# Integrated system for site-specific earthquake hazard assessment with geotechnical spatial grid information based on GIS

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ABSTRACT: An integrated earthquake hazard assessment system with geotechnical spatial grid information was developed based on a geographic information system (GIS). The developed system, built within the framework of GIS, consists of a database (DB) containing all available site information and processed data in the standard formats, and system software that performs various functions to manage and utilize the data in the DB. The system software is divided functionally into an input module, a geostatistical three-dimensional (3D) integration module, a real-time earthquake hazard assessment module, and an output or visualization module. A systematic framework for the construction of a geotechnical spatial grid was developed to consider the local site response characteristics for the target areas. According to the framework, two interrelated assessment procedures were incorporated into the DB on a real-time basis: real-time seismic load determination and real-time liquefaction hazard estimation. The DB and these submodules of the system software were combined and integrated into a single system to provide a familiar and user-friendly working environment with a standard interface. In addition, the integrated system could be linked with real-time seismic accelerations. A simulation of the system was specifically conducted at Busan Port, South Korea, using two seismic records (one at the epicentre and the other at Busan Port) of an actual earthquake event (the 2013 Gyeongju earthquake). The simulation results were visualized as a geotechnical earthquake hazard map to verify the reliability and efficiency of the computer-aided real-time assessment framework.

KEYWORDS: Geotechnical spatial grid, GIS, integrated system, real-time earthquake hazard assessment, site-specific earthquake hazard

## 1 INTRODUCTION.

Recently, some large earthquakes that caused considerable damage occurred in some areas surrounding South Korea: the 2008 Sichuan earthquake (magnitude 8.0), the 2011 Tohoku earthquake (magnitude 9.0), the 2016 Taiwan earthquake (magnitude 6.4), and the Kumamoto earthquake (magnitude 7.0). Meanwhile, in the Korean Peninsula, earthquake hazards were rarely reported in the past decades, but the number of recorded earthquake events continues to increase each year, and the recent cases of earthquake events in nearby countries make it necessary to conduct seismic studies in South Korea. Furthermore, the occurrence of the national record-breaking Gyeongju earthquake (magnitude 5.8) in 2016 drew much concern and led to more relevant research activities.

For geotechnical earthquake hazards, the assessment of the site effect that the seismic waves are amplified as they pass through soil deposits plays a major role in identifying and mitigating the earthquake hazard. Also, seismic disaster management and mitigation require the establishment of effective systems (or methodologies) based on spatial information because the local variation of the geotechnical properties, and thus the site effect, is usually very high. The use of an integrated seismic damage assessment methodology based on a computer-aided system, such as a geographic information system (GIS) tool (Chung et al. 2014), is generally recommended.

For site-specific geotechnical earthquake hazard assessment, it is necessary to construct a reliable geotechnical database (DB) to minimize the spatial uncertainty of the geotechnical properties. These are known in statistics as "outliers" or "outlying observations" (Grubbs 1969, Barnett & Lewis 1994). To select and remove the outliers in measurements, appropriate geostatistical methods are necessary. For the borehole data for site characterization, geotechnical information is provided as a one-dimensional (1D) soil profile. Meanwhile, geophysical tests such as seismic refraction prospecting and electrical resistivity surveys can present the soil properties in a tomographic two-dimensional (2D) form, but they do not guarantee the reliability of the obtained geomaterial values. Therefore, it is desirable for geophysical and boring datasets to be integrated to construct three-dimensional (3D) and continuous geotechnical spatial information structures based on geostatistical methods (Koltermann et al. 1996, Kupfersberger & Deutsch 1999, Weissmann et al. 1999).

In this research, an integrated system for site-specific earthquake hazard assessment with geotechnical spatial grid information based on GIS was developed to respond to earthquake events in near-real time (Kim & Chung 2016), and the system was applied to Busan Port at the event of the 2016 Gyeongju earthquake in South Korea for the validation of its reliability and efficiency.

## 2 CONCEPT OF A REAL-TIME FRAMEWORK FOR EARTHQUAKE HAZARD ASSESSMENT

The integrated framework consists of a DB and system modules. The DB contains all the field and processed data in the system. The submodules execute various functions for managing and utilizing information in the DB: inputting of data, geostatistical 3D integration of the data, real-time earthquake hazard assessment, and output and visualization of data. Fig. 1 shows the details of the integrated framework.

