geo-layer output module, geospatial modeling module, and computation module for seismic response parameters—are combined with an automated linking procedure for earthquake hazard assessment. Figure 4 shows the primary screen of the management system software for the geotechnical database that was constructed for the study areas. The primary management program has various functions: menu, map view, layer content, visualization tool, and site information. Considering the efficiency of data management, the input of geographic information for the subarea information and attribute information was designed to be performed in the input window that forms the attribute information. The construction of the geotechnical database, by inputting the borehole records and the optimum estimation of local site effects, was automatically conducted using the developed system. Accordingly, the existing borehole drilling data included in the geo-data were

Fig. 4 Management program with geo-data for the study area in South Korea. *DB Database*

obtained from approximately 7500 boreholes, which were optimized by removing the outliers (750 boreholes). Additionally, 920 geo-layer records were acquired by a geo-knowledge-based site survey. Therefore, 7670 geotechnical data records were developed as geo-data information in the target areas.

3.2 Geotechnical Spatial Grid Information in Incheon and Bucheon

Figure 5 shows the study area and coordinates of Incheon (including Yeongjongdo Island, where Incheon International Airport was located) and Bucheon, which are the study areas for constructing a GIS-based seismic response information system. The extended area spans 41 km in the east–west direction and 34 km in the north–south direction. In general, the regional GIS or digital topographic maps for a specific city utilize the transverse Mercator (TM) coordinate system, while the GIS results secure clear visibility through vertical direction exaggeration. Therefore, the results of this study also processed the input and output of the GIS database, based on the TM coordinate system (units: m). In the visually presented geotechnical information system, the water distribution, administrative boundaries, road distribution, and structure distribution were, in some cases, displayed redundantly for relative positioning.

According to the proposed procedures of geo-data optimization and geospatial modeling, the geotechnical spatial grid information of the target area was developed. To validate the interpolation accuracy compared with the conventional kriging method, the spatial distribution of the geo-layer thickness was predicted based on ordinary kriging using only the borehole dataset (Fig. 6). After outliers were removed and the geo-knowledge-based dataset was supplemented, the optimized 7670 borehole dataset was constructed. Ordinary kriging was conducted based on a multiscale spatial grid considering kernel density. Consequently, the standard deviation of ordinary kriging was evaluated from 0.08 to 0.28 m based on the cross-validations and evenly distributed throughout the entire target area, because the target area was sectionalized as a multiscale spatial grid containing the interpolated geo-layer thickness. Otherwise, the standard deviation was approximately 2.02 by applying the conventional kriging method. Accordingly, the proposed geospatial modeling using geo-data produced more reliable geotechnical spatial grid information, which was derived from the multiscale grid with mesh sizes from 20 to 200 m.

In addition to the three-dimensional (3D) spatial layer information, to secure practical utilization and spatial visibility, the zonation information, which is a technique for visually representing the conventional 2D contour maps on the 3D ground surface of the study area, was implemented in the geotechnical spatial information system. Figure 7

Fig. 5 Spatial distribution of the borehole records in the study area of Incheon and Bucheon, South Korea

Fig. 6 The Incheon and Bucheon study areas in South Korea: Spatial comparison of standard deviations according to the conventional method and the proposed optimization method by using a geo-data dataset and multiscale grid-based ordinary kriging: **a** multiscale grid-based fill; **b** multiscale grid-based alluvial soil; **c** multiscale grid-

based weathered soil; **d** multiscale grid-based weathered rock; **e** ordinary kriging-based fill; **f** ordinary kriging-based alluvial soil; **g** ordinary kriging-based weathered soil; **h** ordinary kriging-based weathered rock

presents the spatial zonation information for identifying the thickness distribution of the alluvial soil and weathered layer (weathered soil and rock) as the primary layers among the layers on top of the bedrock. The distribution patterns according to the location and topographical factors of each layer can be confirmed. As shown in Fig. 7, plains with coasts and rivers as well as thick alluvial soil in some

hills are developed in the study area and the maximum thickness is approximately 24 m. Additionally, a weathered layer developed by long-term weathering is found in the target area and has a thickness of up to 32 m. Further, geotechnical spatial grid information of the average V_s for each geo-layer in the Incheon and Bucheon areas were estimated (Fig. 8). Generally, relatively high V_s (over

Fig. 7 The Incheon and Bucheon study areas in South Korea: Geotechnical spatial grid information of geo-layer thickness in the Incheon and Bucheon areas: **a** fill; **b** alluvial soil; **c** weathered soil; **d** weathered rock

450 m/s) are spatially distributed focusing on the inland mountainous areas, where the geo-knowledge-based site survey was primarily conducted. Accordingly, the geo-layer of the coast and riverside downtown was predicted as a layer vulnerable to seismic site effects due to the thick fill and alluvial soil (over 15 m). This geotechnical grid information can provide intuitive information for solving geotechnical engineering problems and making decisions.

