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Incremental dynamic analysis of wood-frame houses in Canada: Effects of dominant earthquake scenarios on seismic fragility

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ABSTRACT

Seismic fragility can be assessed by conducting incremental dynamic analysis (IDA). This study extends the current conditional mean spectrum (CMS)-based record selection approach for IDA by taking into account detailed seismic hazard information. The proposed method is applied to conventional wood-frame houses in Canada, across which dominant earthquake scenarios and associated hazard levels vary significantly. Effects due to different seismic environments, site conditions, CMS-based record selection methods, and house models are investigated by comparing various seismic fragility models. Moreover, relative impact of the key characteristics is evaluated in terms of seismic loss curve for a group of wood-frame houses. Importantly, a close examination of regional seismic hazard characteristics using seismic hazard curve and seismic deaggregation facilitates the deeper understanding of the impact of ground motion characteristics on seismic fragility. A comprehensive and systematic assessment of key uncertainties associated with seismic fragility is provided.

1. Introduction

Seismic fragility assessment is a critical and integrated part of quantitative seismic loss estimation methodology and performance-based earthquake engineering framework [1]. It involves prediction of an engineering demand parameter (EDP; e.g. maximum inter-story drift ratio of a structure) for a given intensity measure (IM; e.g. spectral acceleration at the fundamental vibration period of a structure). Seismic fragility models can be developed based on statistical analysis of empirical damage data [2]. Where sufficient empirical data are not available, an alternative option is to conduct extensive numerical investigations of structural models, such as incremental dynamic analysis (IDA) [3]. The IDA repeatedly carries out nonlinear dynamic analysis of a structural model subjected to scaled accelerograms. It is a viable numerical procedure to develop a probabilistic model of EDP for a given IM and to assess collapse capacity of a structure, and has been applied to various types of structures, including wood-frame houses [4,5]. Recent developments of the IDA have focused upon quantification of uncertainty associated with the IDA-based fragility models by taking into account uncertain structural parameters [6,7].

Careful record selection is important to produce unbiased estimates of seismic fragility, when record scaling is conducted based on elastic-based IMs. An alternative approach to obtain unbiased estimates is to use advanced IMs, such as inelastic spectral displacement [8,9]. Typically, several tens of ground motion records that match a target response spectrum or instead resemble some key record features (e.g. earthquake scenarios in terms of magnitude, distance, and faulting mechanism) are selected as input motion. When the response spectrum of a record is compared with the target response spectrum, overall fitness of the record can be evaluated in terms of the sum of squared differences between the record and the target over a range of vibration periods. For the target spectrum, design response spectra, such as uniform hazard spectrum (UHS) and conditional mean spectrum (CMS), are often considered [10]. The use of UHS as target spectrum for record selection is incompatible with its definition, because UHS is a 'composite' of response spectra based on various scenarios that contribute to a selected probability level. Therefore, using a record that matches with the target UHS closely results in more extreme situations; generally, no single record matches the target UHS over a wide period range. In contrast, the CMS represents the expected response spectral ordinates for a specific probability level by taking into account the inter-period correlation of response spectra at different vibration periods [10]. Therefore, the use of CMS as target spectrum is adequate for assessing seismic performance of a structure.

In the CMS-based record selection, which involves record scaling, the response spectral shape is the key record characteristic [11], which is affected by several factors, such as magnitude and site condition. For example, response spectra tend to contain rich long-period spectral content as magnitude increases and

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site condition becomes softer. In cases dominant scenarios have distinct features, record selection should reflect underlying record characteristics by adopting multiple target CMS for different scenarios. The scenarios can be described in terms of earthquake event type (e.g. crustal/interface/inslab) and magnitude–distance combination. The effect of using multiple target CMS, reflecting real situations more closely, is increased variability of the predicted EDP for a given IM. Goda and Atkinson [5] showed how such detailed seismic hazard information from probabilistic seismic hazard analysis (PSHA) can be incorporated in defining multiple target CMS for crustal, interface, and inslab events in western Canada.

This study investigates the effects of dominant scenarios on seismic fragility and seismic loss for conventional wood-frame houses in Canada. The majority of wooden houses in Canada, constructed prior to 1975, are non-engineered and may be deficient in post-yield seismic resistance [12,13]. Quantitative assessment of seismic performance of wood-frame houses provides home owners and emergency officials with valuable information on regional seismic risk exposure. For structural analysis, so-called SAWS models [14] are adopted (Section 2), which were calibrated based on extensive experimental test results [15,16] and are appropriate for typical wooden houses in Canada. Input motions are selected from the PEER-NGA database (http://peer.berkeley.edu/nga/) and the K-NET/KiK-net database (http://www.kik.bosai.go.jp/) based on CMS reflecting regional dominant earthquake scenarios (Sections 3 and 4). In western Canada, three dominant earthquake types, shallow crustal, deep inslab, and offshore Cascadia interface events, contribute significantly to overall regional seismic hazard. In eastern Canada, magnitudes of major scenarios are smaller in comparison with western Canada, yet potentially large destructive earthquakes from the St. Lawrence rift zone might be expected [17], affecting many cities and towns in eastern Canada. Importantly, this work extends the previous work [5] in two aspects: (1) impact of different IDA–CMS-based approaches is assessed in terms of regional seismic risk for a group of wooden houses (beyond the comparison of fragility curves), and (2) seismic hazard estimates as well as dominant earthquake scenarios varying across the territory significantly are taken into account. Systematic investigations of IDA–CMS-based fragility models by considering detailed seismic characteristics across Canada are highlighted. In particular, this study presents comprehensive assessment of seismic fragility of conventional wooden houses in Canada by focusing on regional seismicity (different locations), distinction of earthquake scenarios, and local site conditions (Section 5). Finally, a comparative investigation of seismic loss estimation of multiple wood-frame houses [18] is conducted for different locations using the developed fragility models (Section 6). One of the main objectives is to evaluate the relative impact of 'seismic hazard' versus 'seismic fragility' on the final seismic loss estimation results.

2. Structural models for wood-frame houses

The SAWS (Seismic Analysis of Woodframe Structures) software deals with a so-called pancake structural model subjected to bi-directional horizontal ground shaking [14]. Hysteretic characteristics of a shear-wall element are represented by a nonlinear spring that incorporates strength/stiffness degradation and pinching behaviour of nonlinear sheathing-to-framing connectors using the CASHEW (Cyclic Analysis of SHEar Walls) software [19]. The model parameters of CASHEW can be calibrated based on a series of quasi-static and dynamic tests of wooden wall assemblies with different sheathing and finishing materials, and a validity of full-scale house models can be evaluated by comparing shake-table test results with numerical simulations. For typical residential single-family wood-frame houses in Canada, such experimental and analytical investigations were carried out by researchers at the University of British Columbia (UBC) [15,16]. Eventually, four UBC-SAWS models have been developed: (1) House 1 has blocked plywood/oriented strand board (OSB) shear-walls with exterior stucco cladding and gypsum wallboard (GWB) interior finish; (2) House 2 has blocked plywood/OSB shear-walls with GWB interior finish; (3) House 3 has unblocked plywood/OSB shear-walls with GWB interior finish; and (4) House 4 has horizontal boards with GWB interior finish. Houses 1 and 2 are related to design/construction practice in the U.S. with seismic considerations. On the other hand, Houses 3 and 4 correspond to conventional construction practice in Canada, where gravity and wind loads are mainly concerned as specified in the National Building Code of Canada (NBCC) without seismic provisions.

The generic structural representation and plan view of the UBC–SAWS models are shown in Fig. 1a. The seismic resistance along a wall line in each direction is represented by a nonlinear spring. Shear-wall elements along the X direction are varied for different house models (i.e. W1 to W7), whereas those along the Y direction are the same for the four house models (i.e. W8 to W16). Moreover, stiffness along the Y direction is higher than stiffness along the X direction, reflecting the set-up of uni-directional

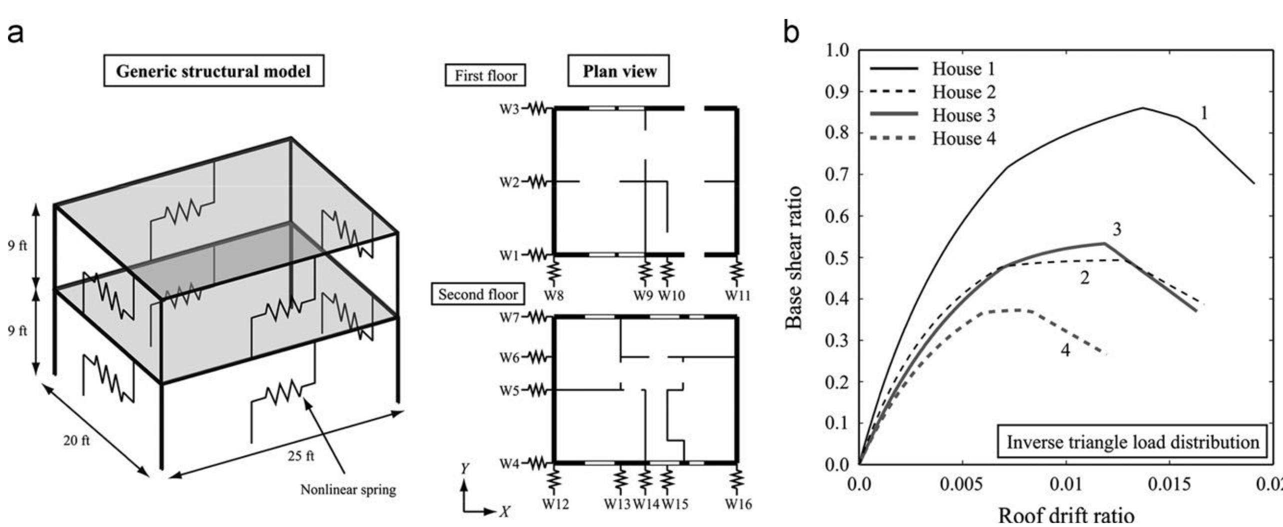

Fig. 1. UBC-SAWS model: (a) structural model and (b) static pushover curve.

