6th International Conference on Earthquake Geotechnical Engineering
1-4 November 2015
Christchurch. New Zealand

Real-time Assessment of Structure Seismic Fragility Considering Site-specific Site Response

H.S. Kim[1], C.K. Chung[2], C.G. Sun[3]

ABSTRACT

Earthquake hazards, such as strong ground motion, liquefaction and landslides, are a significant threat to structures built on seismically vulnerable loose and saturated sandy soils. Therefore, structure failure evaluation method considering site-specific site response is required to establish effective and appropriate strategies to reduce earthquake hazards. In this study, real-time assessment of structure seismic fragility is developed. To evaluate structure susceptibility due to earthquake occurrence in real-time, the seismic fragility function is used as threshold of structure failure, and linked with geotechnical spatial grid assigned with correlation equations for seismic load determination. The real-time assessment is composed with the following procedure. First, the geotechnical spatial grid is constructed based on the geostatistical method to estimate the site-specific site response to be correlated with the earthquake hazard potential. Second, the peak ground accelerations are determined from seismic load correlation and assigned to the geotechnical spatial grid. Third, the damage grade of structure is determined by calculating the failure probabilities of defined damage level and integrating the geotechnical spatial grids for target structure in real time. A simulation of the proposed assessment was specifically conducted at Incheon port, Korea, using actual earthquake event (2013 Baengnyeong Earthquake) and virtual earthquake scenario.

Introduction

Recently, the number of earthquake events keeps increasing every year, and increasing cases of earthquake hazards invoke the necessity of seismic study in Korea, as geotechnical earthquake hazards are a significant threat to structures in port or downtown built on seismically vulnerable loose and saturated sandy soils. Seismic disaster management and mitigation for building structure are required to establish effective and appropriate strategies to reduce earthquake hazards. However, these are not easy tasks, and require considerable resources and analyses (Drabek and Hoetmer, 1991; Xu and Liu, 2009). Their complexity requires the use of a systematic methodology based on a computer-aided system, such as the geographic information systems (GIS) tool. Also to set-up the database and estimate the spatial degree of seismic vulnerability in real time basis, it is indispensable to utilize the wireless network system (WNS) connected with seismometer.

[1]Ph.D._H.S. Kim, Earthquake Research Center, Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea, adoogen@kigam.re.kr
[2]Prof._C.K. Chung, Department of Civil and Environmental Engineering, Seoul National University, Seoul, Korea, geolabs@snu.ac.kr
[3]Ph.D._C.G. Sun, Earthquake Research Center, Korea Institute of Geoscience and Mineral Resources, Daejeon, Korea, pungsun@kigam.re.kr

In this study, the developed systematic procedure for real-time structure seismic fragility assessment consists of has three functional modules with the database: geotechnical spatial grid construction, real-time seismic load determination, and structure fragility evaluation. The prepared datasets for real-time earthquake hazard assessment are composed of geographic, geotechnical, structural, and seismic monitoring data of the target site. A simulation of the proposed assessment was specifically conducted at Incheon port, Korea, using actual earthquake event (2013 Baengnyeong Earthquake) and virtual earthquake scenario.

Real-time Assessment Framework of Structure Seismic Fragility

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 assessment of structure seismic fragility (Figure 1).

