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Development and Application of Information System for Landslide Hazard Map during Earthquakes Based on GIS

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ABSTRACT

Ensuring the stability of slopes particularly during an earthquake through analyzing the behavior of such slopes is one of the most important aspects in earthquake preparation. This is, especially important in Korea where there are many mountainous areas. However, there is still a lack of systematic identification of slopes that are susceptible to instability in Korea. Therefore, a systematic approach on factors affecting the slope stability for earthquake and evaluation methods of slope stability taking into account earthquake inducing factors are needed. In this study, an information system of landslide hazard mapping for earthquakes was developed. The developed system built, within the framework of GIS, consists of a database (DB) containing all site information and processed data in the system in the standard data formats, and the system software performing assessment of earthquake-induced landslide hazard based on the database. The system software is functionally divided into an input module, and earthquake-induced landslide assessment module, and a landslide hazard mapping module. The study area is Cheonggye Mountain in Seoul, and landslide hazard map for seismic factor of safety and seismic displacement is constructed by using amplification factors obtained from geometrical characteristics of slope based on the developed system.

Introduction

Seismically triggered landslides are one of the most damaging hazards associated with earthquakes. They can not only cause damage to lives and structures directly, but also cease the operation of the whole social systems by making roads and/or lifelines useless. For these reasons, securing the slope stability for earthquake by analyzing the behavior of slope structure is one of the most important parts in earthquake preparation, especially in Korea where there are many mountainous areas. However, there is still a lack of systematic research on securing the slope stability for earthquake in Korea. In this research, the systematic research on factors affecting the slope stability for earthquake and evaluation method of slope stability considering earthquake induced factors should be needed.

In this study, information system of landslide hazard map during earthquake was developed. The developed system built, within the frame of GIS, consists of a database (DB) containing all site information and processed data in the system in the standard data formats, and the system software performing various functions to manage and utilize the datasets in the database. The

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system software is functionally divided into an input module, an earthquake-induced landslide assessment module, and a hazard mapping module. The study area was Cheonggae Mountain in Korea, and two-dimensional landslide hazard map for dynamic factor of safety and Newmark displacement was constructed by using amplification factors obtained from geometrical characteristics of slope based on the developed system.

Framework for Earthquakes-induced Landslide Hazard Assessment

Methodologies for Landslide Hazard Assessment during Earthquake

To evaluate the site-specific landslide hazard during earthquake for macro-zonation of Korea (over 4km^2 unit area), the digital map contained topography layer are usually utilized as the backbone datasets (Kim HS, 2014). In this study the, the systematic procedure for earthquake-induced landslide hazard assessment using digital map was newly proposed to develop the digital information system (Figure 1).

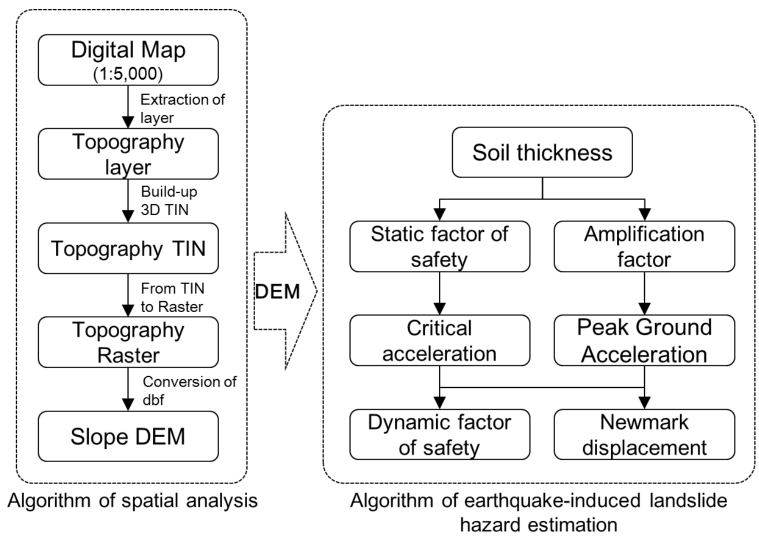


Figure 1. Systematic procedure architecture for landslide hazard assessment during earthquakes

For the processing of spatial analysis based on ArcGIS, digital map (1:5,000 scales) provided by the National Geographic Information Institute of Korea was used. Of the entities within the digital map, only the topography layers (type of polyline) entities were extracted and used. With the elevation layers, triangulated irregular network (TIN) was used for construction of 2D continuous elevation and slope DEM (type of raster). According to the algorithm of TIN, a vector data structure that partitions geographic space into contiguous, non-overlapping triangles was created. The vertices of each triangle are sample data points with x-, y-, and z-values. These sample points are connected by lines to form Delaunay triangles. The TINs are used to store and display surface models of target area. Linked with the DEM obtained from algorithm of spatial analysis, landslide hazard during earthquake can be simply estimated through the dynamic factor of safety and the Newmark displacement derived horizontal amplification factors for flexible slope with inclined bedrock.