shake table tests [15]. The natural vibration periods of the four house models along the X direction range from 0.25 s to 0.4 s, while those for the Y direction are about 0.22 s for all house models. White and Ventura [16] concluded that the accuracy of the UBC–SAWS models in terms of initial vibration period and maximum inter-story drift ratio is reasonable, and the UBC–SAWS models are capable of predicting the maximum inter-story drift ratios up to about 0.04 reasonably well. Their ability to predict higher inter-story drift ratios (exceeding the maximum drift ratio of 0.05) has not been fully validated, and more extensive shake-table tests, reaching high drift ratios close to the collapse limit of a structure [20], are desirable. However, for given resource constraints in experimental programs, calibrated models based on the currently available test results are considered to be acceptable. To compare the seismic capacity of the four houses, nonlinear static pushover curves for the four UBC–SAWS models along the X direction are shown in Fig. 1b. In the figure, both vertical and horizontal axes represent quantities normalised with respect to total weight and total height of a house. Fig. 1b shows that House 1 has superior seismic resistance in terms of both base shear and roof drift ratios; seismic capacities for Houses 2 and 3 are similar; and House 4 has much lower seismic capacity, compared to Houses 1–3. This comparison clearly indicates the benefit of upgrading from House 4 to Houses 1–3 for seismic risk mitigation.

3. Incremental dynamic analysis and conditional mean spectrum

The IDA is an analytical procedure for evaluating the seismic fragility of a structural system and requires a set of carefully selected ground motion records that are appropriate for intended damage states. For example, when the near-collapse damage state is of interest, selected records should reflect key characteristics of expected ground motions that lead to the specified damage state (amplitude, frequency content, duration, etc.). By repeating nonlinear dynamic analyses for scaled records at various IM levels, samples of EDP and IM are generated and are used to develop a probabilistic relationship between EDP and IM. As the amplitude is matched by record scaling, record selection mainly concerns the frequency content of input motion and duration. Luco and Bazzurro [11] suggested that similarity of the response spectral shape of a record to the target response spectrum is important to avoid significant bias caused by excessive record scaling. Moreover, Baker [10] proposed that the use of CMS, rather than UHS, is adequate to represent a target response spectrum, which is derived from PSHA.

The CMS-based record selection procedure begins by specifying a target seismic intensity level, in terms of $S_a(T_n)$, and representative scenarios, in terms of moment magnitude (M_w), distance (R), and epsilon (ε). $S_a(T_n)$ is the spectral acceleration at the fundamental vibration period T_n of a structure. For all UBC–SAWS models, T_n=0.3 s is adopted, as this period is approximately in the middle of the range of the measured vibration periods of the full-scale house models. Epsilon is the number of logarithmic standard deviations of a ground motion with respect to a median ground motion prediction equation (GMPE) for a given scenario in terms of M_w and R. The CMS is given by

$$\mu_{\ln S_a(T_i)|\ln S_a(T_n)} = \mu_{\ln S_a}(\overline{M}_w,\overline{R},T_i) + \rho(T_i,T_n)\overline{\varepsilon}(T_n)\sigma_{\ln S_a}(T_i) \quad (1)$$

where $\mu_{\ln S_a}(\overline{M}_w,\overline{R},T_i)$ and $\sigma_{\ln S_a}(T_i)$ are the median and logarithmic standard deviation of predicted spectral accelerations at T_i, and $\rho(T_i,T_n)$ is the inter-period correlation of spectral accelerations at vibration periods T_i and T_n. $\mu_{\ln S_a}(\overline{M}_w,\overline{R},T_i)$ and $\sigma_{\ln S_a}(T_i)$ are obtained from empirical GMPEs that are used in PSHA, while $\overline{M}_w$, $\overline{R}$, and $\overline{\varepsilon}$ are determined by seismic deaggregation. For $\rho(T_i,T_n)$, several models that are proposed in the literature can be employed, e.g. Baker and Cornell model [21] for the PEER-NGA database and Goda and Atkinson model [22] for the K-NET/KiK-net database.

To capture distinct characteristics of dominant scenarios, multiple CMS for a given probability level can be derived. This is particularly applicable to western Canada, where different types of earthquakes (crustal/interface/inslab) contribute to overall seismic hazard significantly [17]. Such distinction may be effective in capturing source and path effects simultaneously; for instance, the Cascadia subduction events are associated with a specific combination of magnitude and distance for a given site. The consideration of multiple CMS leads to more variation of the expected response spectral shape, and consequently results in increased variability of the final IDA results [5]. Similarly, distinction in terms of magnitude may be applicable to eastern Canada, where large characteristic events (M_w 7.5 class) are likely to be originated from the St. Lawrence rift zone, while local small-to-moderate events (M_w 5.0–6.5) occur elsewhere. In the record selection based on multiple CMS, relative weights for individual scenario cases (either crustal/interface/inslab events for western Canada or small/moderate/large events for eastern Canada) are assigned in proportion to relative contributions of these scenarios to overall seismic hazard. For instance, consider 50 records are required for the IDA, and seismic deaggregation results at a probability level indicate that relative contributions due to crustal/interface/inslab events are 30%, 20%, and 50%, then, 15, 10, and 25 records are chosen respectively from record databases for the specific event types (note: a record database is developed for each event type). The multiple-CMS-based approach is a viable method to incorporate realistic record features of dominant scenario events effectively and to define physically meaningful expected ground motions for record selection. In fact, this method can be viewed as a version of vector-valued probabilistic seismic demand analysis [23].

The final step of the multiple-CMS-based record selection is to identify ground motion records, response spectra of which match the target CMS over a range of vibration periods in a least-squares sense. The fitting is conducted for individual scenario cases (e.g. event type for western Canada and magnitude range for eastern Canada). It is noted that the vibration period range used for the least squares fitting has influence on the developed seismic fragility models, as the vibration period of a structure is gradually elongated with the progress of sustained structural nonlinearity.

4. Dominant earthquake scenarios in western and eastern Canada

4.1. Probabilistic seismic hazard analysis

The multiple-CMS approach requires detailed information on dominant earthquake scenarios from PSHA. It is noteworthy that key features of dominant earthquake scenarios vary across Canada. To concentrate on locations where major urban seismic risk is anticipated, Vancouver, Victoria, Montreal, and Ottawa are focused upon. PSHA is carried out using the updated seismic hazard model for western and eastern Canada [17]. This model is advantageous in producing PSHA results based on recent seismological findings, and incorporates: (i) probabilistic Cascadia subduction scenarios for western Canada (Fig. 2a); (ii) characteristic earthquakes in the St. Lawrence rift zone, combined with segmented local sources for small-to-moderate events (Fig. 2b); (iii) updated magnitude–recurrence relationships for source zones in western and eastern Canada (Fig. 2) using a longer earthquake catalogue based on uniform moment magnitude

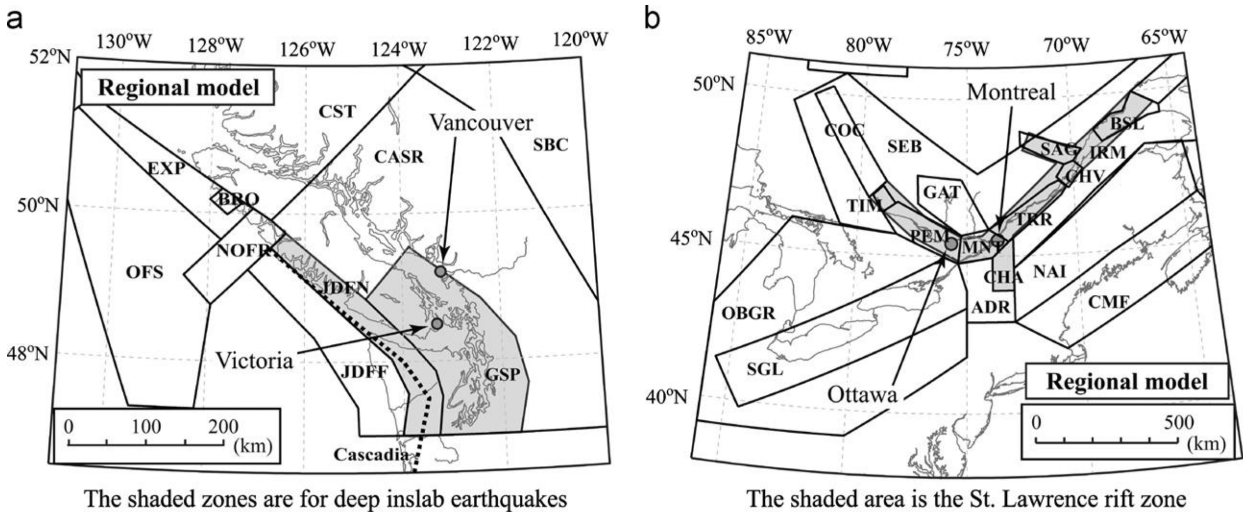

Fig. 2. Seismic source zone model: (a) western Canada and (b) eastern Canada.

