SCENARIO EARTHQUAKE FOR SPATIALLY DISTRIBUTED STRUCTURES

K. Goda[1] and H.P. Hong[2]

[1] *Postdoctoral Fellow, Dept. of Earth Sciences, Univ. of Western Ontario, London, Canada*
[2] *Professor, Dept. of Civil & Environmental Eng., Univ. of Western Ontario, London, Canada*
Email: [1] *gouchan392@hotmail.com*, [2] *hongh@eng.uwo.ca*

ABSTRACT :

The catastrophic nature of seismic risk resides in the fact that a group of structures and infrastructure is simultaneously excited by spatially correlated seismic loads due to an earthquake: thus, both inter-event and intra-event correlations of ground motion measures must be taken into account. The spatial correlation of seismic demand affects aggregate seismic loss and identified scenario seismic events. In this study, a simulation-based seismic risk model for spatially distributed structures is developed. Analysis results indicate that adequate treatment of spatial correlation of seismic demand is essential in assessing the probability distribution of aggregate seismic loss, and that underestimation of spatial correlation of seismic demand leads to possible overestimation of scenario events.

KEYWORDS: Aggregate seismic loss, Scenario earthquake, Seismic loss estimation, Seismic risk deaggregation, Spatial correlation of seismic demand

1. INTRODUCTION

Ground shakings at different sites due to an earthquake are uncertain and spatially correlated. This spatial correlation increases the likelihood of simultaneous damage of structures and infrastructure in a single large seismic event. To cope with uncertainty in seismic loss estimation, one must adopt a probabilistic approach by considering probabilistic characteristics of spatial and temporal earthquake occurrence, spatially correlated seismic excitations, linear/nonlinear seismic demand, and structural capacity. The use of HAZUS-Earthquake (FEMA and NIBS, 2003) facilitates the evaluation of seismic risk for a group of buildings and infrastructure for a given scenario earthquake, although it lacks the consideration of spatially correlated seismic excitations. Recently, probabilistic seismic risk assessments of spatially distributed structures have been investigated by Goda and Hong (2008b) by considering both inter-event and intra-event correlations of seismic demand. The analysis results indicate that the impact due to correlated seismic excitations on seismic loss of a group of structures can be significant and such an effect must be taken into account in dealing with catastrophic seismic risk.

The assessment and mitigation of seismic risk of infrastructure systems often require the identification of scenario earthquakes (e.g., earthquake magnitude and distance measure) that are likely to contribute to a specified hazard/risk level significantly. This can be carried out based on the deaggregation analysis of seismic hazard and seismic risk (McGuire, 1995; Hong and Goda, 2006). Since the seismic risk assessment of a group of buildings is of direct interest to decision makers in municipalities and financial institutions who operate building assets and infrastructure capitals under catastrophic seismic risk, it is valuable to extend the deaggregation analysis of seismic risk for a single structure to that for a group of spatially distributed structures. It is noted that such an extension for seismic hazard deaggregation is not straightforward, since a seismic intensity measure for structures with different dynamic characteristics is difficult to choose.

This study is focused on the deaggregation analysis of seismic risk of spatially distributed buildings. The novel aspects of this study are that simultaneous seismic excitations of multiple structures are directly incorporated and seismic risk deaggregation is carried out by considering a group of buildings. In an adopted simulation-based seismic risk model, each structure is approximated by a bilinear single-degree-of-freedom

(SDOF) system and its maximum inelastic displacement is estimated based on the displacement coefficient method. Numerical examples, considering a set of 1000 hypothetical buildings that mimic an existing building stock in downtown Vancouver, are used to illustrate the effects of correlated seismic demand on aggregate seismic loss and on identified scenario earthquakes.

2. SEISMIC RISK MODEL FOR SPATIALLY DISTRIBUTED BUILDINGS

The overall seismic risk model and assessment procedure are illustrated in Figure 1 by focusing on Canadian environments. More details of the procedure are given in Goda and Hong (2008b).