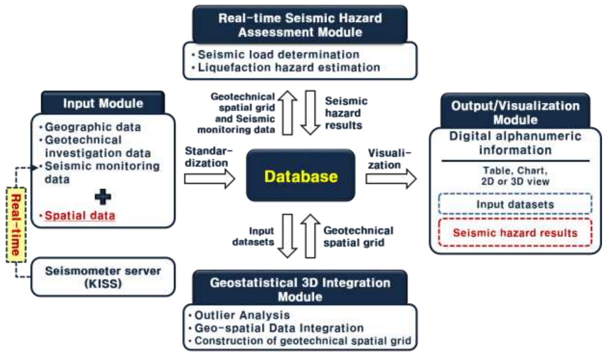



Fig. 1. Integrated framework with geotechnical earthquake hazard assessment procedures.

The DB is the backbone of the developed framework. It stores not only primary collected data such as geography and geotechnical data as well as seismic monitoring data from a seismometer server but also secondary processed data obtained from geostatistical 3D integration and real-time earthquake hazard assessments. The data stored in the DB can be easily utilized in the framework. The input function provides an effective way to store and arrange all the collected and processed data according to a standard format based on a geo-DB (GDB) (Chun et al. 2007).

A methodology for real-time earthquake hazard assessment was proposed, using the schematic concept shown in Fig. 2. The arrows represent the sequential data processing. The graphical schematic flow of the integrated earthquake hazard assessment with geotechnical spatial grid information (composed of two system functions for geostatistical 3D integration and real-time earthquake hazard assessment) is shown (Kim 2014). To accurately determine the geotechnical characteristics of a site with a seismic risk potential, geostatistical 3D integration of the geophysical tomography and borehole soil profile data is conducted based on a GIS platform. In addition, an interrelated procedure for the real-time assessment of the earthquake hazard was developed using geotechnical spatial grid information, to consider the response characteristics of the target site.

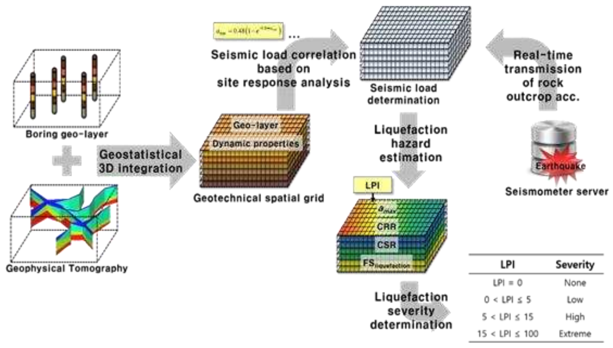



Fig. 2. Schematic flowchart of integrated earthquake hazard assessment with geotechnical spatial grid information.

The 3D geotechnical data for the spatial grid over a selected domain is integrated by applying geostatistical methods to input data at the target site. The 3D integration has three functional modules with the DB: outlier detection, geostatistical integration, and construction of a geotechnical spatial grid. The geotechnical investigation results always reflect the level of soil uncertainty. To determine the level of soil uncertainty, two outlier detection methods based on cross-validation and the generalized extreme value distribution proposed by Kim et al. (2012), which optimize the borehole datasets, are used. In addition, the geostatistical integration method based on indicator kriging is performed using optimized borehole and digitized geophysical tomography data to construct a 3D geolayer (Kim et al. 2016). The 3D geolayer is categorized and subdivided into representative soil profile and dynamic properties to assign a 3D geotechnical spatial grid in the DB. This step must be conducted as a baseline prior to the occurrence of earthquakes (Kim 2014).

The real-time earthquake hazard assessment function has two functional modules with the DB: real-time seismic load determination and real-time liquefaction hazard estimation. In the first phase, which is linked with the 3D geotechnical spatial grid, the correlation between rock outcrop acceleration and the maximum acceleration of each layer considering the site response characteristics is predetermined (Kim et al. 2002). Thus, as earthquake events occur and as soon as the monitored rock outcrop acceleration data are transmitted from the accelerometer, the seismic load at each spatial cell is estimated. In the second phase, the potential damage due to liquefaction is estimated by integrating the factor of safety (composed of the cyclic stress ratio and the cyclic resistance ratio) of each layer based on the simplified liquefaction evaluation method using the liquefaction potential index (LPI) in real time (Chung et al. 2014). As earthquake events occur, the LPI and liquefaction severity class are estimated based on their correlations with the maximum acceleration of each layer in real time (Kim 2014).