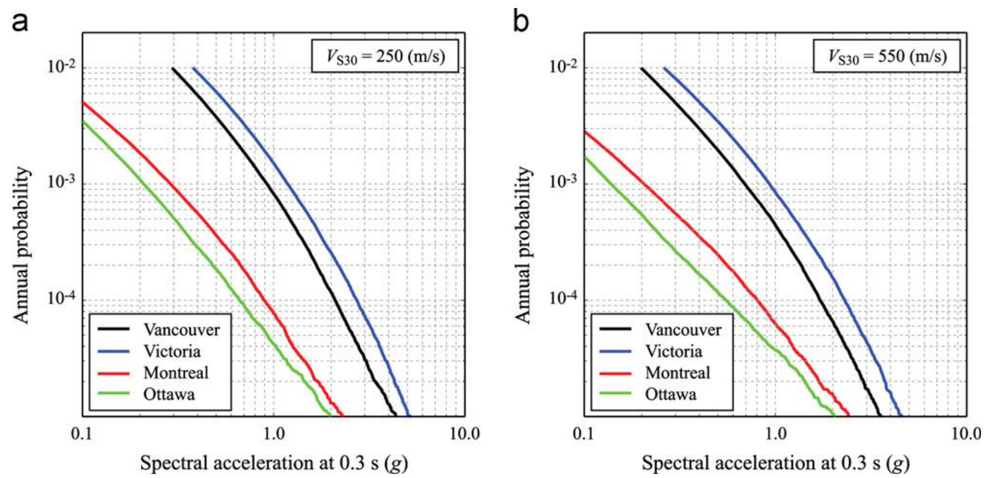

Fig. 3. Seismic hazard curves for Vancouver, Victoria, Montreal, and Ottawa: (a) V_{S30}=250 m/s and (b) V_{S30}=550 m/s.

scale; (iv) finite-fault source representation for evaluating source-to-site distance measures; and (v) newer GMPEs.

For each location, PSHA is conducted for two site conditions, soft soil (i.e. site class D with the average shear-wave velocity in the uppermost 30 m V_{S30}=250 m/s) and firm soil (i.e. site class C with V_{S30}=550 m/s). Fig. 3 shows seismic hazard curves for $S_a(0.3)$ (i.e. IM adopted for the UBC–SAWS models) at the four locations for the two site conditions. The estimated seismic hazards for Vancouver and Victoria are much greater than those for Montreal and Ottawa (as expected). Soft soil conditions result in larger seismic hazard estimates than firm soil conditions when the seismic excitation levels are relatively moderate. As $S_a(0.3)$ increases, the effects of saturation/deamplification of short-period ground shaking (as implemented in individual GMPEs) become greater and thus the differences between the two site conditions (for the same location) decrease gradually. Another important observation is that the slopes of the hazard curves are flatter for eastern Canada than western Canada, indicating different levels of uncertainty associated with seismic hazard estimates across Canada. Moreover, comparison of UHS for the four locations (not presented for brevity) indicates that the response spectral shapes for eastern Canada contain richer spectral content in the short vibration period range than those for western Canada, which is a typical feature of GMPEs for eastern Canada (reflecting less fractured hard bedrock).

To investigate dominant earthquake scenarios contributing to overall seismic hazard at the annual non-exceedance probability of 0.9996 (i.e. 2% in 50 years exceedance probability), which corresponds to the current seismic design level in the NBCC, seismic deaggregation results based on $S_a(0.3)$ for the four locations are displayed in Fig. 4 for soft soil (results for firm soil are omitted for brevity; they are similar to Fig. 4). The deaggregation analysis is based on an 'approximately equal criterion' [24], where seismic events reaching a seismic intensity level between 90% and 110% of the fractile value at the selected return period level are used to produce deaggregation results. The dominant scenarios are represented in terms of magnitude and distance. For western Canada (Fig. 4a and b), scenarios are distinguished based on event type ('crustal', 'interface', and 'inslab'), noting that they correspond to specific combinations of magnitude and distance (e.g. M_w 8.0–9.0 for the Cascadia subduction events). On the other hand, for eastern Canada, results are colour-coded based on magnitude range, where 'small' events are for M_w 4.5–5.5, 'moderate' events are for M_w 5.5–6.5, and 'large' events are for M_w 6.5–7.5, noting that large events are originated from the St. Lawrence rift zone (Fig. 2b). Fig. 4c and d shows that events

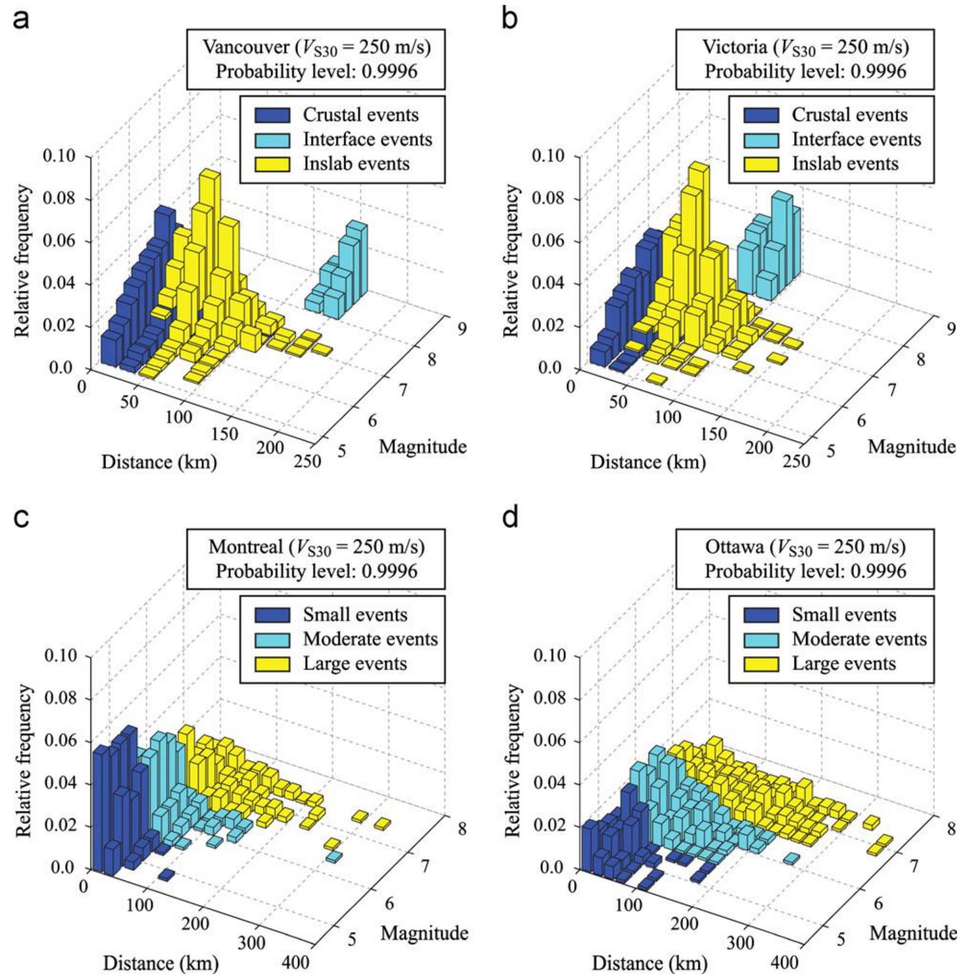

Fig. 4. Seismic deaggregation for soft soil sites (V_{S30}=250 m/s) at the annual non-exceedance probability of 0.9996: (a) Vancouver, (b) Victoria, (c) Montreal and (d) Ottawa.

Table 1
Dominant earthquake scenarios for Vancouver and Victoria.

Location, site condition, and probability level		Combined [$\overline{M}_w$,$\overline{R}$,$\overline{\varepsilon}$]	Crustal [$\overline{M}_w$,$\overline{R}$,$\overline{\varepsilon}$]	Interface [$\overline{M}_w$,$\overline{R}$,$\overline{\varepsilon}$]	Inslab [$\overline{M}_w$,$\overline{R}$,$\overline{\varepsilon}$]	Relative contributions [Crustal, Interface, Inslab]
Vancouver soft	0.998	6.67, 51.0, 1.19	6.32, 26.3, 1.34	8.57, 140.9, 0.99	6.78, 66.1, 1.12	49.8, 9.9 , 40.3
	0.9996	6.89, 44.5, 1.50	6.63, 14.2, 1.44	8.66, 141.3, 1.60	6.94, 57.4, 1.45	43.7, 11.7, 44.6
	0.9999	6.97, 39.1, 1.97	6.85, 10.6, 1.93	8.60, 140.9, 2.42	6.94, 54.3, 1.89	38.3, 7.5 , 54.2
Vancouver firm	0.998	6.68, 51.5, 1.10	6.32, 22.7, 1.20	8.55, 141.7, 0.78	6.76, 67.5, 1.17	46.7, 11.3, 42.0
	0.9996	6.91, 47.4, 1.48	6.62, 12.5, 1.30	8.63, 140.9, 1.50	6.89, 59.2, 1.59	39.5, 16.2, 44.3
	0.9999	7.08, 39.0, 1.79	6.98, 8.5 , 1.25	8.72, 140.3, 2.03	6.99, 54.3, 1.84	41.1, 15.0, 43.9
Victoria soft	0.998	6.79, 51.7, 1.19	6.29, 19.6, 1.39	8.51, 80.0, 0.79	6.84, 61.1, 1.19	38.3, 13.5, 48.1
	0.9996	6.99, 48.8, 1.59	6.63, 10.7, 1.56	8.58, 80.0, 1.36	6.94, 53.3, 1.67	31.4, 19.0, 49.5
	0.9999	7.05, 48.8, 1.98	6.64, 7.7 , 1.97	8.60, 78.6, 1.80	7.00, 51.6, 2.05	25.1, 20.5, 54.4
Victoria firm	0.998	6.82, 52.9, 1.05	6.34, 16.5, 1.17	8.49, 80.0, 0.55	6.83, 61.4, 1.19	35.8, 16.2, 48.0
	0.9996	7.02, 49.0, 1.38	6.69, 8.9 , 1.30	8.55, 78.6, 1.24	6.94, 53.2, 1.60	32.3, 23.2, 44.5
	0.9999	7.13, 49.5, 1.72	6.90, 4.8 , 1.42	8.62, 77.5, 1.68	7.00, 51.8, 1.97	32.0, 26.0, 42.0

with different magnitudes contribute significantly to overall seismic hazard and the characteristic events originated from the St. Lawrence rift region might affect the sites even at far distances. If only one scenario is considered to represent the overall hazard characteristics (in calculating CMS), it may obscure the diversity of dominant earthquake scenarios.