4 Spatial Zonation Based on Site-Specific Seismic Response Parameters

The site-specific seismic response (ground motion amplification) assessment for the metropolitan areas of Incheon and Bucheon was performed by applying multistep data processing and expert knowledge to the entire area using the developed geotechnical spatial grid and GIS, rather than measuring or analyzing the local sites (Sun et al. 2008; Sun 2012). The ground motion for seismic design can be determined by performing site classification and subsequently calculating the site coefficients using the site classification system that includes H , V_{S30} , and T_G as classification criteria. Figure 9 presents the site

classification based on H , V_{S30} , and T_G , which were derived by the individual or combined utilization of the spatial geotechnical layer information (geo-layer thickness and V_S for each geo-layer) for Incheon and Bucheon.

The study area has a maximum bedrock depth of approximately 48 m, while a bedrock of over 20 m depth is primarily distributed in the plains near the coast (Fig. 9a). V_{S30} is distributed from approximately 320–500 m/s in the areas including plains near the coast, where residential and industrial facilities are concentrated (Fig. 9b). The site period is distributed from approximately 0.2–0.5 s in most of the plains near the coast (Fig. 9c). Considering earthquake vulnerability based on the structure resonance possibility using the site period distribution information, earthquake vulnerability can be predicted for facilities between two and five floors in plains dense with residential and industrial facilities. This is based on the natural period of 0.1 s according to the building floor (Kim et al. 2002); however, major sites in Incheon and Bucheon show approximately 0.2–0.5 s site periods. Considering that the study area is not only residential but also an industrial and commercial area, it is likely that seismic performance assessment and seismic reinforcement are required for a large number of buildings and structures.

Fig. 8 The Incheon and Bucheon study areas in South Korea: Geotechnical spatial grid information of average V_s for each geo-layer in the Incheon and Bucheon areas: **a** fill; **b** alluvial soil; **c** weathered soil; **d** weathered rock

Generally, resonance in earthquake engineering means the amplification of earthquake response when a natural period of input wave and that of the target system coincide. Although site period is not identical with natural period of a structure, the coincidence between the natural period (or frequency) of the input earthquake wave and the site period double the resonance potential of the facility. The site-specific soil amplification in low-to-moderate seismic regions significantly affect the amplitude, frequency, and duration of earthquake ground shaking, thereby influencing occurrence and degree of damage to buildings and other structures. According to Jones et al. (1996), a strong coincidence existed between the area of maximum damage and the geographical extent of quaternary sediments and landfill during the 1989 Newcastle earthquake (M_L 5.6) in New South Wales, Australia. Although this level of damage was unusual for such a moderate magnitude earthquake, the local site conditions, particularly the soil thickness, contributed to the reduced resilience to ground shaking of high-vulnerability building stock (Chandler et al. 1991; McPherson and Hall 2013; Hout et al. 2017).

Incheon and Bucheon have diverse site classification distribution, in which the amplification of earthquake ground motion is expected in plains near rivers, where

residential and commercial facilities are concentrated and industrial facilities are located. That means, site classifications C (C1–C4) and D (D1–D4), which are vulnerable in terms of geotechnical earthquake engineering, are distributed. Although a considerable area corresponds to site classification C where the magnitude of ground motion is amplified to relatively small values, such site distribution requires more comprehensive and systematic precision zonation of the study area. As shown, the same site can have different site classifications depending on H , V_{S30} , and T_G , which are the geotechnical earthquake engineering parameters.

5 Comparison and Analysis of the Spatial Distribution of Seismic Response Parameters

Sun (2010) showed a linear relationship ($T_G = 0.01 H$) between the bedrock depth and site period in South Korea, where the depth is a hundredfold of the site period. The site-specific seismic response characteristics have regional differences even within the same area, owing to the biased spatial density of the geotechnical data for each target area and the distribution of statistical characteristic values.

Fig. 9 The Incheon and Bucheon study areas in South Korea: Geotechnical spatial grid information of seismic site classes in the Incheon and Bucheon areas: **a** H ; **b** V_{S30} ; **c** T_G

According to the geotechnical classification criteria based on the site period applied in this study, spatial variabilities between major classes (B, C, D, and E) were found in local

areas. Therefore, for site classification at the preliminary level in the study area, the spatial correlations of the maps

Fig. 10 The Incheon and Bucheon study areas in South Korea: Spatial difference between H , V_{S30} , and T_G in the Incheon and Bucheon areas:
a H and V_{S30} ; **b** V_{S30} and T_G ;
c T_G and H

based on site classifications were compared and analyzed to determine the optimal seismic response parameters.