The output function displays all the attributive data in the DB using tables and graphics, according to its characteristics, either on the screen or as a document. In addition, all the data in the DB can be outputted as a chart or a graphic (Chun et al. 2007). The graphic functions, such as the 2D plane view, 2D sectional view, and 3D view, display data interpolated with the field data over an arbitrary domain. Then all the charts, graphs, and drawings can be printed. In particular, the earthquake hazard can be visualized and forecasted as 2D or 3D maps overlain by satellite images.

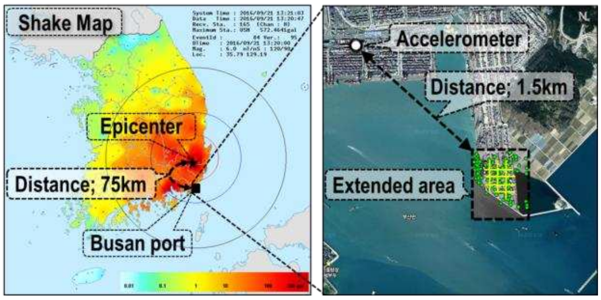
Several assumption conditions and preceding assessments are used to estimate the possible geotechnical earthquake hazard for a target site in real time, as soon as the earthquake occurs. The prior works, such as the building of the DB, the construction of the geotechnical spatial grid, and the site response analysis for the overall target area, should be completed. Then, as an earthquake occurs near a target site, the possible hazard can be estimated in real time by linking them with the rock outcrop acceleration data obtained through monitoring with an accelerometer.

## 3 FIELD APPLICATION OF THE DEVELOPED SYSTEM TO THE BUSAN PORT AREA AT THE 2016 GYEONGJU EARTHQUAKE EVENT IN SOUTH KOREA

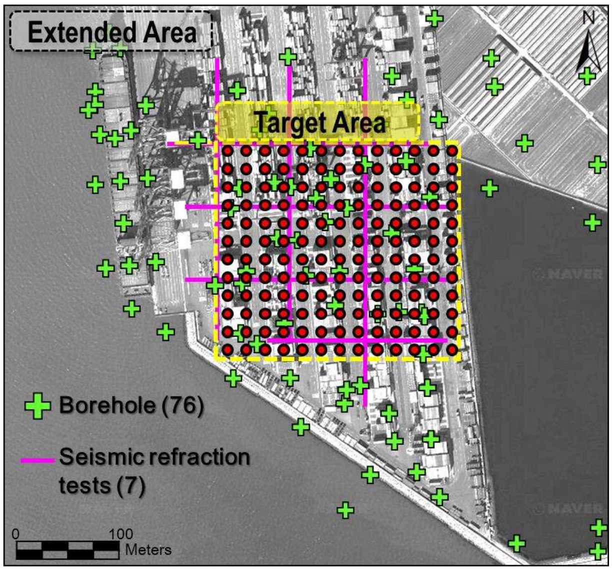
The real-time assessment framework of the spatial liquefaction hazard was applied to Busan Port in the event of the 2016 Gyeongju earthquake to verify the applicability of the proposed framework. The target area was located about 75 km away to the south from the earthquake's epicenter in Gyeongju, as shown in Fig. 3. The subsoil of Busan Port consists of seismic-susceptible soils such as reclaimed or backfill granular soil. Thus, it can be regarded as a relatively seismic-vulnerable area.

A downhole accelerometer was installed in the bedrock at Busan Port (1.5 km away from the center of the target area), and continuous monitoring of the earthquake event has been conducted since 2010. The greatest earthquake that had ever occurred in South Korea after the earthquake event started to be recorded, hit Gyeongju City on September 12, 2016. This event caused the significant damages of the roof structures of the traditional Korean houses made of ceramic roof tiles, but it did not cause the damages of the main structures of the houses and the buildings. Shown in Fig. 4 are the monitoring records at the nearest station from the epicenter and the target area in the Gyeongju earthquake event (magnitude 5.8). The maximum rock accelerations were recorded as 0.32 and 0.10 g, respectively.