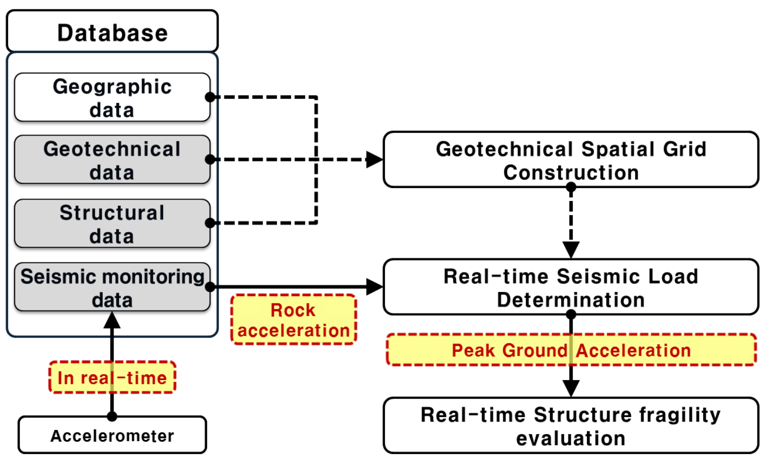


Figure 1. Computer-based framework architecture for the real-time assessment of structure seismic fragility

In the first phase, a geotechnical spatial grid is constructed based on the geostatistical method mainly related to geotechnical characteristics of the target area to provide the site-specific ground conditions to be correlated with the structure fragility. 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 peak ground acceleration considering site response characteristics are predetermined. To compute seismic loads causing structure failure in real-time, correlations derived previously between the bedrock acceleration transmitted from accelerometers and peak ground acceleration are assigned into the geotechnical spatial grid. Thus, as earthquake events occur, with monitored rock acceleration data transmitted from the accelerometer, seismic load at each spatial grid is estimated, immediately.

In the third phase, the structure failure due to earthquake occurrence is evaluated based on seismic fragility curve. The fragility curve of structure is the function which represents the excess probability of defined damage level for specific earthquake intensity. And the correlated peak ground acceleration is used as intensity index of fragility functions and probabilities of failure are calculated. After all, damage grades of superstructures are determined and they depend on the probabilities of failure. According to the proposed framework, the structure fragility is evaluated in near real-time (within 30 seconds), liked with KISS (Korea Integrated Seismic System).

Geotechnical Spatial Grid Construction

The first phase is defined as geotechnical spatial grid construction based on the geostatistical method. In the procedure, prerequisite information related to geotechnical zonation is inputted into a 3D spatial database (geotechnical spatial grid) to utilize as primary data for subsequent procedures and to determine the ground conditions to be correlated with the seismic response causing structure failure. To build a reliable spatial grid for the current ground conditions of target site, it is necessary to consider the geographic conditions as well as the dynamic geotechnical properties from site investigations and earthwork records. Additionally, the spatial distribution characteristics of target structures related to seismic performance is taken into account to estimate the structure seismic fragility.

Real-time Seismic Load Determination

To compute seismic loads (PGA) causing structure failure in real-time, correlations derived previously between the bedrock acceleration transmitted from accelerometers and the PGA are assigned into the geotechnical spatial grid. Figure 2 shows the procedure for real-time seismic load determination consisted with an input database, preceded site response analysis and derivation of seismic load correlation equation (nonlinear optimization of a regression model) (Kim et al. 2012).

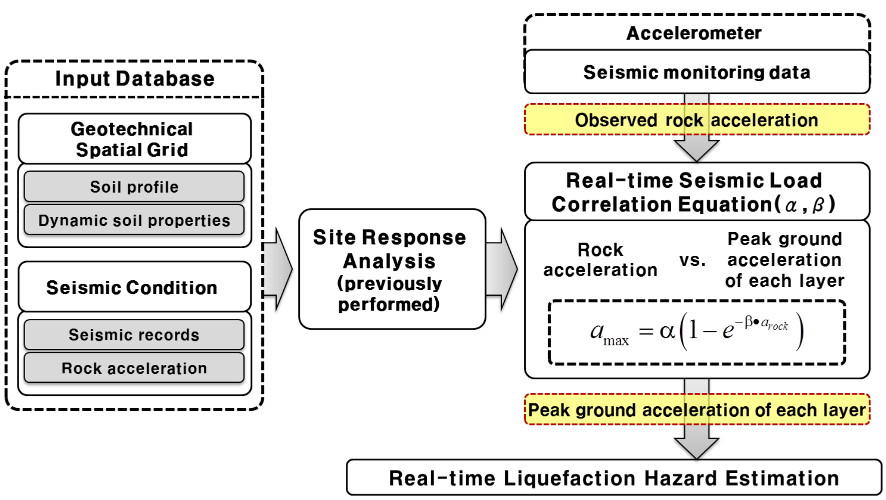


Figure 2. Procedure for real-time seismic load determination classified into the database, preceded site response analysis and nonlinear optimization of a regression model to compute seismic loads in real-time