To evaluate the seismic stability of a landslide, both the pseudo-static method and the Newmark sliding block method (1965) are most often used simultaneously. In both methods, the target area is assumed to have an infinite slope. To obtain the factor of safety of the slope in a static condition, a relatively simple limit-equilibrium model of an infinite slope in material having both friction and cohesive strength can be used. The factor of safety (FS_{static}) in static conditions is as follows:

$$FS_{static} = \frac{c}{\gamma_t h \sin\alpha} + (1 - \frac{s\,\gamma_\omega}{\gamma_t})\frac{\tan\phi}{\tan\alpha} \quad (1)$$

where c is viscosity, γ_t is total unit weight, γ_ω is unit weight of water, ϕ friction angle, and α is slope angle.

The pseudo-static method for seismic slope stability is based on assumptions of the limit equilibrium and is still the most popular method in geotechnical engineering practice. The pseudo-static analysis provides an index of stability (the factor of safety) but no information concerning deformations associated with slope failure. Because the serviceability of a slope after an earthquake is controlled by deformations, analyses that predict slope displacements provide a more useful indication of the seismic slope stability (Kramer, 1996). Newmark's method (1965) is a landslide model to determine the cumulative displacement of a landslide as a rigid-plastic block that slides on an inclined plane. The block has a known critical (or yield) acceleration a_c, which is simply the threshold base acceleration required to overcome shear resistance and initiate sliding. The analysis calculates the cumulative permanent displacement of the block relative to its base as it is subjected to an earthquake acceleration a(t). The cumulative displacement is calculated by double integrating the area under the accelerogram that exceeds the critical acceleration. However, several simplified approaches for estimating Newmark displacement have been suggested empirically by several researchers because a Newmark analysis is time-consuming, and performing a double integration is notably difficult (Ambraseys and Menu, 1988; Yegian et al., 1991; Jibson, 1993; Cho et al., 2003). In this study, the models of Ambraseys and Menu(1988), Jibson, R.W.(1993), Cho and Kim(2003) are used among several empirical models (Table 1).

Table 1. Empirical formulas for Newmark displacement

	Empirical formula
Ambraseys and Menu(1988)	$\log D_N = 0.9 + log\left[\left(1 - \frac{a_c/g}{a_{max}/g}\right)^{2.53}\left(\frac{a_c/g}{a_{max}/g}\right)^{-1.09}\right]$
Jibson, R.W.(1993)	$\log D_N = 1.460 \log I_a - 6.642 a_c + 1.546$
Cho and Kim(2003)	$\log D_n = 2.49 - 9.95\left(\frac{a_c}{a_{max}}\right) + 16.15\left(\frac{a_c}{a_{max}}\right)^2 - 11.73\left(\frac{a_c}{a_{max}}\right)^3$

D_N = Newmark displacement (cm)
a_c (Critical acceleration, g) = $[(FS - 1)\sin\alpha]g$
I_a = Arias Intensity (m/sec)
α = Slope angle (°)

System program

Based on the design schema described above, the system structure consisting of a database and three modules was established, as shown in Figure 2. The spatial database using GIS platform is the backbone of the developed system. It stores not only primary collected field data such digital map, and topography layer but also secondary processed data obtained from the application of the modules of the system. An input module provides an effective way to store and arrange all collected field data in the DB according to standard data formats. In the earthquake-induced landslide assessment module, spatial analysis algorithm using digital map and landslide hazard estimation algorithm are designed as functional program language for automatically systematic procedure (Figure 1). The hazard mapping module provides visual functions such as 2D plane views, and 3D views together with tabular formats in real-time.

With system software installed in a client PC, connected to the server by network, a user manages and utilizes the information in the DB. The system software focuses on user friendly functions and real-time applications. In particular, field data can be entered into the DB very simply. Once stored in the DB, all data can be utilized without difficulty in each module of the system software.