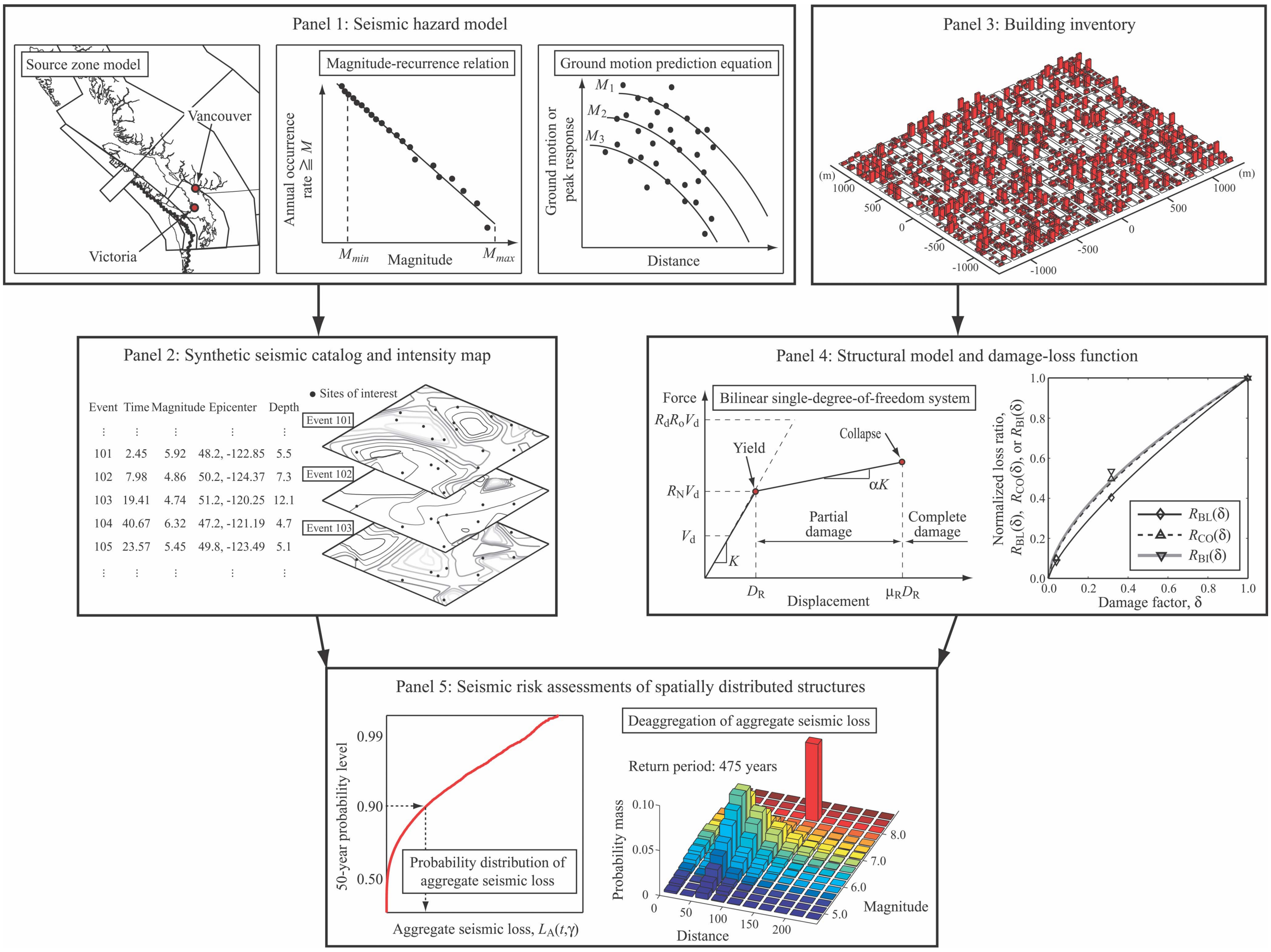

Figure 1 Seismic risk assessment procedure for spatially distributed structures: Panel 1) seismic hazard model, Panel 2) seismic catalog and intensity map, Panel 3) building inventory, Panel 4) structural model and damage-loss function, and Panel 5) seismic risk assessment of spatially distributed structures

The characterization of elastic seismic demand in terms of the pseudo-spectral acceleration (PSA) can be obtained by carrying out probabilistic seismic hazard analysis that incorporates earthquake occurrence models, seismic source zones, magnitude-recurrence relations, and ground motion prediction equations (GMPE) (Panel 1 in Figure 1). In this study, the seismic hazard model developed by Adams and Halchuk (2003) is adopted and used in a simulation-based approach, which facilitates the development of a synthetic earthquake catalog and event-dependent seismic intensity maps (Panel 2 in Figure 1 for illustration).

For western Canada, two sets of GMPEs are considered: the first set GMPE-1 includes the equations developed by Boore et al. (1993) for shallow crustal earthquakes and by Youngs et al. (1997) for interface and intraslab subduction earthquakes, which were adopted by Adams and Halchuk (2003), whereas the second set GMPE-2 includes the equations developed by Hong and Goda (2007) for shallow crustal earthquakes and by Atkinson and Boore (2003) for interface and intraslab subduction earthquakes. GMPE-2 can cope with different local site conditions, since the shear wave velocity in the uppermost 30 m, V_s, is incorporated.