First of all, the input dataset should contain the geotechnical spatial grid (soil profile, dynamic soil properties, etc.) to evaluate the likely site response characteristics of the continuous 3D ground conditions of the target area. And various seismic data (e.g., earthquake records, rock acceleration) are also applied to characterize the normalized seismic trend according to the input seismic load. As a result, a series of ground response values for each geotechnical spatial grid cell are derived from nine levels of rock acceleration and three types of actual and simulated earthquake records. Then, correlations between the rock acceleration and peak ground acceleration of each layer (having 27 relationships) at particular cell of the specific geotechnical spatial grid are determined, based on no distinct effect of earthquake types. And the nonlinear optimization of the regression model is performed considering the nonlinearity of the soil layers.

Real-time Structure Fragility Evaluation

To evaluate structure susceptibility in real-time, the fragility function is used as threshold of structure failure, linked with geotechnical spatial grid (assigned with correlation equations for seismic load determination). The superstructure for seismic fragility evaluation can be simply classified with two groups: structure above soil layer and structure above rock (Figure 3). The fragility of structure above soil layer is evaluated based on peak ground acceleration linked with seismic load correlation, to consider site-specific response characteristics. Meanwhile, the fragility of structure above rock, where seismic wave is passed on directly, is evaluated linked with rock outcrop acceleration transmitted from accelerometer.

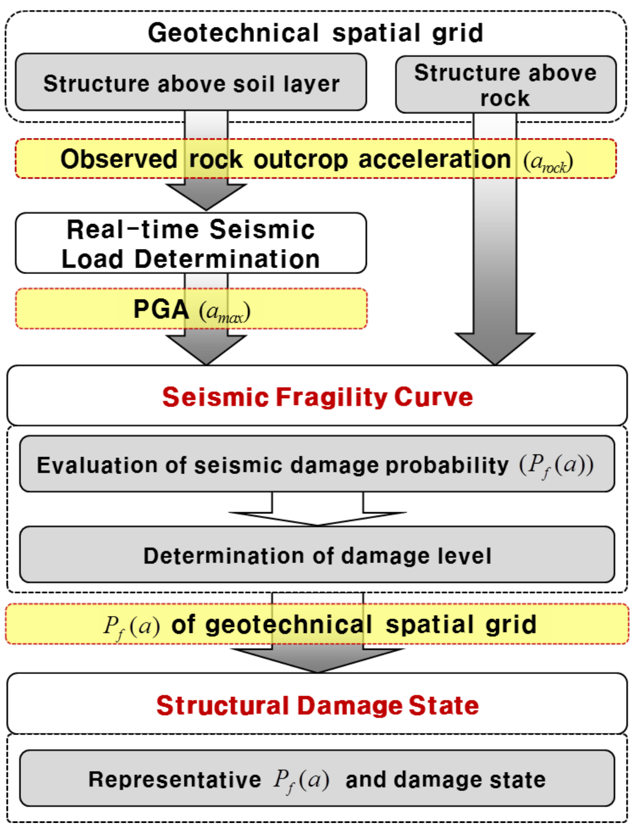


Figure 3. Procedure for real-time fragility evaluation method

The fragility curve is categorized by professional structural engineer based on various seismic numerical analyses, and grouped as representative type of target structures. Fragility function of structure is the function which represents the excess probability of defined damage level for specific earthquake intensity. Intensity index which means earthquake intensity is needed to represent damage probability. Spectral acceleration (S_a) and spectral displacement (S_d) are usually used as intensity index by characteristics of structure. It is convenient to calculate damage probability of structure instant by using peak ground acceleration (PGA) as intensity index. Damage probability of superstructure is expressed as

$$PF_{ij} = PROB[D \geq C_i \mid EQ_j] \tag{1}$$

where PF_{ij} is the probability of exceeding i level for the earthquake in the intensity of j, D denotes effect of the load by an earthquake, and C_i $a_{max}$is strength of the structure for damage level i.