Furthermore, identified dominant scenarios for different event types/magnitude ranges are summarised in Tables 1 and 2 for the four locations. In the tables, mean statistics of the identified scenarios (i.e. $\overline{M}_w$, $\overline{R}$, and $\overline{\varepsilon}$) for the 'combined' case (which is the overall average without distinction) and 'individual' cases (crustal/interface/inslab events for western Canada and small/moderate/large events for eastern Canada) are listed for three probability levels and two site conditions. Relative contributions of the individual cases are also indicated in the tables. As seen in Fig. 4, mean scenario characteristics for different event types or magnitude ranges in terms of $\overline{M}_w$, $\overline{R}$, and $\overline{\varepsilon}$ vary, depending on the probability level. Scenarios are quite different between western

Table 2
Dominant earthquake scenarios for Montreal and Ottawa.

Location, site condition, and probability level		Combined $[\overline{M}_w,\overline{R},\overline{\varepsilon}]$	Small $[\overline{M}_w,\overline{R},\overline{\varepsilon}]$	Moderate $[\overline{M}_w,\overline{R},\overline{\varepsilon}]$	Large $[\overline{M}_w,\overline{R},\overline{\varepsilon}]$	Relative contributions [Small, Moderate, Large]
Montreal soft	0.998	5.71, 48.0, 0.79	4.98, 26.3, 0.97	5.97, 61.8, 0.82	6.87, 123.1, 0.36	41.8, 36.0, 22.2
	0.9996	5.94, 26.3, 1.21	5.02, 17.1, 1.64	5.97, 26.6, 1.03	6.96, 52.3 , 0.88	33.5, 35.0, 31.5
	0.9999	6.35, 21.1, 1.55	5.24, 10.7, 1.94	6.19, 21.0, 1.55	7.12, 31.2 , 1.10	23.2, 38.4, 38.4
Montreal firm	0.998	5.72, 46.7, 0.79	4.98, 25.5, 0.96	5.98, 59.1, 0.85	6.85, 124.8, 0.40	41.8, 34.8, 23.4
	0.9996	5.86, 23.6, 1.12	5.01, 14.6, 1.48	5.95, 25.4, 0.89	6.99, 48.8 , 0.94	35.2, 37.2, 27.6
	0.9999	6.27, 16.8, 1.09	5.29, 9.9 , 1.55	6.07, 15.4, 1.04	7.12, 22.6 , 0.65	22.7, 39.2, 38.1
Ottawa soft	0.998	5.82, 90.2, 0.95	5.09, 52.1, 1.49	5.95, 96.5, 0.91	6.81, 174.2, 0.31	35.3, 42.3, 22.4
	0.9996	6.32, 56.7, 1.17	5.11, 29.8, 1.67	6.06, 54.2, 1.27	6.98, 99.2 , 0.88	18.6, 38.3, 43.0
	0.9999	6.68, 32.3, 1.18	5.13, 14.1, 1.78	6.06, 30.9, 1.80	7.03, 36.7 , 0.95	10.3, 31.7, 58.0
Ottawa firm	0.998	5.82, 90.9, 0.99	5.09, 51.9, 1.51	5.95, 97.5, 0.95	6.82, 175.2, 0.34	35.4, 42.6, 22.0
	0.9996	6.28, 50.3, 1.13	5.16, 23.1, 1.51	6.07, 47.9, 1.23	6.91, 91.5 , 0.81	20.9, 38.0, 41.1
	0.9999	6.76, 25.3, 0.89	5.13, 13.0, 1.43	6.01, 23.4, 0.94	6.98, 30.4 , 0.69	11.6, 26.2, 62.2

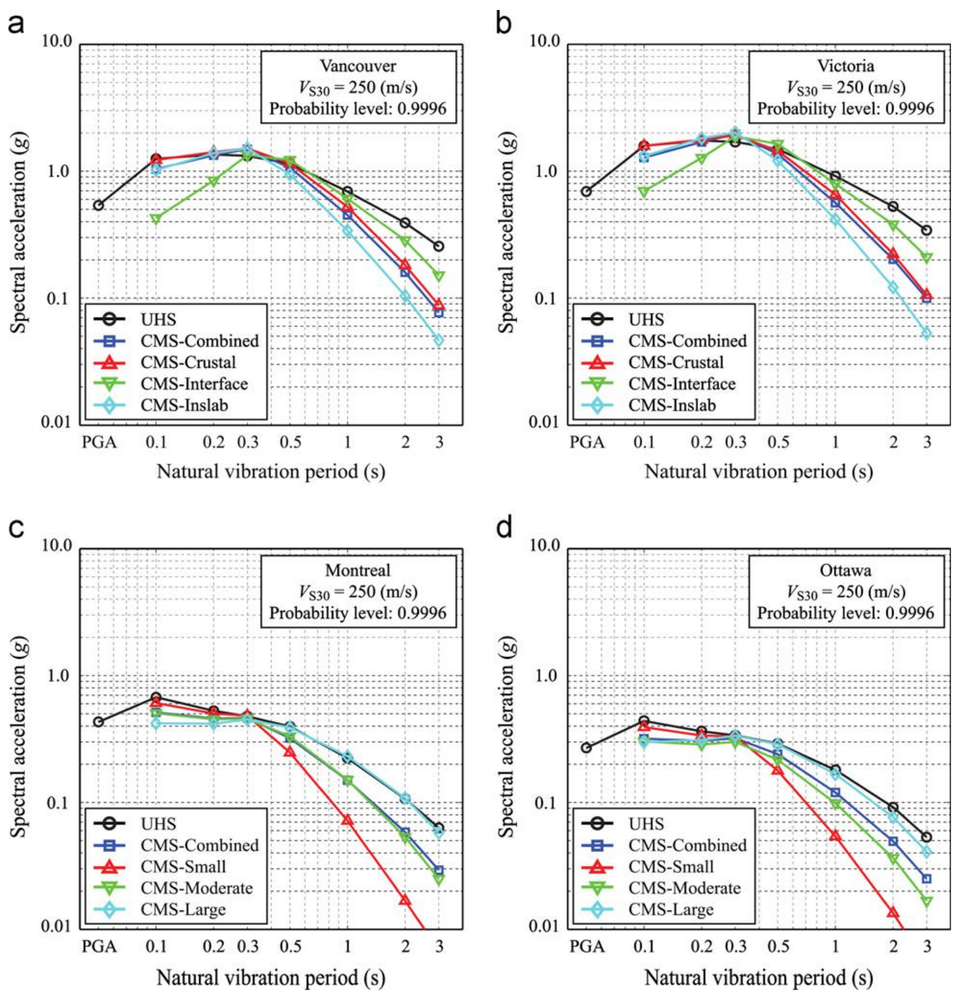

Fig. 5. Uniform hazard spectrum and conditional mean spectra for soft soil sites (V_{S30}=250 m/s) at the annual non-exceedance probability of 0.9996: (a) Vancouver, (b) Victoria, (c) Montreal and (d) Ottawa.

and eastern Canada, and are sufficiently distinctive for different locations within the same seismic region. The relative contributions of events with specific event types or magnitude ranges are also affected by the probability level, site condition, and location. Generally, for western Canada, the most significant influence is originated from inslab events, followed by crustal events, noting that the impact of interface Cascadia events is greater in Victoria than Vancouver (due to proximity to the subduction zone). For eastern Canada, the influence of the characteristic events from the St. Lawrence rift zone becomes more significant with the increase of the annual non-exceedance probability level; in Montreal, both small and moderate events contribute significantly to overall seismic hazard, whereas in Ottawa, the influence of small events is relatively minor. Such features of dominant earthquake scenarios may affect the multiple CMS, and a quantitative investigation of such impact on seismic fragility and loss estimation is worthy of further research.

4.2. Record selection based on conditional mean spectra

The CMS can be constructed by using GMPEs, scenario characteristics, and inter-period correlation models. The GMPEs should be consistent with those used in PSHA. When multiple GMPEs are implemented in a logic tree, relative weights for individual GMPEs can be determined by examining detailed deaggregation results. For the inter-period correlation models, existing relationships by Baker and Cornell [21] and Goda and Atkinson [22] are employed. The former is suitable for shallow crustal events, whereas the latter is applicable to interface and inslab events. The CMS for the four locations are developed by distinguishing the 'combined' case and 'individual' cases, and the results are shown in Fig. 5 for the soft site condition. The annual non-exceedance probability level of 0.9996 is considered. Overall, the UHS and CMS at the vibration period of the adopted IM (i.e. 0.3 s) agree well (without any scaling), which is a desirable feature of the CMS. For western Canada, the CMS for crustal, interface, and inslab events are different; the CMS-Inslab is associated with rich spectral content in the short vibration period range, whereas the CMS-Interface has rich spectral content in the long vibration period range. The CMS-Combined and the CMS-Crustal, which is an intermediate between the CMS-Inslab and the CMS-Interface, are similar. For eastern Canada, the effects of magnitude ranges on the response spectral shapes of the CMS can be clearly seen; with increasing magnitude, spectral content in the long vibration period range becomes richer. It is also noticed that the response spectral shapes for the CMS-Combined and the CMS-Moderate are similar (as expected). Therefore, distinction of record characteristics based on either event type or magnitude range results in different target CMS. It is noteworthy that the response spectral shapes of CMS-Combined at different probability levels (for the same location) are similar to those shown in Fig. 5. This is because the response spectral shapes of UHS are similar at different probability levels and the inter-period correlation models do not depend on the probability level. However, relative contributions from different cases change with the probability level, affecting the CMS-Combined to some extent (note: individual CMS for different event types or magnitude ranges are affected more significantly). This observation should not be generalised to other seismic regions, because changes of dominant scenarios with probability level depend on regional seismic hazard characteristics.