To assess PSA responses at multiple sites for a given seismic event, the correlation model of residuals associated with an adopted GMPE needs to be considered. For this, the correlation model developed by Goda and Hong (2008a) is used. The correlation coefficient $\rho(T_{n1},T_{n2},\Delta)$ of residuals (in terms of the logarithm of PSA responses) at two sites with a separation distance Δ (km) is given by,

$$\rho(T_{n1},T_{n2},\Delta)=\frac{\rho_1(T_{n1},T_{n2})\left(\sigma_1(T_{n1})\sigma_1(T_{n2})+\rho_2(\Delta,T_{\max})\sigma_2(T_{n1})\sigma_2(T_{n2})\right)}{\sigma_\varepsilon(T_{n1})\sigma_\varepsilon(T_{n2})}, \tag{2.1}$$

where T_{n1} and T_{n2} are the natural vibration periods of linear elastic SDOF systems at two sites; T_{max} is the larger of T_{n1} and T_{n2}; and $\sigma_1(T_n)$, $\sigma_2(T_n)$, and $\sigma_\varepsilon(T_n)$ are the standard deviations of inter-event, intra-event, and total residuals, respectively. $\rho_1(T_{n1},T_{n2})$ is the correlation coefficient of inter-event residuals, which can be estimated by using the empirical equation developed by Baker and Cornell (2006), whereas $\rho_2(\Delta,T_{max})$ is the correlation coefficient of intra-event residuals and can be approximated by $\rho_2(\Delta,T_{max}) = \exp((0.16\ln(T_{max})-0.68)\Delta^{0.44})$ (Goda and Hong, 2008a).

An adequate choice of the structural model and analysis method is important for seismic loss estimation, since they affect overall accuracy of seismic risk assessments. For efficiency, FEMA and NIBS (2003), ATC (2005), and Hong and Hong (2007) considered the use of an equivalent SDOF system with the capacity spectrum method and/or the displacement coefficient method to estimate the maximum inelastic displacement demand. Since this study aims at carrying out seismic loss estimation of spatially distributed structures over a very long period of time, the use of equivalent SDOF systems is considered to be suitable. More specifically, for a building inventory consisting of m buildings (Panel 3 in Figure 1 for illustration), the i-th structure in the inventory with the yield displacement capacity D_{Ri} and the displacement ductility capacity μ_{Ri}, is approximated by a bilinear SDOF system whose force-displacement curve is illustrated in Panel 4 of Figure 1. The maximum inelastic displacement of a bilinear SDOF system can be characterized by using the probabilistic model of the ductility demand μ_D developed by Hong and Hong (2007). Given PSA responses for the j-th seismic event and D_{Ri}, the ductility demand μ_{Dij} can be sampled from the probability distribution of μ_D, and the corresponding damage factor δ_{ij}, which is defined as the ratio of μ_{Dij}-1 to μ_{Ri}-1 and ranges between 0 and 1, can be evaluated for a simulated sample of μ_{Ri}. The structural characteristics of the bilinear models can be related to codified designs (e.g., NRCC (2005)) by using the ratio of the yield strength of a designed structure to the minimum required design yield strength, R_N (Panel 4 in Figure 1).

To relate damage severity with the replacement cost for various seismic loss categories, one can adopt discrete damage-loss relations based on comprehensive information on damage states and damage costs provided in FEMA and NIBS (2003). For convenience, seismic losses associated with building operation are categorized into building-related loss $L_{BL}(\delta)$, contents-related loss $L_{CO}(\delta)$, and business-interruption-related loss $L_{BI}(\delta)$, where δ is the damage factor relating the ductility demand and capacity. By approximating the normalized loss ratios R_k, defined as $L_k(\delta)/L_k(1)$ where k denotes BL, CO, or BI and $L_k(1)$ is the unit replacement cost, by a power function with the exponent parameter β_k, continuous damage-loss functions are developed (i.e., exponent parameters β_{BL}, β_{CO}, and β_{BI} are obtained; see Panel 4 in Figure 1) and used to evaluate damage costs.

Based on the aforementioned seismic risk model, the discounted aggregate seismic loss $L_A(t,\gamma)$ for m buildings subject to $n(t)$ earthquakes that occur at time τ_j in a period of t years, is calculated as,

$$L_A(t,\gamma) = \sum_{j=1}^{n(t)} L_{Agg,j} \text{ ,} \tag{2.2}$$

where γ is the discount rate, and $L_{Agg,j}$ is the present value of aggregate seismic loss of *m* buildings due to the *j*-th earthquake occurring at time τ_j and causing damage severity δ_{ij} to the *i*-th building, which is given by,

$$L_{Agg,j} = \sum_{i=1}^{m} \left(L_{BL}(\delta_{ij}) + L_{CO}(\delta_{ij}) + L_{BI}(\delta_{ij}) \right) \exp(-\gamma\tau_j) \text{ .} \tag{2.3}$$

The use of seismic loss as a "deaggregating" variable facilitates the identification of scenario seismic events for a group of buildings with different dynamic characteristics.