Indexes which properly represent structural damage should be selected. Fragility is cumulative log-normal distribution function and normally expressed as

$$P_f(s) = \phi\left[\frac{\ln s - \ln \bar{s}}{\beta}\right] \tag{2}$$

where $P_f(s)$ is damage probability of structure at s, $\phi[]$ denotes Gaussian cumulative log-normal distribution function, $\bar{s}$ a_{max} is Median of PGA at ground surface, s a_{max} is PGA of the earthquake, random variable, and β is standard deviation of log value of PGA at ground surface.

Damage level of structure when an earthquake occurs is represented as probability of failure by fragility function. In this study, it is applied that the method of determination of damage grade is based on the probability of failure at each damage level to estimate the seismic damage of structures. First, the failure probability of each structure is calculated by transmitted rock outcrop acceleration from accelerometer or correlated PGA based on statistical correlation for seismic load.

Second, the seismic damage probability ($P_f(a)$) with geotechnical spatial grid is determined by transmitting the a_{rock} or PGA in the seismic fragility function. It is assumed that the damage grade is given in case that the probability of each damage level is over 50%. The most severe damage grade among the probable damage grades for the target structure is determined as its grade. For example, in the case of concrete frame, the probabilities of ‘Slight’ and ‘Moderate’ level are both over 50%, then the damage grade of the structure is confirmed as ‘Moderate’ (Figure 4).

Third, the structural damage state (or class) for target structure is evaluated considering occupied area ratio of geotechnical spatial grids having $P_f(a)$ value. If the occupied area ratio of $P_f(a)$ determined as damage state (ex. Slight, Moderate, etc.) is more than 50%, the structural damage state of target structure is ‘Failure’ corresponding to the damage level.

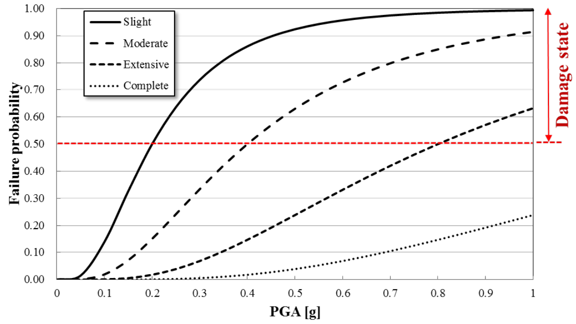


Figure 4. An example of fragility curve and damage state for unreinforced concrete structure modified from FEMA (2003).

Real-time Assessment of Structure Seismic Fragility for Incheon Port in Korea

Simulation Conditions

The real-time assessment framework of the structure seismic fragility was applied to the Incheon port, Korea, using actual and virtual earthquake events based on computer-based spatial information to verify the applicability of the proposed framework. 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. Figure 5 describes the target area with the real-time transmission of the seismic monitoring data at earthquake event. At the testing site, two accelerometers are installed to monitor the free-field ground motion (at lock) and structure motion (at passenger terminal).

In 2013, the noticeable earthquake events were occurred in waters west of Baengnyeon Island in Korea, and the seismic monitoring datasets were measured from the accelerometers installed at coast pier of Incheon port. The magnitude of Baengnyeong Island earthquake event is 4.9 and the epicenter is located in waters west of Incheon port (distance; about 41km). The condition of Baengnyeong Island earthquake for simulation tests is obtained from Korea Meteorological Administration. The Baengnyeong Island earthquake event is 5th largest magnitude since seismic monitoring in Korea (1978). Unfortunately, as the significant major earthquake events have not been recorded up to now, hypothetical earthquake was additionally simulated. For the hypothetical Uljin earthquake, monitored records at the epicenter were applied.