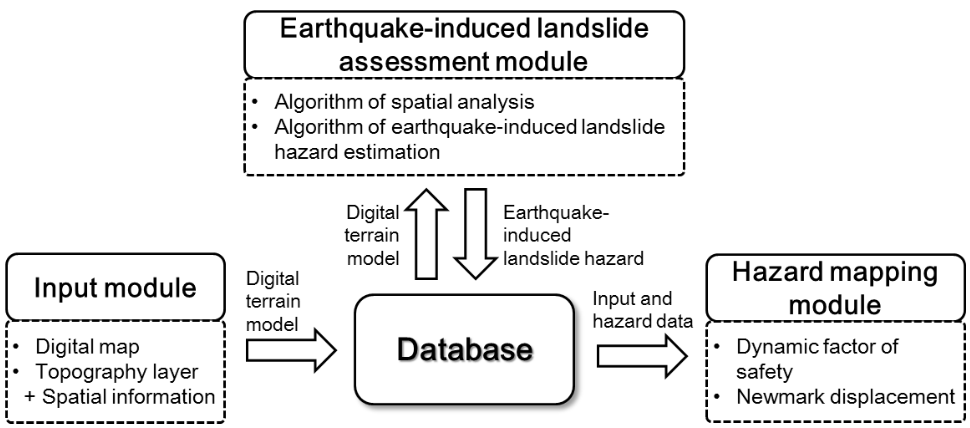


Figure 2. Composition of framework for landslide hazard assessment during earthquakes

Microsoft SQL Server was chose for the GDBMS of the developed system because of the robustness and scalability of its GDBMS. Residing on the DB server, the GDB contains information on all seven classes: three primary collected field data and four processed data. The data was standardized by accompanies by establishing a relation between geographic locations and other attribute information.

DB is the basic data format for GISs to refer to attribute information, and to correlate and analyze various datasets spatially. DB of the developed system was established based on a two-dimensional coordinate system. Sub-areas for a wide target area are generally used in fields to promote the efficiently of site-specific landslide hazard management. Also, a digital map can be used as basic topographical information of the system because it offers an easy way to construct topographical information for a target area. And topography layer (polyline) and digital terrain model (raster) are extracted from digital map to construct the DEM having numerical spatial information.

Earthquake-induced landslide hazard information consists of DEM information contained spatial analysis results and hazard parameters. Spatial analysis results contain the slope DEM, and soil thickness DEM. And the hazard information (dynamic factor of safety, Newmark displacement) are automatically determined and stored in to database with DEM.

Management of input or analysis results data is the fundamental and indispensable function to run the system software based on the DB. Therefore, prior to input of attribute information, landslide hazard information must be input in the DB. Management of data is performed in the independent window form according to the database structure. Based on the management module, sub-modules are combined using management program with automated linking procedure: input module, earthquake-induced landslide assessment module, and hazard mapping module.

The main management program has various functions: menu (①), visualization tool (②), layer content (③), map view (④), set-up window of earthquake scenario (⑤), spatial coordinate content (⑥). From the menu, when users select the menu function, the related sub-modules can be implemented as sharing database. And site information inputted from input modules and landslide hazards estimated proposed assessment framework are visualized on the map view, which display the 2D spatial distribution of the satellite map.

Project information and topographic information of site information are managed in a same window form, because this information generally is used to identify locations of attribute information spatially. Also, digital or satellite map are directly converted into topographic information. Considering the efficiency of data management, input of geographic information for sub-area information and attribute information was designed to be performed in input window forms for attribute information. Geographic information for attribute information is used to display locations of attribute information on topographic map, that is, background map. The window forms for management of geographic information for target site are shown Figure 3.