The final step of the CMS-based record selection is to find a set of records whose response spectra match the target CMS closely. For this purpose, large record sets are constructed from the PEER-NGA and the K-NET/KiK-net databases by including records with appropriate features in terms of magnitude, distance, site condition, and event type. As the record characteristics for western and eastern Canada are quite different, two record sets are prepared, and then they are used for the final record selection based on the CMS. Specifically, the 'western record set' should include crustal/interface/inslab records and relatively large events (M_w 8.0–8.5 class, such as the 2003 Tokachi-Oki records). On the other hand, the 'eastern record set' should contain crustal events and reflect regional seismicity due to relatively small local events (M_w 5.0–6.0 class) as well as large characteristic events (M_w 7.5 class).

In light of the above requirements, preliminary record selection is conducted based on general criteria for developing seismic fragility models and inelastic demand prediction models [25–27]. The adopted criteria are: (i) two horizontal components are recorded on the ground surface (for the PEER-NGA database, free-field observations in one-story building of light construction are also considered); (ii) magnitude–distance cut-off limits considered by Goda and Atkinson [27] are applied with the minimum moment magnitude equal to 6.0 and 5.0 for the western and eastern record sets, respectively; (3) V_{S30} is between 100 m/s and 1000 m/s; and (4) geometric means of the peak ground acceleration (PGA) and peak ground velocity (PGV) of two horizontal components are greater than 0.1g and 10 cm/s, respectively. The preliminary selection criteria identify 593 and 520 records for the western and eastern record sets, respectively. Amongst the western record set, 187 records are from the PEER-NGA (California) database, 129 records are from the PEER-NGA (non-California) database, 89 records are from the K-NET/KiK-net database (Crustal), 63 records are from the K-NET/KiK-net (Interface) database (containing the 2003 Tokachi-Oki records), and 125 records are from the K-NET/KiK-net (Inslab) database. Amongst the eastern record set, 251 records are from the PEER-NGA (California) database, 133 records are from the PEER-NGA (non-California) database, and 136 records are from the K-NET/KiK-net database (Crustal). The data characteristics in terms of magnitude–distance distribution are shown in Fig. 6 for the western and eastern record sets. Generally, large records are associated with either NGA-NonCA or KK-Interface subset. The KK-Inslab subset has relatively large rupture distance in comparison with others.

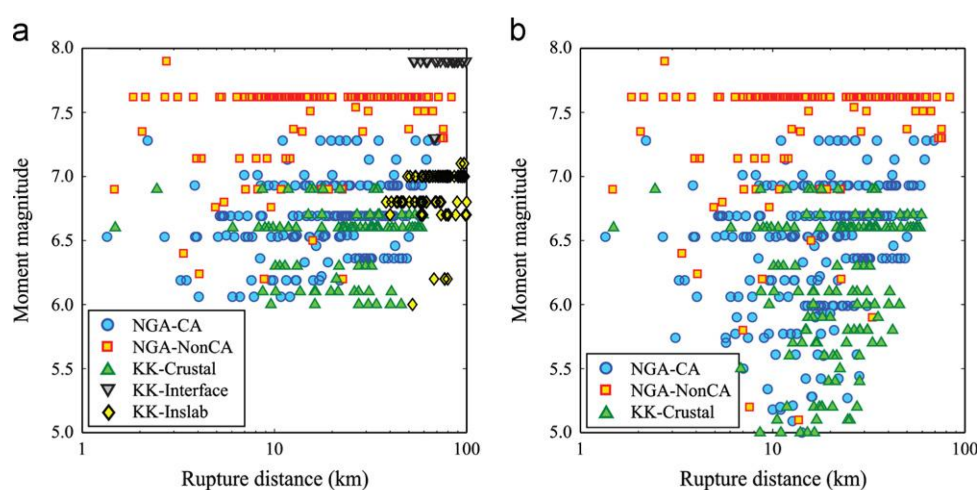

Fig. 6. Magnitude–distance plot of the preliminary ground motion datasets: (a) western record set and (b) eastern record set.

To prepare a dataset of the maximum inter-story drift ratio at the first story level of the UBC–SAWS models (i.e. EDP) for different seismic intensity levels, IDA is carried out using the preliminary western and eastern record sets. In the IDA, the seismic intensity level $S_a(0.3)$ is varied from 0.1g to 8.0g (109 levels); severe seismic intensity levels are considered to ensure that the collapse state of the house models is reached by the majority of the selected records. For each record, two analyses are conducted by alternating two horizontal components along the X and Y directions. In scaling a ground motion record (i.e. one pair of two horizontal components), the scaling factor is calculated as the target seismic intensity level divided by the geometric mean of $S_a(0.3)$ due to two horizontal components, and the same scaling factor is applied to both horizontal components. In total, 517,096 and 453,440 runs of nonlinear dynamic analysis are conducted for the western and eastern datasets (i.e. 593/520 records × 2 input directions × 109 intensity levels × 4 house models). The constructed datasets of the maximum inter-story drift ratio are used in the CMS-based record selection to develop seismic fragility models for different locations.

5. Seismic fragility assessment of wood-frame houses in western and eastern Canada

In this section, seismic fragility of the UBC–SAWS models (Houses 1–4) is assessed by selecting a set of 50 records based on the CMS. The number of 50 records is employed to achieve a reasonable balance between tight and loose fitting of the selected records to the target, given the limitation of available record sets. Overall, the impact of using more/less records is not significant (i.e. median is similar while variability tends to increase gradually as the number of records increases). In developing the IDA curves, spectral acceleration at 0.3 s (i.e. $S_a(0.3)$) and maximum inter-story drift ratio at the first story level are taken as IM and EDP, respectively. To succinctly describe the key features of the IDA curves, 0.50-, 0.16-, and 0.84-fractile curves, are focused upon. Once the IDA curves are obtained, it is straightforward to develop seismic fragility models. For each location and site class, a base case is set up by considering: House 3, CMS-Event/Mag approach, annual non-exceedance probability of 0.9996, and vibration period range between 0.1 s and 1.0 s. The upper vibration period of 1.0 s is chosen because the vibration periods of the damaged houses after shaking table tests ranged from 0.81 s to 1.02 s [16] (note: these houses were not collapsed). When the CMS-based record selection is conducted, records observed at sites with V_{S30} of 100–360 m/s are considered to be applicable to soft soil, whereas those with V_{S30} of 250–750 m/s are adopted for firm soil (overlapping of the V_{S30} range was inevitable due to the scarcity of available records). Subsequently, these parameters are varied to investigate the sensitivity of the IDA curves. The main reasons for focusing on a particular probability level in developing seismic fragility models are that the annual non-exceedance probability of 0.9996 corresponds to the current seismic design level in Canada and that the impact of the probability level is considered to be relatively minor.

5.1. Effects of locations on IDA curves

From loss estimation viewpoints, it is important to investigate whether the IDA curves for different locations (i.e. different dominant scenarios) are similar/dissimilar. For this purpose, the IDA curves for the four locations (by considering the base case) are compared in Fig. 7a for the soft soil condition. Broadly, overall characteristics of the IDA curves are similar for the four locations. In particular, results for the same region are close, while about 10–20% differences of the IDA curves can be noticed for different regions. It is reminded that overall similarity does not mean that seismic risks at the four locations are similar because seismic fragility is a conditional assessment and does not include relative extent of regional seismic hazard.

To examine the causes of the similarity of the IDA curves (despite different dominant earthquake scenarios), the normalised UHS and (individual) CMS for Vancouver and Montreal are compared in Fig. 7b for different event types and magnitude ranges (note: normalisation is conducted based on the spectral ordinate at the vibration period of 0.3 s). For the individual CMS, relative contributions (in percentage) are also indicated in the figure. In terms of UHS, Montreal is associated with richer spectral content in the short-period range, which may interact with higher vibration modes. However, dynamic behaviour of the UBC–SAWS models is predominantly influenced by the fundamental vibration mode, and consequently, the rich spectral content in the short-period range does not affect the IDA curves significantly. Overall, the target CMS for Montreal are slightly less than those for Vancouver, but relative contributions due to large/interface events (which results in richer spectral content in the long-period range)

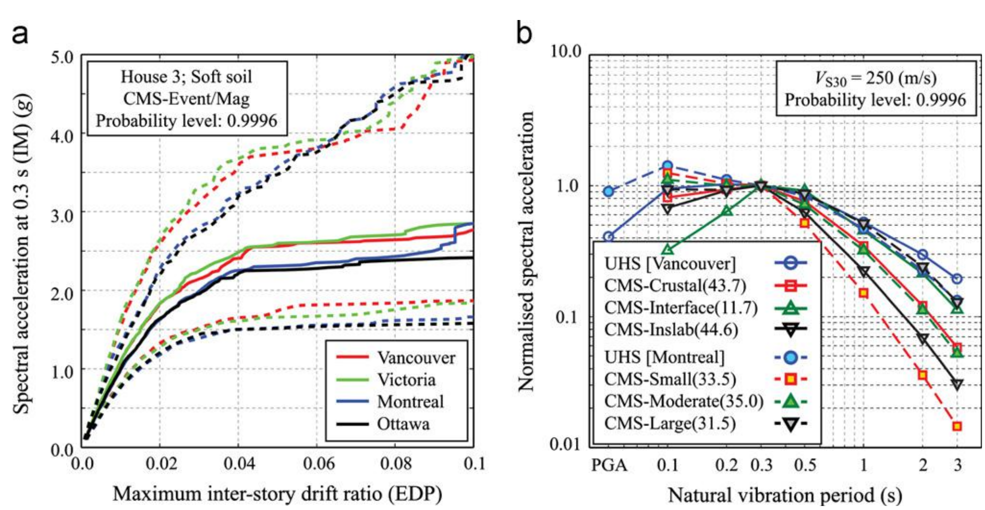

Fig. 7. (a) Comparison of IDA curves for four locations and (b) comparison of CMS for Vancouver and Montreal. In (a), the solid line corresponds to a 0.50-fractile IDA curve, while the broken lines correspond to 0.16- and 0.84-fractile IDA curves.

are greater for Montreal than Vancouver. These features of dominant scenarios (response spectral shape and relative contribution) cancel out each other.