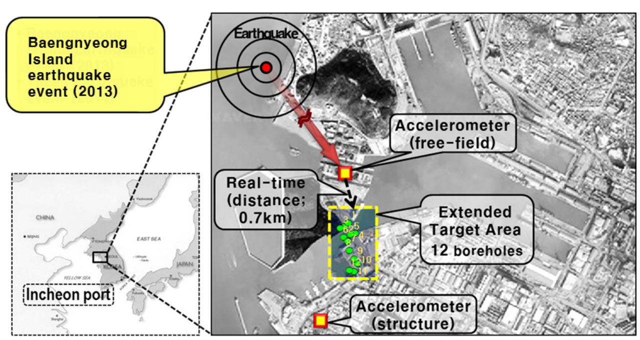
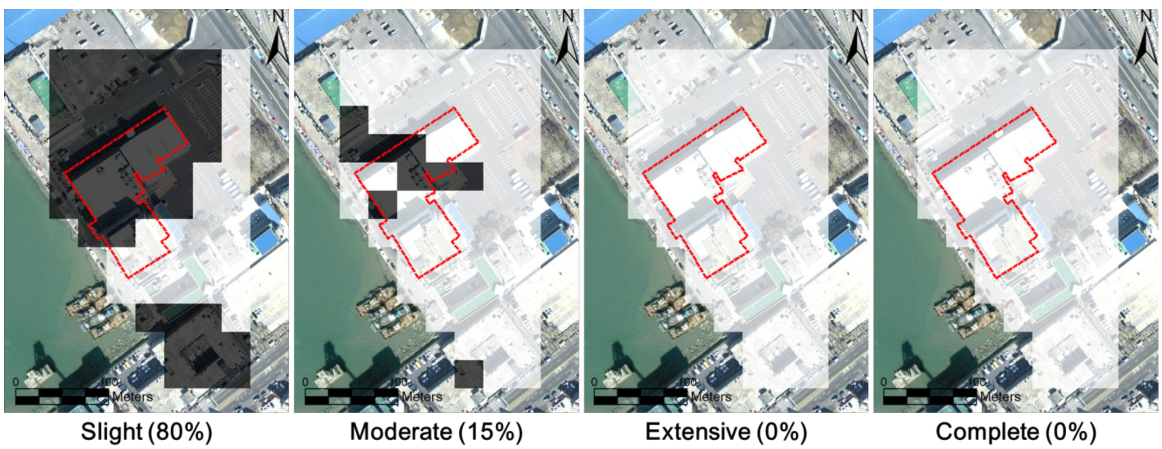


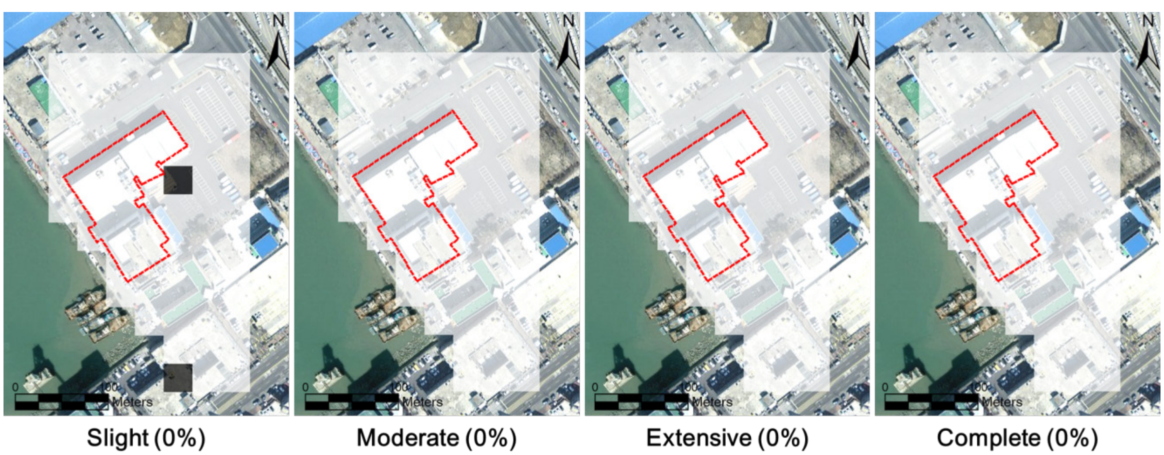
Figure 5. Simulation tests conditions for earthquake scenarios for the Incheon port, Korea