3. DEAGGREGATION OF SEISMIC RISK OF MULTIPLE BUILDINGS

3.1. Building Inventory

For numerical analysis, a set of 1000 hypothetical buildings located in Vancouver (49.2°N, 123.2°W) is considered. The seismic hazard for Vancouver is based on both historical and regional seismicity models together with the Cascadia subduction events (Adams and Halchuk, 2003). The set of 1000 hypothetical buildings, which is randomly distributed over a square area of 2 km by 2 km and is illustrated in Panel 3 of Figure 1, is constructed based on the statistical information on existing buildings located in downtown Vancouver reported in Munich Re (1992) and Onur (2001). The local site condition in Vancouver is assigned as the site class C (Cassidy and Rogers, 2004), where V_s equal to 555 m/s is adopted for the base case.

The inventory consists of 18 building types with different structural systems and occupancies (400 residential buildings and 600 commercial buildings). Detailed information on configuration, structural system, occupancy, damage-loss relations, and structural capacity of each building type can be found in Goda and Hong (2008b). The structural capacity parameters R_N and μ_R are considered to be lognormally distributed with the assigned statistics in agreement with those given in the literature (Onur, 2001; FEMA and NIBS, 2003; Ibarra, 2003; NRCC, 2005). In the following, the aggregate seismic loss $L_A(t,\gamma)$ of the 1000 hypothetical buildings with γ = 0.05 and t = 50 (years) is evaluated using the above-mentioned seismic risk model. The simulated samples are used to assess the probability distribution of $L_A(t,\gamma)$ and to carry out deaggregation analysis based on L_{Agg} (Panel 5 of Figure 1).

3.2. Aggregate Seismic Loss of 1000 Buildings in Vancouver

The probability distributions of $L_A(t,\gamma)$ for three correlation cases, namely, no correlation case, full correlation case, and partial correlation case that uses Eqn. 2.1, based on two sets of GMPEs are shown in Figure 2, where the samples of $L_A(t,\gamma)$ are plotted on Gumbel probability paper. For the analysis, the coefficient of variation (cov) of R_N, cov of μ_R, cov of unit costs, and mean and cov of V_s denoted as [cov of R_N, cov of μ_R, cov of unit replacement costs, mean of V_s, cov of V_s] is set equal to [0.15, 0.3, 0.0, 555, 0.0]. The results shown in Figure 2a indicate that the probability distribution for the partial correlation case is bounded by those obtained for the no and full correlation cases, and that the mean of $L_A(t,\gamma)$ is insensitive to the correlation cases, whereas the standard deviation of $L_A(t,\gamma)$ and Prob($L_A(t,\gamma)$>0) are affected by the considered correlation cases. Similar observations can be made from the results shown in Figure 2b which are obtained by using GMPE-2. The comparison of Figures 2a and 2b suggests that the use of GMPE-2 rather than GMPE-1 leads to lower seismic loss estimates.

To investigate the impact of uncertain model parameters on $L_A(t,\gamma)$, we denote the results shown in Figure 2b for the partial correlation case as Case A, and repeat the analysis for [cov of R_N, cov of μ_R, cov of unit costs, mean of V_s, cov of V_s] equal to [0.3, 0.6, 0.3, 555, 0.3] as Case B and equal to [0.3, 0.6, 0.3, 360, 0.3] as Case C. The obtained results for Cases B and C using GMPE-2 are shown in Figure 2b. The assigned values of model parameters are based on the information given in Ibarra (2003), Cassidy and Rogers (2004), and PEER Center (2006). Note that unit costs as well as V_s are considered to be lognormally distributed, and possible correlation for these variables is ignored. The comparison of the results for Cases A, B, and C indicates that the increased uncertainty in R_N, μ_R, unit costs, and V_s leads to 40% increase of the mean of $L_A(t,\gamma)$, whereas the use of V_s = 360 (m/s) rather than V_s = 555 (m/s) leads to 60% increase of the mean of $L_A(t,\gamma)$ additionally. The results highlight the importance of uncertainty in the model parameters as well as the average local soil conditions in addition to the treatment of spatial correlation of seismic demand.