Geostatistical 3D integration was performed using 76 optimized borehole datasets and 7 seismic-wave tomography datasets (with $V_P$ values) to the extended area (126,000 m$^2$: 300 m west to east × 420 m north to south) encompassing the target area (62,400 m$^2$: 260 m west to east × 240 m north to south). The ground coverage at Busan Port varied over the last 40 years due to the soil dredging and reclamation activities; thus, for the areas without post-construction site investigation data, the gap between the present elevation of the ground coverage based on the aerial photographs and the elevation observed at the site investigation before the construction was assumed to be filled with dredged soils from the seabed.

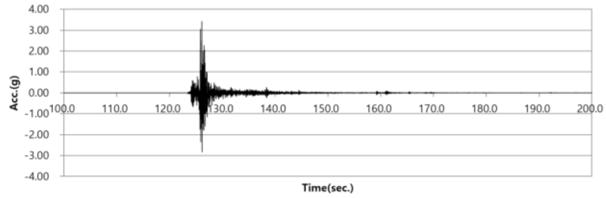



(a)

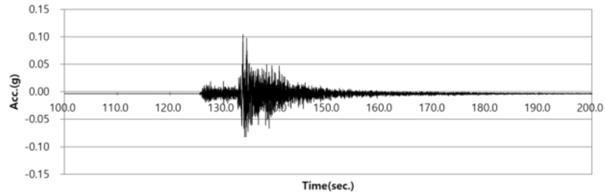



(b)

Fig. 3. Simulation conditions and shake map for the earthquake scenarios for Busan Port, South Korea: (a) shakemap during the main shock of the 2016 Gyeongju earthquake and the Busan Port area; and (b) extended and target areas in Busan Port.




(a)




(b)

Fig. 4. Acceleration waveforms of the 2016 Gyeongju earthquake: (a) at the station near the epicentre; and (b) at the station of Busan Port.

The 3D geotechnical DB on the site conditions of the target area was determined according to the geotechnical spatial grid construction procedure using the GIS platform, as shown in Fig. 3(b). A total of 156 cells (13×12 cells) of the geotechnical spatial grid (covering the ground surface) with constant 20 m intervals were selected for the study area. Vertically, the cells were constructed with 1 m intervals to the bedrock. 3D indicator kriging was performed on the target area to the bedrock. The soil profile (including the weathered rock) to the bedrock was determined, as shown in Fig. 5. The soil was thicker (45 m), and the depth to the bedrock was greater (about 55 m), towards the northwest (or west).

Linked with the geotechnical spatial grid, the correlations between the rock accelerations of the earthquake records and the PGA values of each layer were established. The $FS_{liquefaction}$ of each geolayer for the spatial grid could be computed using the 3D geotechnical DB. The LPI values and the site-specific liquefaction severity based on the spatial grid were determined by integrating the $FS_{liquefaction}$ for each geolayer using the liquefaction hazard assessment module of the system (Chung et al. 2014).

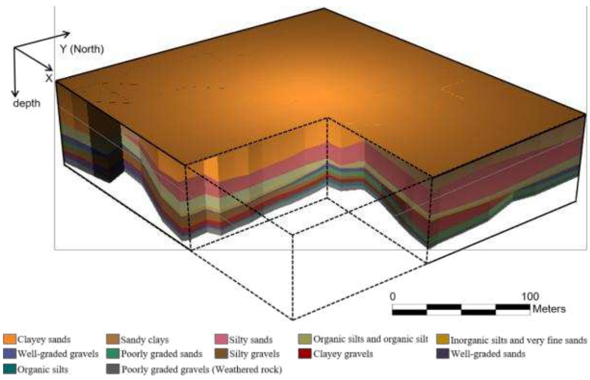



Fig. 5. Three-dimensional soil profile with a cross-sectional view for the current ground conditions based on the geotechnical spatial grid in the study area.

For the Gyeongju earthquake event, only the minor indications were estimated with only 4 cells of the low severity class based on the acceleration data transmitted at Busan Port (Fig. 6(a)). Meanwhile, with the acceleration record at the epicenter, 22 cells of the geotechnical spatial grid among the 156 cells covering the ground surface were classified into the "low" liquefaction severity class, and 3 cells had a slightly high potential of liquefaction with near-lower-boundary values of the high severity level, whereas the others belonged to the "none" class. The cells of the southwest region have a high potential of liquefaction hazard because of the relatively thick gravel and sand fills.