The testing site is partial area of the passenger terminal of Incheon, and 12 borehole datasets are stored into the database. From the design report and a satellite image of the database for the target port, the extended target area (73,600 m^2: 160 m west to east × 460 m north to south). At the target site, there is a passenger terminal (visualized as dotted black line at Figure 8) built using unreinforced concrete method. Based on the real-time structure fragility evaluation method, the fragility function of the concrete frame structure at study area was determined. The fragility functions of concrete frame with unreinforced masonry infill wall (concrete frame) are applied to real-time structure fragility evaluation method based on the FEMA (2003) (visualized as dotted red lines at Figure 4). The damage levels are arranged as ‘Slight’, ‘Moderate’, ‘Extensive’, ‘Complete’.

Structure Seismic Fragility



(a) Hypothetical Baengnyeong Island earthquake scenario



(b) Baengnyeong Island earthquake event

	(0< Fragility ≤50%)	(50%< Fragility ≤100)
Damage class	☐ Safe	■ Failure (overturn)

Figure 6. Structure fragility zonation maps of four damage levels for the target port for two earthquake scenarios

The framework was applied for two earthquake scenarios at the study area based on the geotechnical spatial grid for the soil profile. Linked with geotechnical spatial grid, which are assigned seismic load correlation equations, the PGA is determined in real-time. The correlations between the rock acceleration and PGA were determined for every 68 cells of the top layer of geotechnical spatial grid based on the real-time seismic load determination. Accordingly, the PGAs for two earthquake events were calculated at the 2D satellite image. For the hypothetical Baengnyeong Island earthquake scenario, the 80% spatial grid of the PGA for the target building was estimated more than 0.11g. Otherwise, for the Baengnyeong Island earthquake event, every cells of the geotechnical spatial grid excepted center zone were corresponded less than 0.01*g*.

The structure fragilities are automatically estimated based on real-time structure failure evaluation framework. The fragility curve (Fig. 4) is linked with correlated peak ground accelerations (PGAs) based geotechnical spatial grid. Consequently, the failure probabilities in four damage levels of unreinforced concrete structure are calculated by correlated PGAs based on geotechnical spatial grid. Figure 6 presents the geotechnical spatial grid for the damage class based on fragility curve. And occupied ratio of cells which were evaluated as failure level (over 50% of failure probability) is utilized to determine the failure status of each four damage levels for target structure. The ratio was presented as caption of Figure 6.

For the hypothetical Baengnyeong Island earthquake scenario, the overall study area for passenger terminal (which had 14 cells among 17 cells covering the ground surface) was classified into failure state at the 'Slight' failure level. The east of the study area (with 18 cells covering the ground surface) was regarded as a safe region for the structure fragility, classified as having 'Safe' damage state because the topsoil generally consisted of non-amplifiable boulder stone or dredged silty clay. Therefore, the passenger terminal was determined failure status having 8% failure probability for seismic fragility, because the structure occupied most of the cells (having 80% occupied ratio of cells) evaluated as 'Slight' damage state (Figure 6(a)).