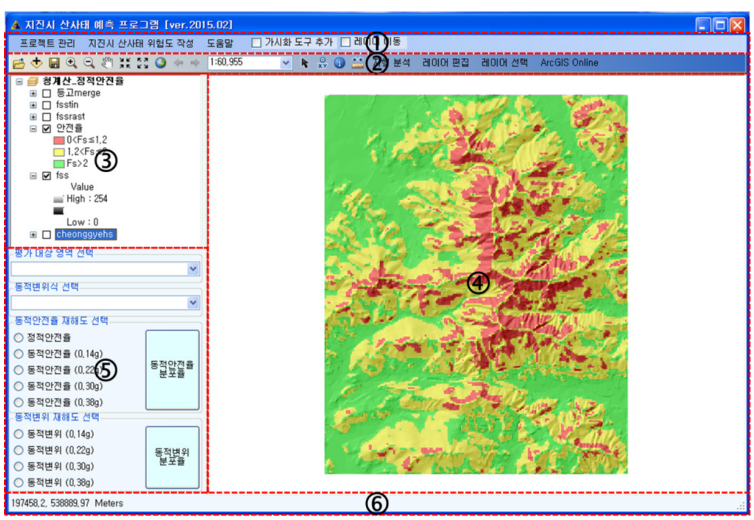


Figure 3. Main management program and detailed function

Even though the earthquake events and earthquake hazards are rapidly occurred at wide region, site-specific earthquake hazard assessment, which is established by considering the amplification factor obtained from geometrical characteristics of slope. And these methods are not simply applied at various site conditions, as providing possible landslide hazard in every instance. Therefore the wizard functions for sequential earthquake-induced landslide hazard assessment are developed in the integrated system. And the wizard functions upon were arranged at left-side of window form (⑤). Users want to see desired information in the DB in user-friendly and functional manner. The output of attribute information, which is provided by graphic user interface (GUI), can be displayed in a tabular form and graphic form. Tabular forms are generally used to input, edit and view information in the DB, and graphic forms provide intuitive views of the spatial relationship between attributive information.

Systematic field application

Simulation Conditions

In this research, to validate the applicability and effectiveness of the integrated earthquake-induced landslide hazard assessment system based on GIS, the systematic field application was performed. Cheonggae Mountain in Korea is selected as the target area, and the GIS technique is used to construct a hazard map. Using the developed system program, a pseudo-static analysis is used to determine the factor of safety, and Newmark sliding block analysis is used to determine the seismic displacement. Figure 4 describes the satellite map for target area.

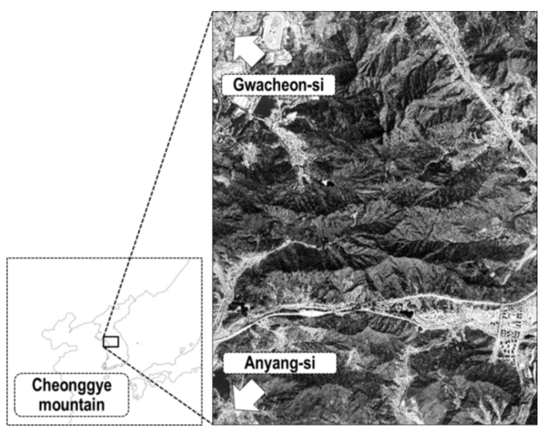


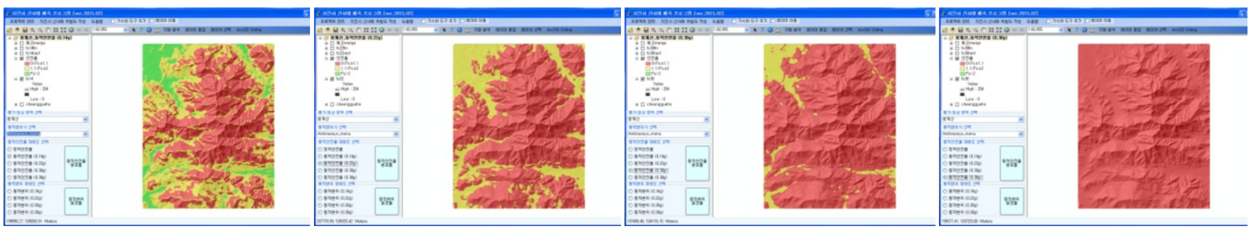
Figure 4. Simulation tests conditions of earthquake scenarios for the Cheonggye Mountain, Korea

To construct a hazard map for a seismic landslide, ArcGIS 10.1, provided by Environmental System Research Institute, Inc. (ESRI), and a 1:5,000 digital map provided by National Geographic Information Institute are used. According to the soil survey of a site, the SPT-N value from a standard penetration test is from 20 to 50. In this study, the soil survey information is assumed to govern our entire target area, and the SPT-N value of 35 is used to construct a hazard map. From the SPT-N value, the internal friction angle of 40° is predicted by empirical correlation between N and friction angle suggested by Meyerhof in 1956.