Consequently, even in the event of the record-breaking earthquake in South Korea, the significant indications of liquefaction were not estimated at the area with seismic-vulnerable subsoil conditions. Considering the recent increase trend of the frequencies and intensities of earthquake events in the Korean Peninsula and nearby countries, however, it can no longer be said that the Korean Peninsula is an earthquake-safe zone. Continuing interest in and research work on seismic hazards are thus necessary, based on the inherent characteristics of the earthquakes and subsoils of South Korea.

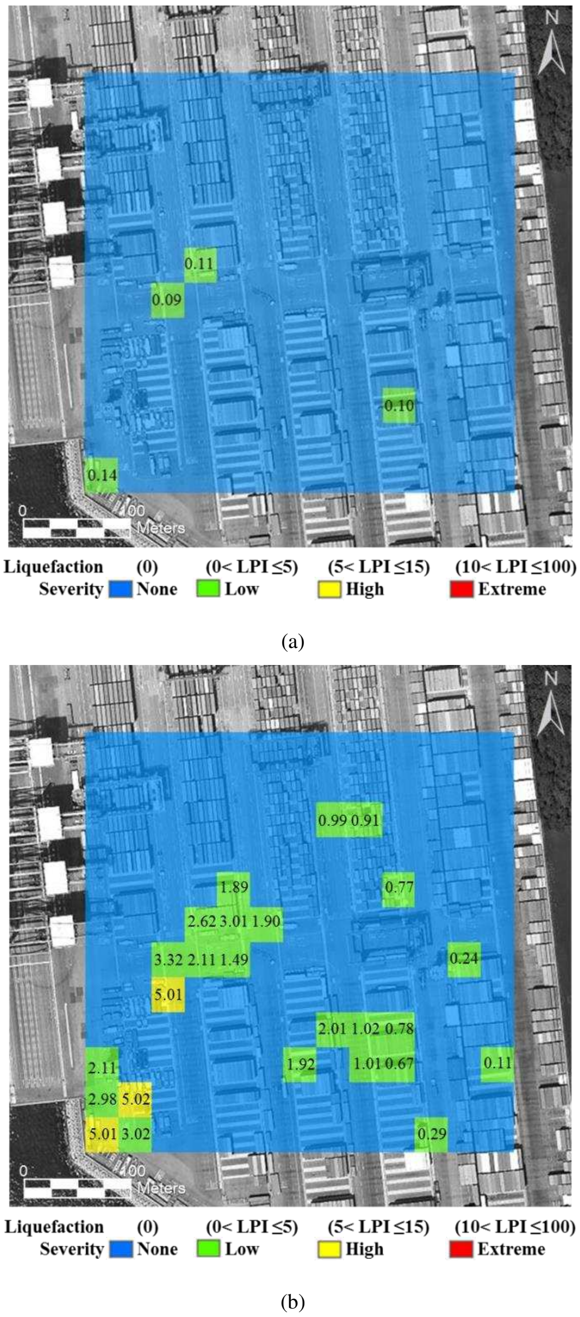



Fig. 6. Liquefaction severity zonation maps for the 2016 Gyeongju earthquake using the earthquake records: (a) at the station of Busan Port; and (b) at the station near the epicentre

## 4 CONCLUSIONS AND RECOMMENDATIONS

An integrated system for geotechnical seismic-hazard assessment in real time based on a geographic information system (GIS) was developed. A geostatistical three-dimensional (3D) integration method for geo-information data and real-time earthquake hazard assessment (liquefaction) were applied to the system. Through the application of field examples, it was confirmed that this system provides a reliable geotechnical information database (DB) and is a systematic and convenient way to access site-specific liquefaction hazards. Thus, it is possible to rapidly recognize the inherent geotechnical seismic failure at the target site, which is invisible to the naked eye. The real-time assessment of seismic hazards can assist the decision-making required for earthquake risk management as well as the development of optimized evacuation paths and restoration plans for port or urban structures. There are still some possible improvements that can be made, however, for data availability and compatibility based on DB replication. In addition, other shortcomings may be detected by additional field applications, and these can be addressed to develop a more reliable system.

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