To consider the regional correlation between the site-specific seismic response parameters of Incheon and Bucheon, classification differences between the site

Fig. 11 The Incheon and Bucheon study areas in South Korea: Site class of administrative subunits by computing the average T_G for each unit and the seismic fragility-based zonation in the Incheon and

Bucheon areas: **a** administrative subunit-based zonation; **b** example of fragility-based zonation

seismic response parameters were derived as shown in Fig. 10 based on the spatial zoning information constructed in Fig. 9. The site classification spatial correlation based on H and V_{S30} revealed that Yeongjongdo Island and some coastal plain areas (4%) showed differences of more than two grades, while 44% of areas exhibited a difference of one grade, and 51% of areas were determined as identical site classification (Fig. 10a). For V_{S30} and T_G , more than 21% of the plain region spatial grids showed more than two grade differences in site classification, 68% of the areas exhibited a difference of one grade, and only 16% of the

areas had identical site classifications (Fig. 10b). In Fig. 10c, in regard to the relationship between H and T_G , 44% of the areas were assessed as identical regarding site classification and 55% of the areas showed a difference of one grade. Therefore, the spatial heterogeneity of the site classification, according to the bedrock depth and site period, was assessed to be relatively low. For Incheon and Bucheon, except for some regional deviations, the bedrock depth and site period exhibited a relatively high linear relationship (Sun 2010) and spatial correlation for the site-classification criteria.

6 Representative Seismic Site Classification for Seismic Response Decision Making in Incheon and Bucheon

Site-specific seismic response characteristics can be represented by site period (Kim et al. 2002), and ground motions that reflect the site-specific seismic response characteristics can cause resonance phenomena depending on the natural period of structures (Sun et al. 2005). Therefore, a site-specific seismic response prediction method based on site period enables a rapid seismic response assessment for predicting regional seismic hazards, including seismic vulnerability of structures, without numerical techniques. It can be used directly for seismic design and seismic performance assessment through the designed ground motion decision for each site (Sun 2009). This study performed T_G -based zonation based on the geotechnical information constructed using GIS.

Administrative area-based site classification was performed based on the site period calculated for 165 administrative subunits in Incheon and Bucheon, and the discontinuous spatial zoning information visualized in the 3D space frame is shown in Fig. 11a. The site classification in Fig. 11a is similar to the continuous distribution of site classification (see Fig. 9). Therefore, for providing practical information and securing its applicability for regional rapid seismic response, the average value of the site period of all polygons on the spatial plane for each administrative subunit (*dong*) was calculated for Incheon and Bucheon. Most of the areas were C (C1–C4) class and were evaluated as vulnerable sites in terms of geotechnical earthquake engineering. In particular, as the coastal reclaimed area is evaluated as D2 class, it is highly likely that its ground motion is significantly amplified in a considerable area.

Site-specific classification for vulnerable building blocks and lots in the target area was visualized and extracted, as shown in Fig. 11b. Structure resonance information was obtained from the T_G distribution. With this information, the seismic vulnerability of buildings between two and five floors in plains that are dense with residential and industrial facilities can be predicted. This is based on the natural period of 0.1 s according to the building floor (Kim et al. 2002), but major downtowns in Incheon and Bucheon show approximately 0.2–0.5 s of T_G . Figure 11b shows the extracted seismic site classification for residential buildings, where the spatial coincidence between T_G and the natural period according to the building floor was identified. To predict the site-specific seismic vulnerability, the correlations with T_G , the natural period, and the predominant frequency based on the response spectrum should be assessed and linked with seismic monitoring datasets assuming the target buildings had no

structural defects prior to the earthquakes. Seismic hazard zonation based on the site period and its utilization is suggested in this study as a demonstrative case. It can be applied as a method for providing base information for the purposes of seismic hazard prediction, seismic utilization, and rapid seismic response in major domestic metropolitan cities, where vast geotechnical survey data exist owing to city development.

7 Conclusion

In this study, quantitative regional seismic response characteristics were evaluated, and the site-specific zonation of seismic site effects was visualized based on the optimized 7670 geotechnical records for Incheon and Bucheon—coastal cities in South Korea. The advanced expert GIS-based seismic response information system was optimized for predicting the regional seismic site effects of the study area. Based on the optimized geo-data by removing outliers and utilizing geo-knowledge-based site survey data, a spatial zoning map for each site-specific seismic response parameter was constructed based on a multiscale spatial grid. The spatial zonation on site classification, which can determine the site coefficients for seismic design, was performed for each site-response parameter in the entire study area and compared. Accordingly, the site period-based site classification distribution map, which can be used to determine the conservative seismic design site coefficients, was secured. This study confirmed the possibility of applying the spatial zonation for the geo-data-based site response parameters depending on the administrative area and seismic fragility of buildings to support decision making for seismic hazard reduction in coastal metropolitan cities.

Preliminary site coefficients can be calculated at all sites in the study area and the design ground motion can be determined using only the geotechnical classification information in the present data conditions. Additionally, the constructed regional site period zonation can be used, first, as basic information for urban development decision making, such as in setting a facility plan considering the site effect when a new facility is developed or redeveloped. Second, it can be used as preliminary information for seismic design at any site in the region. In this study, the single-level seismic risk zonation of a large area is limited to the provision of preliminary-level information. Thus, it is reasonable from the reliability point of view to conduct high-precision, site-specific seismic response characteristic zonation for divided plane areas, and to summarize or merge the zonation results for seismic risk prediction zonation of the metropolitan region. Therefore, when many

sites with vulnerable geotechnical characteristics exist, the application of more systematic and quantitative high-precision techniques is essential.

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