In this analysis, both c and s are assumed zero, and γ_t is assumed as 18 kN/m^3 in eq (1). Four cases of Peak Ground Acceleration (PGA), 0.14g, 0.22g, 0.30g, and 0.38g, are used in this analysis, and the information of the amplification factor corresponding to the slope is used to evaluate a_c. In addition, the Newmark displacement was calculated using the representative empirical formula proposed by Ambraseys and Menu in 1988.

Landslide hazard map during earthquakes

By using the slope DEM, soil depth, and internal friction angle information, the factors of safety for static and seismic slope stability are obtained. Figure 5 shows the results on the factor of safety under four cases of different PGAs. The severity class of dynamic factor of safety was categorized 3 levels (‘Low’, ‘Moderate’, ‘High’). From Figure 5, the factor of safety lower than 1 (‘High’ level) is common in the four case for the Cheonggye Mountain. And the area that has the distribution of the factor of safety lower than 1 increases as the PGA increase. In addition, the area that has the distribution of the factor of safety higher than 2 decreases as the PGA increases.

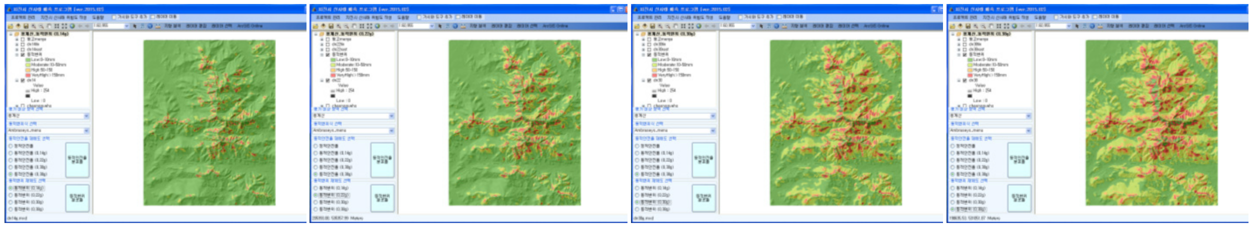


(a) Factor of safety (0.14g) (b) Factor of safety (0.22g) (c) Factor of safety (0.30g) (d) Factor of safety (0.38g)

Dynamic factor of safety: Low FS>2 Moderate $1.1<FS\leq 2$ High $0<FS\leq 1.1$

Figure 5. Dem of dynamic factor of safety for earthquake scenarios

Figure 6 shows the results of Newmark displacement for each PGA event. The yield acceleration is calculated, with factor of safety from eq (1), and the Newmark displacement in each case is calculated using Table 1. And the severity class of Newmark displacement was categorized 4 levels (‘Low’, ‘Moderate’, ‘High’, ‘Very high’). In case of 0.14g, displacement more than 99% area is produced within 10mm because most of the factor of safety values in each case is higher than 1, as shown in Figure 8(a), and many factors in Table 1 are assumed or neglected in this analysis. On the other hand, most of target area (more than 85%) for the three case of PGA events (0.22g, 0.30g, 0.38g) are evaluated as ‘High’ level or ‘Very high’ level. Considering synthetically the dynamic factor of safety and Newmark displacement, it is possible that the Cheonggye Mountain can be damaged to a ‘High’ level ($0<FS\leq 1$, displacement>50mm), in condition of a PGA event exceeding 0.22g.



(a) Newmark displacement (0.14g) (b) Newmark displacement (0.22g) (c) Newmark displacement (0.30g) (d) Newmark displacement (0.38g)

Newmark displacement : Low(0−10mm) Moderate(10−50mm) High(50−150mm) Very High(>150mm)

Figure 6. Newmark displacement for earthquake scenarios

Conclusions and Discussions

In this study, information system of landslide hazard map during earthquake was developed. The developed system built, within the frame of GIS, consists of a database (DB), and the system software performing assessment of earthquake-induced landslide hazard. The system software is functionally divided into an input module, earthquake-induced landslide hazard assessment module, and hazard mapping module. Study area is Cheonggae Mountain in Korea, and two-dimensional landslide hazard map for dynamic factor of safety and Newmark displacement was constructed by using amplification factor obtained from geometrical characteristics of slope based on the developed system. In addition, the verified information system for landslide hazard map during earthquakes was built into the Earthquake Disaster Response System operating in the National Emergency Management Agency in Korea. After that additional simulation using low, intermediate and strong ground motions for the method and system, the occurrence and location of the landslides caused by earthquakes was reliably predicted and managed in real-time.

Acknowledgements

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