5.2. Effects of site conditions on IDA curves

Fig. 8 compares IDA curves for Vancouver and Montreal at soft soil and firm soil conditions; results for Victoria and Ottawa are similar to those for Vancouver and Montreal, respectively (Fig. 7a) and thus are omitted for brevity. All other settings for detailed CMS-based record selection are the same as the base case. The firm soil cases result in less severe seismic fragility than the soft soil cases (i.e. all three IDA curves are shifted upwards), indicating that for a given IM level, the corresponding value of EDP is greater for the soft soil condition than the firm soil condition. This can be explained by inspecting the response spectral shapes for different site conditions. The target spectra for the soft soil condition have richer spectral content in the long-period range than the firm soil condition; when the house models behave nonlinearly, the structural systems are affected more significantly by the long-period spectral content (i.e. vibration period elongation). The results indicate that distinction of the site condition has significant influence on the IDA curves.

5.3. Effects of annual non-exceedance probability levels on IDA curves

Fig. 9 shows IDA curves for Vancouver and Montreal, which are developed based on the CMS-Event/Mag approach corresponding to different annual non-exceedance probability levels of 0.998, 0.9996 (base), and 0.9999, for the soft soil condition. The impact of the probability level is not significant for Vancouver, Victoria, and Montreal, while more significant change is seen for Ottawa. For Vancouver and Victoria, all three scenario statistics $\overline{M}_w$, $\overline{R}$, and $\overline{\varepsilon}$ for crustal and inslab events are influenced by the probability level (Table 1). An increase in $\overline{M}_w$ and a decrease in $\overline{R}$ with the probability level have counteracting effects on the response spectral shape, leading to relatively minor overall change of the target response spectral shape in terms of probability level. In contrast, the values of $\overline{M}_w$ and $\overline{R}$ for interface events do not change much with the probability level, and result in a more peaked response spectral shape due to a large change in $\overline{\varepsilon}$. In terms of relative contributions, inslab events become more dominant with the probability level. The combined effects from these factors determine the shapes of the target response spectrum based on the CMS-Event approach for Vancouver and Victoria. Consequently, the impact of the probability level for the CMS-Event approach is not pronounced. On the other hand,

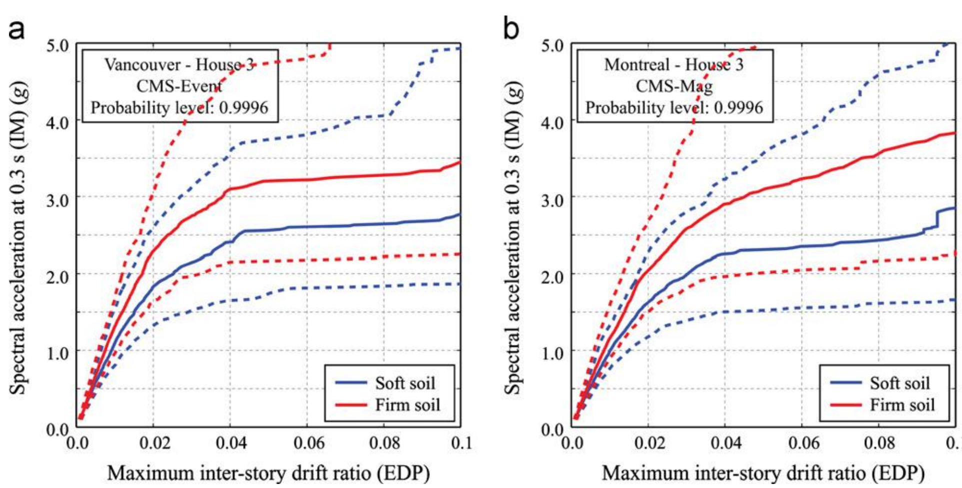

Fig. 8. Comparison of IDA curves for different soil conditions: (a) Vancouver and (b) Montreal. The solid line corresponds to a 0.50-fractile IDA curve, while the broken lines correspond to 0.16- and 0.84-fractile IDA curves.

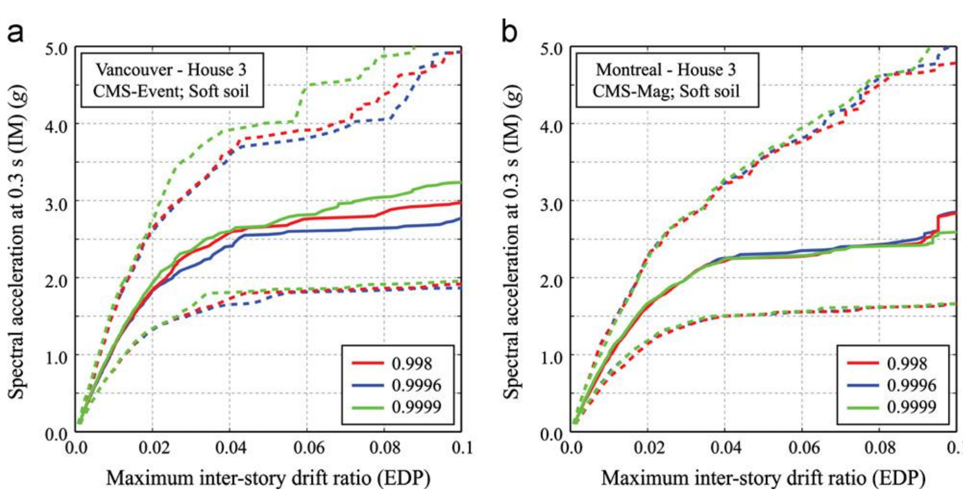

Fig. 9. Comparison of IDA curves for different annual non-exceedance probability levels: (a) Vancouver and (b) Montreal. The solid line corresponds to a 0.50-fractile IDA curve, while the broken lines correspond to 0.16- and 0.84-fractile IDA curves.

with increasing probability level, impact due to large earthquakes becomes more dominant for Montreal and Ottawa (Table 2; this effect is more remarkable for Ottawa), resulting in greater seismic risk potential. Importantly, major features of the IDA curves can be explained by examining record characteristics of dominant earthquake scenarios. This is indeed advantageous because the explanations can be related to well-known seismological influence on the response spectra.

5.4. Effects of vibration period ranges on IDA curves

Fig. 10 compares IDA curves for Vancouver and Montreal by considering three vibration period ranges for fitting a candidate record to the target, 0.1–0.6 s, 0.1–1.0 s (base), and 0.1–1.5 s for the soft soil condition. The lower vibration period covers the second and third vibration modes of the UBC–SAWS models, whereas the selection of the upper vibration period, ranging from $2T_n$ to $5T_n$, is determined by the secant vibration period for simplified bilinear structural systems. The wide range up to $5T_n$ may be relevant when a soft-story failure mechanism is initiated. The upper vibration period of 1.5 s ($=5T_n$) is chosen based on the inspection of drift time-history of a shaking table test [16]. The results shown in Fig. 10 indicate that the consideration of narrower vibration period ranges leads to severer seismic fragility assessments (i.e. lower curves). This is caused due to the loose matching of the response spectral shape outside the specified vibration period range; the use of the CMS for a wider vibration period range can match the steeper decay of the CMS ordinates.

5.5. Effects of CMS-based approaches on IDA curves

Fig. 11 compares IDA curves for Vancouver and Montreal based on the CMS-Event/Mag approach (base) versus the CMS-Combined approach for the soft soil condition. The difference of the two CMS-based approaches is whether three CMS for different event types or magnitude ranges are used as the target spectra. Overall, the effects of adopting the CMS-Event/Mag approach are revealed as increased variability of the IDA curves (i.e. difference between the two broken lines in Fig. 11). The median curves are similar for both CMS-based approaches. The reason for the increased variability is due to variation of the target response spectra for individual scenarios. It is important to recognise that the increased variability (for the same median) makes the fragility curve flatter; thus it can be conservative or unconservative, depending on the damage probability level. Since the distinction of earthquake types or magnitude ranges is physically meaningful, the use of the CMS-Event/Mag approach is appropriate for assessing seismic performance of structures.