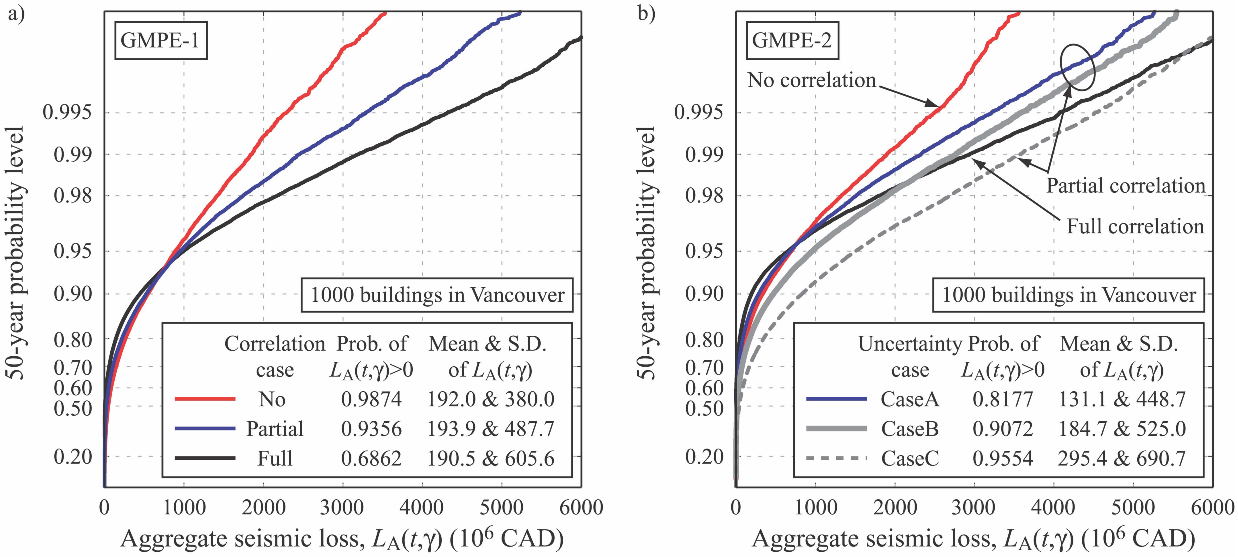

Figure 2 Probability distributions of $L_A(t,\gamma)$ of 1000 buildings plotted on Gumbel probability paper considering three correlation cases: a) GMPE-1 and b) GMPE-2

Deaggregation of seismic risk for a group of buildings is carried out by adopting the discounted aggregate seismic loss L_{Agg} as the deaggregating variable. This is done by considering three correlation cases and the return period of 475 years, and the obtained probability mass functions in terms of the magnitude M and the distance R are shown in Figure 3 for GMPE-1 and GMPE-2. For each deaggregation result, the estimated damage occurrence rate per year λ_D, mean and modal statistics of M and R, and the corresponding fractile of L_{Agg} are shown in the figures.

Figure 3 shows that for the considered return period level, the deaggregation results for the three correlation cases are similar and the statistics of M and R as well as the overall peakedness of the probability masses for the partial correlation case are bounded by those for the no and full correlation cases. The latter is in agreement with the results obtained from the probability distribution of $L_A(t,\gamma)$. A higher spatial correlation of seismic demand results in smoother appearances of the probability masses. This can be explained by noting that if seismic demand is highly correlated, moderate combinations of M and R, which occur more frequently, can result in relatively large seismic losses, whereas if seismic demand is less correlated, relatively large seismic losses are likely to be attained for more extreme combinations of M and R. Thus, underestimation of spatial correlation of seismic demand can result in possible overestimation of scenario events. Note that the use of GMPE-2 rather than GMPE-1 increases the relative impact of the Cascadia subduction events. This is due to the difference between the Youngs et al. relation and the Atkinson and Boore relation for interface and intraslab subduction earthquakes. It is noteworthy that for all cases, the impact of the Cascadia subduction events is not negligible, and they deserve serious considerations in assessing seismic risk.