Otherwise, for the Baengnyeong Island earthquake event, every cells of the geotechnical spatial grid are evaluated as 'Safe' of damage state ($0 <$ Fragility $\leq 50\%$). Therefore, the target structure was determined as safe for seismic fragility (Figure. 6(b)). The simple safety test analysis for the target structure concluded that the structure is not affected by structure failure. As a result, considering site-specific seismic ground amplification in real-time using geotechnical spatial grid, the type of damage status such as differential settlement can be defined by determining the zonal failure probability of structure. It is potentially useful for stabilizing work to immediate restoration and post evaluation of structure safety.

Conclusions

A systematic framework for real-time assessment of the structure seismic fragility was developed to consider local site response characteristics. According to the framework, three interrelated assessment procedures were incorporated in a database on a real-time basis: geotechnical spatial grid construction, real-time seismic load determination, and real-time structure fragility evaluation. Previously, the geotechnical spatial grid was constructed based on 3D kriging of geotechnical data to constitute the 3D seismic ground conditions to be correlated with the structure fragility function. Second the previously derived correlation equations between the

PGA and the rock outcrop acceleration were incorporated in the geotechnical spatial grid to consider site-specific response characteristics. The correlated peak ground accelerations are linked with fragility functions and probabilities of failure are calculated. Seismic damage grades of superstructures are determined and they depend on the probabilities of failure. And the proposed framework has been specifically applied to the Incheon port, Korea, using Baengnyeong Island earthquake event and hypothetical scenario based on the GIS platform. The simulation results were visualized as a structure fragility hazard map to verify the applicability of the computer-aided real-time assessment framework.

Acknowledgements

This study was supported mainly from the project 'Establishment of seismic response monitoring system for port facilities and development of related technologies' sponsored by the Ministry of Land, Transport and Maritime Affairs of Korea and Seoul National University Engineering Research Institute.

References

ATC-13. *Earthquake damage evaluation data for California ATC-13* Report. Applied Technology Council, Redwood City, CA *1985*.

Au SK, and Beck JL. Subset simulation and its application to seismic risk based on dynamic analysis, *J. Eng. Mech. 2003;* **129**(8): 901-917.

Campbell KW and Bozorgnia Y. Updated near-source ground-motion (attenuation) relations for the horizontal and vertical components of peak ground acceleration and acceleration response spectra, *Bulletin of the Seismological Society of America. 2003;* **93**(1):314-331.

Chung CK, Kim HS, and Sun CK. Real-time assessment framework of spatial liquefaction hazard in port areas considering site-specific seismic response, *Computers and Geotechnics.*2014*;* **61**: 214-253.

Drabek TE and Hoetmer GJ. *Emergency Management: Principles and Practice for Local Government, Washington, DC: International City Management Association 1991*.

FEMA. *HAZUS-MH Technical Manual.* Federal Emergency Management Agency, Washington, D.C 2003.

Gardoni P, Der Kiureghian A, and Mosalam KM. Probabilistic capacity models and fragility estimates for RC columns based on experimental observations, *J. Eng. Mech.* 2002; **128**(10): 1024-1038.

Kim HS, Cho NG, and Chung CK. *Real-time LPI-based assessment of the liquefaction potential of the Incheon port in Korea, Proceeding of 15th World Conference of Earthquake Engineering, Lisbon, Portugal. 1120-1131. 2012.*

Kiureghian DA. Structural reliability methods for seismic safety methods for seismic safety assessment: A review, *Eng. Struct.* 1996; **18**(6): 412-426.

Lupoi G, Franchin P, Lupoi A, and Pinto PE. Seismic fragility analysis of structural systems, *Proc., 13th World Conf. Earthquake Engineering, Vancouver, Canada Paper No. 4008. 2004.*

NIBS. *Earthquake Loss Estimation Technology HAZUS*, Federal Emergency Management Agency, Washington D. C 1997.