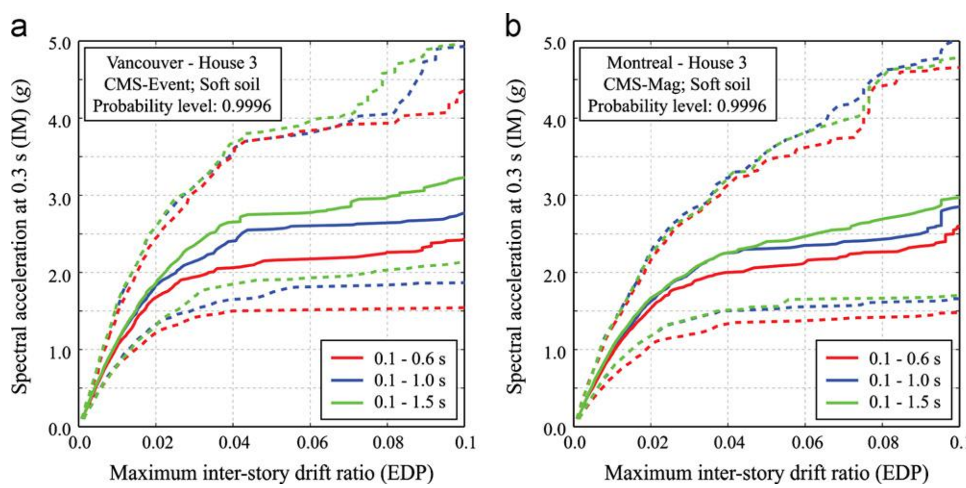

Fig. 10. Comparison of IDA curves for different vibration period ranges: (a) Vancouver and (b) Montreal. The solid line corresponds to a 0.50-fractile IDA curve, while the broken lines correspond to 0.16- and 0.84-fractile IDA curves.

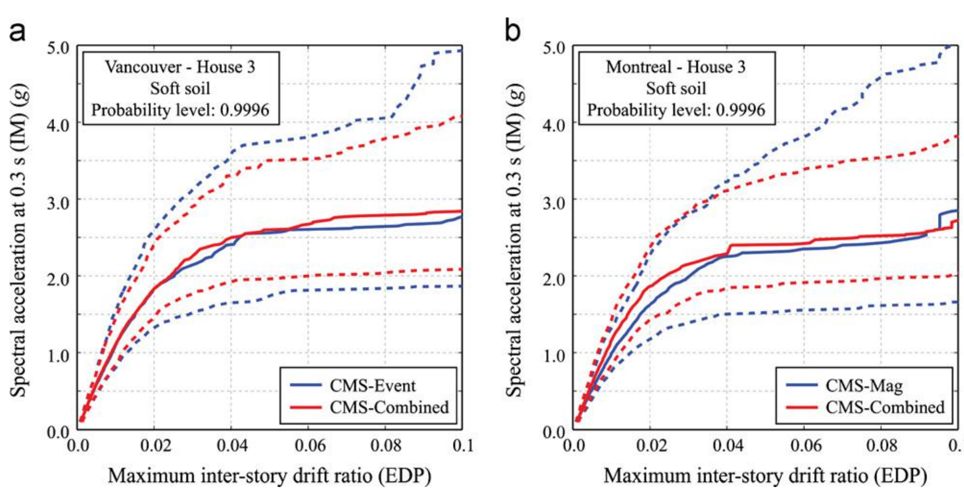

Fig. 11. Comparison of IDA curves for different CMS-based approaches: (a) Vancouver and (b) Montreal. The solid line corresponds to a 0.50-fractile IDA curve, while the broken lines correspond to 0.16- and 0.84-fractile IDA curves.

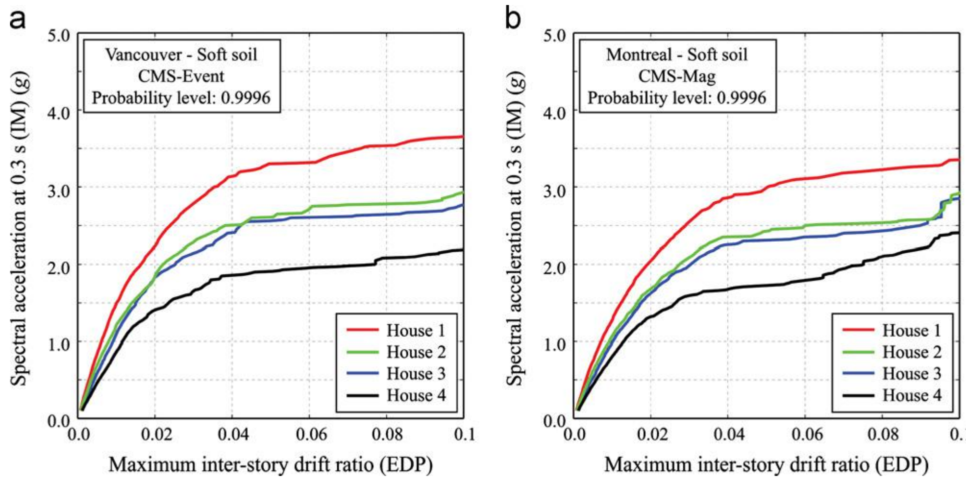

Fig. 12. Comparison of 0.50-fractile IDA curves for different house models: (a) Vancouver and (b) Montreal.

5.6. *Effects of house models on IDA curves*

The horizontal load-resisting systems (i.e. shear walls with different nailing plans and horizontal board) have remarkable influence on seismic fragility assessment. This is because they affect seismic capacity of the systems. The impact of adopting different shear-wall types (i.e. Houses 1–4) on the nonlinear response potential for Vancouver and Montreal is shown in Fig. 12 for the soft site condition (note: 0.50-fractile curves only are shown to focus on the most important trends). The results indicate that amongst the four house models, House 1 is the least vulnerable, while House 4 is the most vulnerable; the extent of predicted seismic demand for Houses 2 and 3 are similar. The effectiveness of 'engineered shear-walls' in mitigating seismic risk is highlighted clearly, and if shear-walls are not seismically designed or constructed (House 4), seismic upgrading to more resistant wall types (with a denser nail schedule) is an effective means to reduce seismic damage.

6. Seismic loss estimation of wood-frame houses in western and eastern Canada

Seismic loss estimation involves convolution of seismic hazard and seismic fragility over all possible scenarios. The seismic loss curve for a portfolio of buildings and infrastructure, i.e. plot of aggregate seismic loss versus annual probability, provides useful information on earthquake risk exposure at various probability levels. Furthermore, comparison of seismic loss curves for different building portfolios and different seismic environments facilitates the better appreciation of regional seismic risk at stake and promotes the informed decision-making on risk mitigation measures.

This section presents a comparative investigation of the effects of seismic hazard characteristics and seismic fragility on aggregate seismic loss of a group of wood-frame houses in Canada. For this purpose, a seismic risk model for multiple wood-frame houses, developed by Goda et al. [18], is adopted. The details of the seismic risk model can be found there. The results presented in this section are based on simulation over 1 million years. Specifically, a set of hypothetical 500 wood-frame houses is considered. The building portfolio is placed at four locations (Vancouver/Victoria/Montreal/Ottawa) to evaluate the impact of seismic hazard environments; at each location, these houses are distributed randomly in space within a 1 km by 1 km area. Two site conditions, soft soil and firm soil, are taken into account. The

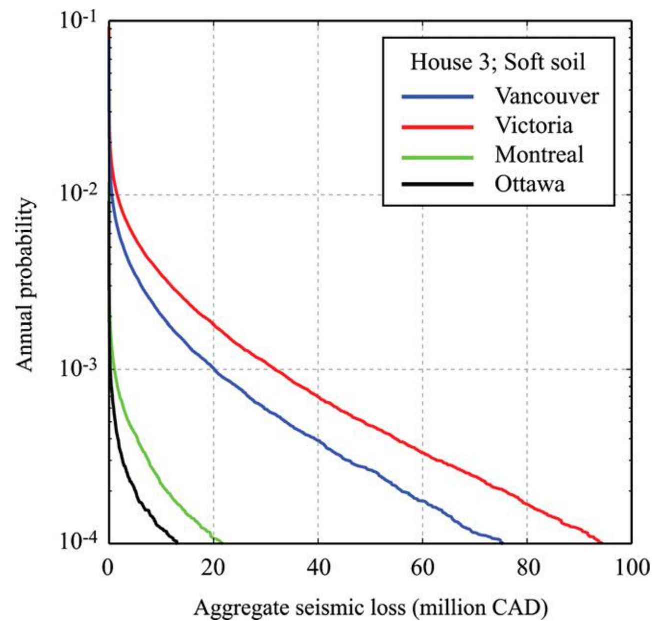

Fig. 13. Seismic loss curves for different locations (500 House 3; Soft soil; CMS-Event/Mag).

500 buildings belong to the same house model class (House 1/2/3/4); to account for uncertainty of seismic resistance of individual structures, their yield and ultimate capacities are varied based on the assumed statistical information of the capacity parameters (see [18] for details). The same damage-loss and cost functions as in [18] are adopted; the total loss of the 500 buildings amounts to about 140 million Canadian dollars (CAD). For the base case, the seismic fragility models based on the CMS-Event/Mag approach are employed for the specific locations (Section 5); two additional cases are considered to examine the impact of the CMS-based record selection methods on the estimated seismic loss. It is emphasised that the main focus of the investigations in this section is to examine the impact of key variables (seismic hazard characteristics due to regional seismicity, site condition, IDA-CMS-based fragility model, and house model type) on seismic loss curve; therefore, the relative positions of seismic loss curves, rather than their absolute values, are mainly discussed. This limited focus is inevitable as anticipated seismic risk to vulnerable parts of the existing building stocks in Canada has not yet realised (i.e. no actual damage data to validate seismic loss

predictions is available). Nevertheless, importance of findings based on the relative impact of the estimated seismic loss curves discussed in the following should not be diminished.

6.1. Effects of locations on seismic loss curves

Fig. 13 compares seismic loss curves of 500 houses (House 3) at soft soil condition for different locations. The seismic loss curves for the four locations differ significantly. This is due to different seismic hazard levels at these locations (see Fig. 3). The relative positions of the seismic loss curves for the four locations are the same as those for the seismic hazard curves. For this house class and soil condition, the seismic risks for Vancouver and Victoria are high at probability levels around 10^{-2} to 10^{-3}, where decisions regarding seismic risk management are often made. This result highlights the critical influence of seismic hazard on earthquake risk; different degrees of risk mitigation measures should be implemented across Canada.