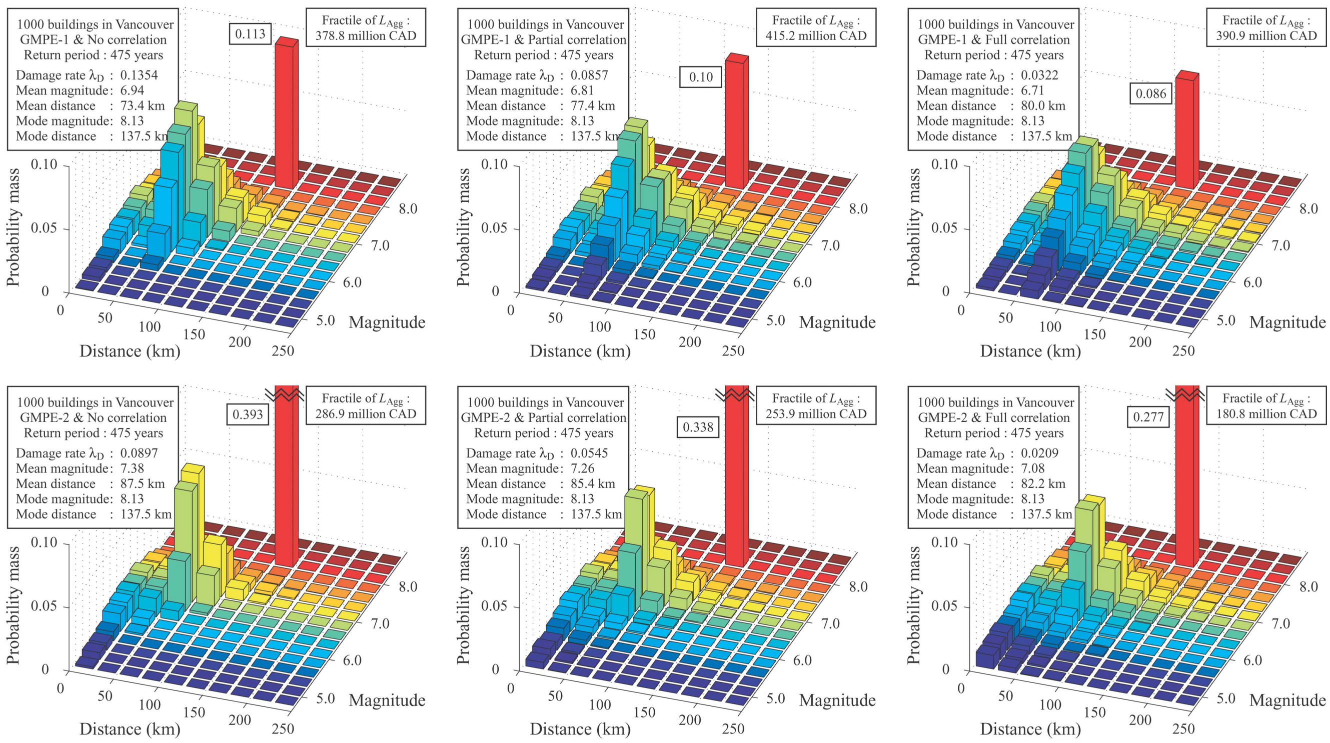

Figure 3 Deaggregation of L_{Agg} of 1000 buildings for the 475-years return period considering three correlation cases and using GMPE-1 (top) and GMPE-2 (bottom)

