Computers and Geotechnics 61 (2014) 241–253

Contents lists available at ScienceDirect

Computers and Geotechnics

journal homepage: www.elsevier.com/locate/compgeo

Real-time assessment framework of spatial liquefaction hazard in port areas considering site-specific seismic response

Choong-Ki Chung [a,1], Han-Saem Kim [a,*], Chang-Guk Sun [b,2]

[a] Department of Civil and Environmental Engineering, Seoul National University, 1 Gwanak-ro, Gwanak-gu, Seoul 151-742, Republic of Korea
[b] Earthquake Research Center, Korea Institute of Geoscience and Mineral Resources, 124 Gwahak-ro, Yuseong-gu, Daejeon 305-350, Republic of Korea

ARTICLE INFO

Article history:
Received 22 November 2013
Received in revised form 29 May 2014
Accepted 3 June 2014
Available online 24 June 2014

Keywords:
Real-time assessment
Liquefaction hazard
Geostatistical method
Site-specific seismic response
Port areas
GIS

ABSTRACT

This paper proposes a systematic framework for real-time assessment of spatial liquefaction hazard of port areas considering local seismic response characteristics based on a geographic information system (GIS) platform. The framework is integrated and embedded with sequential, interrelated subprocedures and a database for liquefaction-induced damage evaluation that standardizes and both individually and collectively quantifies analytical results. To integrate the current in situ condition of a selected port area, the framework functions as a spatial database system for geotechnical and structural data and as a recipient of automatic transmission of seismic monitoring data. The geotechnical profile correlated with liquefaction potential is compiled into a geotechnical spatial grid built by geostatistical methods. Linked with the geotechnical spatial grid, the processing of site-specific responses is automatically interpreted from previously derived correlations between rock acceleration and maximum acceleration of each soil layer. As a result, the liquefaction severity is determined based on a combined geotechnical spatial grid with seismic load correlation in real-time according to a simplified procedure, allowing calculation of the liquefaction potential index (LPI). To demonstrate practical applications of the framework in estimating the liquefaction hazard in real-time, liquefaction-hazard maps were visualized for two earthquake scenarios, verifying the applicability of the proposed framework.

1. Introduction

Because international trade and travel have been growing rapidly in recent years, seaports or harbors in coastal areas are increasingly vital to the local and regional sustainability of industries and economies. Further, ports are now being developed into larger areas by reclaiming land from the sea. Port areas that consist of huge facilities, buildings, and yards underlain by various soil deposits have experienced serious disasters from recent earthquakes around the world [1]. In particular, earthquake-induced liquefaction is a significant threat to manmade structures built on loose and saturated sandy soils [2], which are widely distributed in coastal port areas.

Liquefaction can be triggered by the rapid loading invoked by seismic shear wave energy when there is insufficient time for excess pore-water pressure to dissipate through natural drainage [3]. Liquefaction can also be triggered by rapid straining along discrete horizons, such as landslides and lateral spreading. Any type of rapid loading situation that serves to elevate the pore-water pressure can result in cyclic softening of fine-grained soil materials or liquefaction in porous materials of relatively low density with little or no cohesion [4]. Various types of liquefaction damage, such as landslides, lateral spreading, and sand boil events, have occurred in port areas constructed by earthwork, such as dredging and reclamation. Extensive liquefaction-induced damage has frequently been observed in recent earthquake events, such as the 1964 Niigata, 1983 Nihonkai-chubu, 1993 Hokkaido-nansei-oki, 1995 Hyogoken-nanbu, 1999 Kocaeli, 1999 Duzce, 2010 Haiti, 2010 Chile, and 2011 Tohoku earthquakes [1,3,5–8].

Seismic disaster management and mitigation are required to establish effective and appropriate strategies to reduce liquefaction vulnerability. However, these are not easy tasks, and require considerable resources and analyses [9,10]. Their complexity dictates the use of an integrated liquefaction damage assessment methodology based on a computer-aided system, such as the geographic information systems (GIS) tool. GIS supports spatial decision-making based on multiple georeferenced datasets, and thereby makes possible liquefaction hazard assessment for

* Corresponding author. Tel.: +82 2 880 7347; fax: +82 2 875 6933.
E-mail addresses: geolabs@snu.ac.kr (C.-K. Chung), adoogen@snu.ac.kr (H.-S. Kim), pungsun@kigam.re.kr (C.-G. Sun).
[1] Tel.: +82 2 880 7347; fax: +82 2 875 6933.
[2] Tel.: +82 42 868 3176; fax: +82 42 861 1872.

http://dx.doi.org/10.1016/j.compgeo.2014.06.001
0266-352X/

reducing or mitigating damage caused by earthquake shaking [11–13]. Comprehensive frameworks for seismic damage scenarios and liquefaction risk analysis, including GIS-based evaluation tools, have been developed and proposed as part of major loss estimation systems: HAZUS [14]; RADIUS [15]; Risk-UE [16]; DBELA [17]. Moreover, evaluation of reliable site-specific seismic response characteristics in an entire area of interest is best handled on a GIS platform, because the liquefaction-induced hazard is seriously affected by local site effects. Accordingly, the effective construction of a spatial database system is considered in this paper for reliable liquefaction zonation mapping.