6.2. Effects of site conditions on seismic loss curves

Fig. 14 shows seismic loss curves of 500 houses (House 3) in Vancouver or Montreal at two site conditions. It is obvious that the building portfolio on firm soil anticipates significantly less earthquake risk, compared with that on soft soil. The result clearly illustrates the importance of classifying local site conditions (e.g. seismic micro-zoning map). The differences between the seismic loss curves for soft and firm site conditions are contributed by two factors: one is reduced seismic hazard for firm sites (Fig. 3a versus Fig. 3b) and the other is reduced seismic fragility for firm sites (Fig. 8). The influence from reduced seismic fragility on overall reduction of seismic loss increases with the probability level.

6.3. Effects of IDA–CMS-based fragility models on seismic loss curves

In this subsection, the impact of using different IDA–CMS-based fragility models is investigated. Specifically, three cases are considered: the first is to use the CMS-Event/Mag approach while the second is to use the CMS-Combined approach. The third option is to use the CMS-Event/Mag approach but developed for different locations; this is referred to as the 'CMS-Inconsistent' approach; such a situation may arise when applicable fragility models are not readily available. Fig. 15 shows seismic loss curves of 500 houses (House 3) in Vancouver and Montreal at soft soil condition for the three CMS-based approaches. For the CMS-Inconsistent approach, the fragility model for Montreal is used for Vancouver, whereas the fragility model for Vancouver is applied to Montreal (Fig. 11). The result shown in Fig. 15 indicates that the use of the CMS-Combined approach, instead of the CMS-Event/Mag approach, leads to slight underestimation of the seismic loss curves; this is due to reduced variability of the fragility model. When the inconsistent fragility model is adopted, some minor bias may be introduced to the estimated seismic loss; for the case of Vancouver, the use of the fragility model for Montreal leads to slight overestimation of the seismic loss curve due to the difference of the fragility curves; the opposite situation is applicable for the case of Montreal with the fragility model developed for Vancouver.

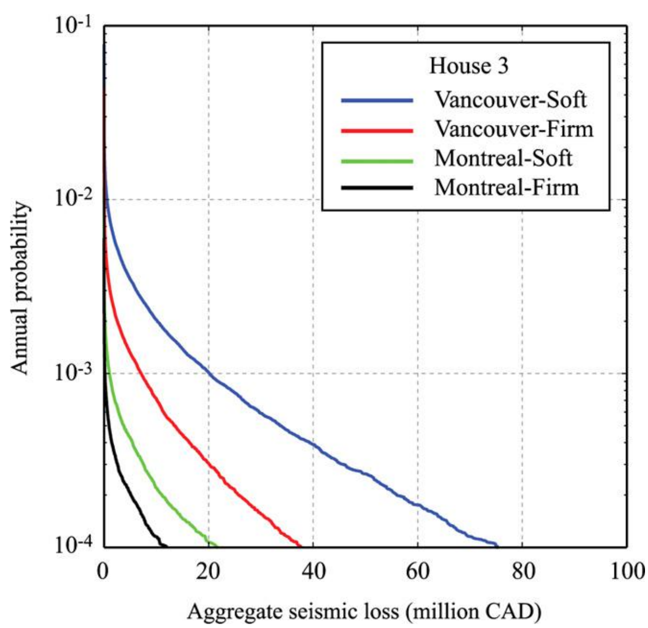

Fig. 14. Seismic loss curves for different site conditions (Vancouver/Montreal; 500 House 3; CMS-Event/Mag).

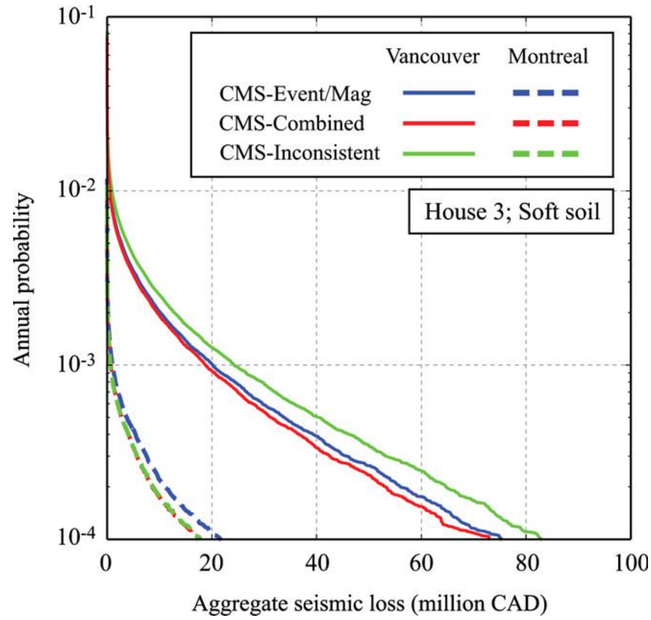

Fig. 15. Seismic loss curves for different IDA-CMS curves (Vancouver/Montreal; 500 House 3; Soft soil).

6.4. Effects of house models on seismic loss curves

Finally, the impact of different house models (i.e. seismic capacity) on seismic loss curves is evaluated. The seismic loss curves for Houses 1–4 at soft site condition are compared in Fig. 16 for Vancouver and Montreal. As expected, the effects of house models have significant impact on the estimated seismic loss (Fig. 12). In particular, House 4 is much more vulnerable compared with other house types; in reality, wooden houses under this category should be prioritised for seismic retrofitting and upgrading. It is noted that the significant differences of the seismic risks for different house types are contributed by two factors: one is the seismic capacity as represented by the UBC–SAWS models (i.e. different structural/hysteretic parameters for nonlinear springs) and the other is the yield and ultimate capacity limits that are used to define the incurred damage factor given seismic excitation, as implemented in the seismic loss model [18] (i.e. lower yield and ultimate drift limits are considered for House 4, in comparison with other house models). In active seismic regions, strict implementation/enforcement of seismic provision

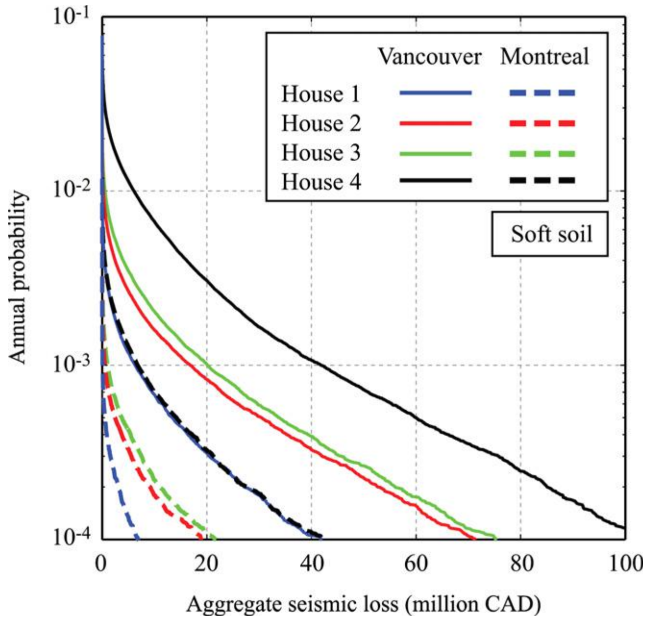

Fig. 16. Seismic loss curves for different house models (Vancouver/Montreal; Soft soil; CMS-Event/Mag).

and practice is important to enhance seismic protection against catastrophic earthquakes.

7. Summary and conclusions

The occurrence of extremely large earthquakes is a serious concern for risk management of urban infrastructure. Existing wood-frame houses in Canada, which were constructed prior to the establishment of appropriate seismic design provision and practice, may be vulnerable. To take appropriate counter measures for seismic risk mitigation proactively, accurate evaluation of potential seismic risk is essential. This study developed seismic fragility models for conventional wood-frame houses, represented by the UBC–SAWS models, by taking into account detailed and up-to-date seismic hazard information across Canada. The fragility models are constructed through the IDA; as the IDA involves scaling of input ground motion records, adequate record selection is important. For this purpose, an innovative record selection method based on multiple CMS was implemented. This procedure allows the incorporation of physically meaningful information, such as earthquake event type and scenario magnitude, into the current version of the single-CMS-based method. The extension of the method is demonstrated for western and eastern Canada, where distinct earthquake scenarios contribute to overall seismic hazard. Using the ground motion record sets from the PEER-NGA and K-NET/KiK-net databases, extensive IDA analyses were carried out; various aspects of the seismic fragility models were investigated, including the effects of regional seismicity, site condition, CMS-based record selection method, and house model. Moreover, the relative impact of the above-mentioned features was investigated in terms of seismic loss curve for a group of wood-frame houses.

The results obtained from this work provide several valuable findings and perspectives. Firstly, a close examination of regional seismic hazard characteristics using seismic hazard curve and seismic deaggregation facilitates the deeper understanding of the impact of ground motion characteristics on seismic fragility. Importantly, the overall effects on seismic fragility are qualitatively predictable. When comparative studies of seismic risk assessment are conducted, the effects may be complex and thus careful consideration is needed (e.g. change of dominant earthquake scenarios in terms of probability level). Secondly, the influence due to seismic environment, local site condition, and structural capacity is paramount from both seismic fragility and seismic loss estimation viewpoints (as widely recognised by various studies). In this study, such results are obtained based on comprehensive and systematic assessment of key uncertainties associated with seismic fragility. Therefore, stronger confidence/support can be gained to promote seismic micro-zoning and to make informed decisions regarding seismic retrofitting/upgrading.

Acknowledgements

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