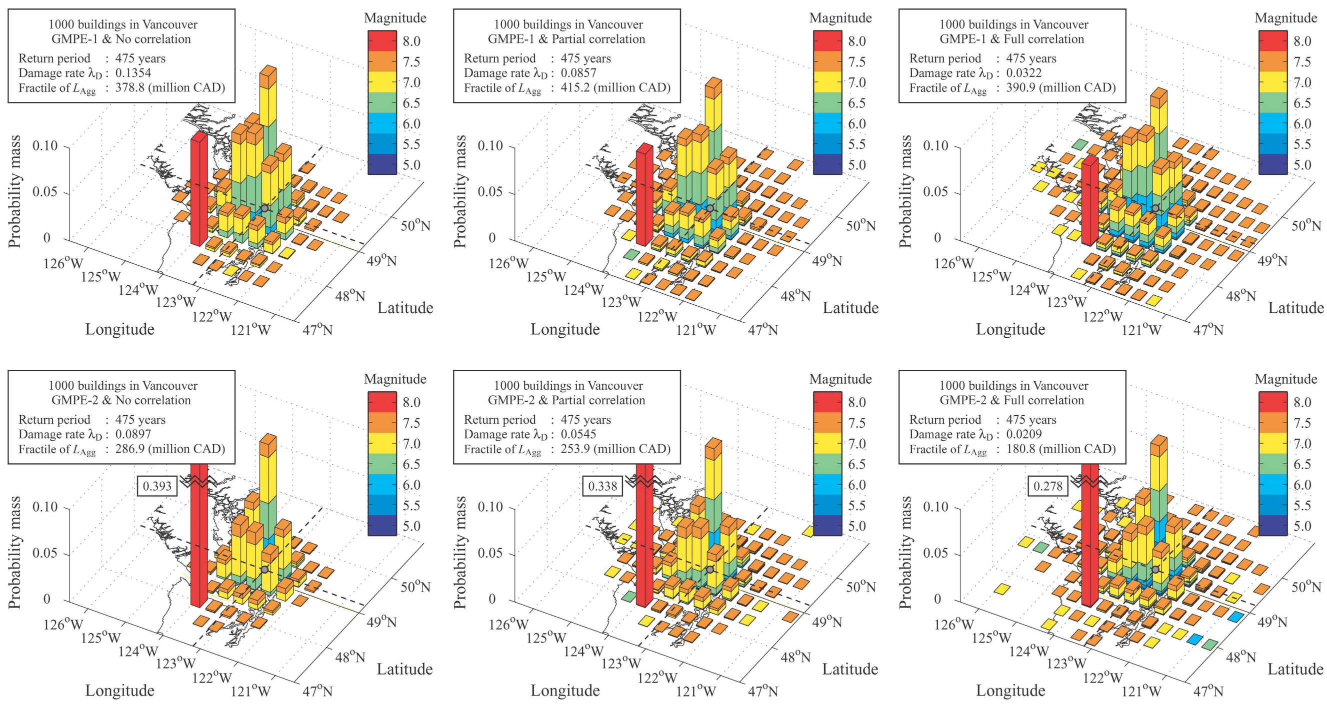

Figure 4 Geographic deaggregation of L_{Agg} of 1000 buildings for the 475-years return period considering three correlation cases and using GMPE-1 (top) and GMPE-2 (bottom)

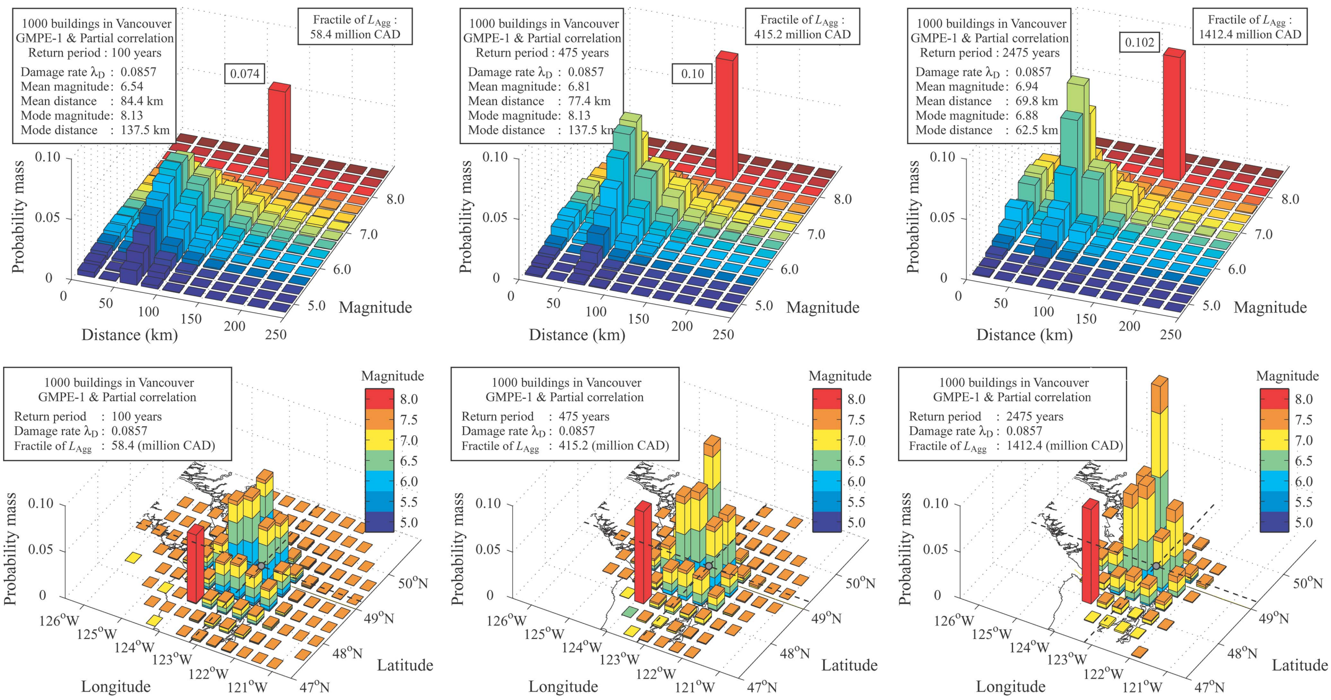

Figure 5 Deaggregation of L_{Agg} of 1000 buildings for the return periods of 100, 475, and 2475 years considering the partial correlation case and using GMPE-1

To investigate the geographical distribution of seismic events contributing to a selected seismic risk level specified in terms of L_{Agg}, geographical deaggregation analysis is carried out for the return period of 475 years, and the obtained results are shown in Figure 4. It is observed that the values of M for the cases using GMPE-2 tend to be higher than those for the cases using GMPE-1, and that the geographical locations of epicenter for the former tend to be closer to the site than those for the latter. These observations reflect the difference between the Youngs et al. relation and the Atkinson and Boore relation in the attenuation rate of predicted ground motions. Moreover, to investigate the appearances of the deaggregation results for different return periods, the deaggregation results for the partial correlation case using GMPE-1 are shown in Figure 5 by considering the return periods of 100, 475, and 2475 years. The results indicate that the probability masses become more peaked and concentrated at higher values of M as the return period level increases, which are expected.