Although appropriate for liquefaction hazard assessment over the long term, GIS can provide immediate and rapid estimation of the liquefaction hazard over a target area, and is essential to effective emergency control due to the unexpected and sudden nature of earthquakes [18]. Thus, real-time assessment considering the site-specific liquefaction hazard using GIS is appropriate for supporting rapid emergency response in port areas. In this paper, a systematic framework for real-time assessment of the spatial liquefaction hazard considering site response characteristics was developed for ports in preparation for earthquake events. Furthermore, a real-time assessment of the liquefaction hazard was conducted for the Busan port, Korea, by analyzing two earthquake scenarios based on a computer-based spatial information system to verify the applicability of the proposed framework.

2. General assessment of liquefaction potential

2.1. Previous studies of liquefaction potential evaluation

Assessing the liquefaction potential is an important issue in geotechnical earthquake engineering. Several methods have been proposed to evaluate the liquefaction potential of sandy soils for which insufficient geotechnical data exist. In situ tests, such as the standard penetration test (SPT), cone penetration test (CPT), Becker penetration test (BPT), and field measurements of the shear wave velocity (V_S), have been used as empirical tools to evaluate the liquefaction resistance of soil layers that may liquefy during an earthquake [19–21]. A simplified procedure based on SPT–N values is commonly used in liquefaction assessments in most countries [22], including Korea.

The original simplified procedure based on empirical rules has been modified and improved over the years [19,23,24]. And Iwasaki et al. [25] proposed the liquefaction potential index (LPI), which evaluates liquefaction potential over the length of a boring or a CPT. Toprak and Holzer [26] also published a field assessment study of the LPI using CPT soundings at sites that had already experienced liquefaction. Elkateb et al. [27] discussed the site-specific effects of soil heterogeneity and methods of geotechnical evaluation, including liquefaction of the local ground condition. Baise et al. [28] evaluated the liquefaction potential based on the stratigraphic layer; however, the depth dependence was ignored within single layers.

Several researchers have applied GIS tools to describe the liquefaction potential results based on the simplified procedure to determine the LPI [4,27–29]. However, most previous applications have focused on one-dimensional (1D) or two-dimensional (2D) evaluations of liquefaction. Luna and Frost [4] considered the three-dimensional (3D) geologic ground conditions of the liquefaction hazard of Treasure Island in San Francisco Bay during the 1989 Loma Prieta earthquake by comparing individual two-foot slices. Similarly, most research that integrates GIS and earthquake hazard estimation has been restricted to 3D spatial modeling rather than producing cartographic depictions [30]. And earthquake disaster modeling has long been in need of an integrated framework for effective real-time assessment. In short, there are no proposed applications to estimate the liquefaction potential in real-time for the entire continuous areas, with the utilization of seismic monitoring information.

2.2. Real-time assessment of spatial liquefaction hazard in port areas

A methodology was proposed for real-time assessment of spatial liquefaction hazard for port areas using the schematic concept shown in Fig. 1. The arrows represent the sequential data processing. This framework functions as a database for geotechnical and port structure data and is able to receive automatic transmissions of seismic monitoring data. Initial state of the seismic load can be monitored as rock acceleration records automatically obtained from accelerometers and transmitted to the framework in real-time. The records from either downhole accelerometers placed below the liquefiable layer or on nearby outcrops of bedrock are used to predict ground motions. Seismic waves are amplified as they pass through soil deposits according to site-specific response characteristics [3,24]. And the site-specific liquefaction hazard can be evaluated in real-time based on the database.

Ultimately, the earthquake damage due to liquefaction affecting port structures can be evaluated by simulating synthetically the amplified seismic load and dynamic ground properties for the current state of a port area on a real-time basis. For the real-time approach, the methodology includes an integrated liquefaction damage assessment composed of sequential subprocedures. The interrelated assessment procedures are incorporated with the database on a real-time basis, interpreted, and presented as 2D and 3D visualizations of geotechnical earthquake parameters.

3. Real-time assessment framework of spatial liquefaction hazard

3.1. Framework architecture

The real-time framework has three functional modules with the database: geotechnical spatial grid construction, real-time seismic load determination, and real-time liquefaction hazard estimation (Fig. 2). The database is composed of geographic, geotechnical, structural, and seismic monitoring data of the target port. In the first phase, a geotechnical spatial grid is constructed based on the geostatistical method mainly related to geotechnical characteristics of the target port area to confirm the site-specific ground conditions to be correlated with the liquefaction potential. This step must be conducted as a baseline prior to the occurrence of earthquakes.

In the second phase, linked with the geotechnical spatial grid, correlations between rock acceleration and maximum acceleration of each layer considering site response characteristics are predetermined. Thus, as earthquake events occur, as soon as monitored rock acceleration data are transmitted from the accelerometer, seismic load at each spatial grid is estimated. Finally, the potential damage due to liquefaction is estimated by integration of the geotechnical spatial grid and correlated maximum acceleration of each layer based on the simplified LPI evaluation method in real-time. The liquefaction hazard can be visualized as 2D or 3D maps overlain by satellite images, from which the liquefaction severity of the target port structure can be determined using zonation criteria.

In this paper, the computer-based framework for real-time assessment of spatial liquefaction hazard was embedded based on a stand-alone program developed using Microsoft Visual BASIC, the Esri ArcGIS developer tool [31,32], and the GSLIB of Stanford University [33]. The ArcGIS developer tool was mainly used for spatial development of the database, evaluation of the results, and spatial visualization. In addition, a sophisticated kriging inter-