4. SUMMARY AND CONCLUSIONS

Seismic risk deaggregation of a group of spatially distributed structures is carried out by using a simulation-based seismic risk assessment framework and by taking spatial correlation of seismic excitations into account. The deaggregation analysis identifies scenario seismic events or most likely seismic events leading to aggregate seismic loss for a specified probability of exceedance level. The analysis results indicate that adequate treatment of spatial correlation of seismic demand is of high importance in assessing seismic risk of a group of spatially distributed structures, since the spatial correlation model could significantly affect fractiles of aggregate seismic loss and deaggregation results. The overestimation and underestimation of spatial correlation can lead to decreased and increased severity of scenario events, respectively, and the impact of the Cascadia subduction events on aggregate seismic loss of spatially distributed buildings in Vancouver is not negligible. Moreover, the sensitivity analysis results highlight that seismic risk is sensitive to the uncertainty in structural capacity parameters and the average local soil condition.

ACKNOWLEDGEMENTS

The financial supports of the Natural Science and Engineering Research Council of Canada and the University of Western Ontario are gratefully acknowledged.

REFERENCES

Adams, J. and Halchuk, S. (2003). Fourth Generation Seismic Hazard Maps of Canada: Values for over 650 Canadian Localities Intended for the 2005 National Building Code of Canada, Open-File 4459. Geological Survey of Canada, Ottawa, Canada.

ATC (2005). Improvement of Nonlinear Static Seismic Analysis Procedures, FEMA-440, Applied Technology Council, Washington, D.C.

Atkinson, G.M. and Boore, D.M. (2003). Empirical ground-motion relations for subduction-zone earthquakes and their application to Cascadia and other regions. *Bull. Seism. Soc. Am.* **93**, 1703-1729.

Baker, J.W. and Cornell, C.A. (2006). Correlation of response spectral values for multicomponent ground motions. *Bull. Seism. Soc. Am.* **96**, 215-227.

Boore, D.M., Joyner, W.B. and Fumal, T.E. (1993). Estimation of Response Spectra and Peak Accelerations from Western North American Earthquakes: an Interim Report, Open-File 93-509, U.S. Geological Survey, Menlo Park, CA.

Cassidy, J.F. and Rogers, G.C. (2004). Variation in ground shaking on the Fraser River delta (Greater Vancouver, Canada) from analysis of moderate earthquakes. Proc. 13WCEE, Vancouver, Canada, Paper No. 1010.

FEMA and NIBS (2003). HAZUS-Earthquake - Technical Manual. Federal Emergency Management Agency and National Institute of Building Sciences, Washington, D.C.

Goda, K. and Hong, H.P. (2008a). Spatial correlation of peak ground motions and response spectra. *Bull. Seism. Soc. Am.* **98**, 354-365.

Goda, K. and Hong, H.P. (2008b). Estimation of seismic loss for spatially distributed buildings. *Earthquake Spectra* **24** (in press).

Hong, H.P. and Goda, K. (2006) A comparison of seismic hazard and risk deaggregation. *Bull. Seism. Soc. Am.* **96**, 2021-2039.

Hong, H.P. and Goda, K. (2007). Orientation-dependent ground-motion measure for seismic-hazard assessment. *Bull. Seism. Soc. Am.* **97**, 1525-1538.

Hong, H.P. and Hong, P. (2007). Assessment of ductility demand and reliability of bilinear single-degree-of-freedom systems under earthquake loading. *Canadian J. Civil Eng.* **34**, 1606-1615.

Ibarra, L.F. (2003). Global Collapses of Frame Structures under Seismic Excitations, Ph.D. Dissertation, Stanford University, Stanford, CA.

McGuire, R.K. (1995). Probabilistic seismic hazard analysis and design earthquakes: closing the loop. *Bull. Seism. Soc. Am.* **85**, 1275-1284.

Munich Re (1992). A Study of the Economic Impact of a Severe Earthquake in the Lower Mainland of British Columbia, Munich Reinsurance Company of Canada, Vancouver, Canada.

NRCC (2005). National Building Code of Canada 2005, National Research Council of Canada, Ottawa, Canada.

Onur, T (2001). Seismic Risk Assessment in South Western British Columbia, Ph.D. Dissertation, University of British Columbia, Vancouver, Canada.

PEER Center (2006). Next Generation Attenuation Database, Pacific Earthquake Engineering Research Center, http://peer.berkeley.edu/nga/index.html.

Youngs, R.R., Silva, W.J. and Humphrey, J.R. (1997). Strong ground motion attenuation relationships for subduction zone earthquakes. *Seism. Res. Lett.* **68**, 58-72.