SEISMIC RISK ASSESSMENT TOOL FOR SEISMIC MITIGATION OF SCHOOLS IN BRITISH COLUMBIA

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ABSTRACT

The British Columbia Ministry of Education is currently embarking on an ambitious $1.5 billion seismic mitigation program for provincial schools. To assist the Ministry in the safe, cost-effective implementation of this program, the Association of Professional Engineers of British Columbia, in collaboration with the University of British Columbia, has developed a performance-based probabilistic tool for both the seismic risk assessment and retrofit of low-rise buildings. This tool incorporates a tri-hazard incremental probabilistic non-linear dynamic analysis methodology to provide local engineers with a sophisticated analytical tool in a user-friendly format. This methodology uses a comprehensive hazard analysis that includes deaggregated crustal, deaggregated sub-crustal and subduction ground motions. Risk is given by the probability of excessive damage in a school building over a specified duration. The excessive damage is associated to large inelastic deformation of structural systems. Probabilities are based on annual frequencies of exceeding the damage state for each earthquake type individually and calculated from a temporal probability model. This paper describes into detail the formulation of this seismic risk assessment methodology and its application to a characteristic low-rise building subjected to a triple seismic hazard.

Introduction

The Ministry of Education (MOE) of British Columbia is implementing an ambitious seismic safety program to make all public elementary and secondary school buildings safe. The Association of Professional Engineers and Geoscientists of British Columbia (APEGBC) has been contracted by MOE to develop a set of state-of-the-art performance-based technical guidelines for structural engineers to use in the seismic risk assessment and retrofit design of low-rise school buildings. This technical development program is now in its seventh year, with

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the third edition of the technical guidelines to be published in the summer of 2010.

In undertaking this technical development program, APEGBC contracted a research team from the Earthquake Engineering Research Facility of the University of British Columbia (UBC) to draft the performance-based technical guidelines for seismic mitigation of BC schools. The technical guidelines address several issues cumulated from previous guideline editions (APEGBC 2006). Overall descriptions of these guidelines are described elsewhere (Ventura *et. al* 2010, Hanson *et al.* 2009, Taylor *et al.* 2009)

The main contribution from the UBC research team is the development of a seismic risk assessment (SRA) methodology. This methodology uses differential movement between floors, or drift, to quantify building damage due to lateral shaking. A wide range of possible ground shaking is considered, from moderate shaking (small earthquakes) to extreme shaking (large infrequent earthquakes). The approach permits the probability of excessive damage (shear deformation in excess of the drift limit) to be determined for a specified building life (e.g., 50 years) and most earthquake scenarios based on the local seismic hazard data.

Earthquake scenarios in this project refer not only to different ground shaking intensities, but also to different types of earthquakes expected to occur in this region. Southwestern British Columbia, where about 80% of the population of the province lives, has significant hazard contributions from crustal, subcrustal and subduction earthquakes (Adams and Halchuck 2003). The proposed SRA methodology is formulated to capture this multiple-earthquake hazard scenario.

This paper describes the formulation of the SRA methodology along with much needed practical and rational assumptions for its efficient use in this massive project. This procedure is an analogy to Probabilistic Seismic Hazard Analyses, PSHA (e.g. Kramer 1996). Risk is given in terms of probabilities of drift exceedance (building damage state) over a given time. Probabilities are calculated from annual frequencies of drift exceedance or number of events in a year by assuming a temporal probability model. The procedure is applied to a characteristic low-rise building in BC for the sake clarity.

Formulation

Risk is given by the probability of drift exceedance, *PDE*, of a structural system undertaking earthquake loads. The annual frequency of drift exceedance, λ_{te}, associated to this *PDE* is calculated for crustal, subcrustal and subduction earthquakes, individually. For the *te*-th earthquake type, this frequency is given by:

$$\lambda_{te} = \nu_{te} \cdot \sum_{ls=10\%}^{250\%} P(Dr > dr \mid LS, TE) \cdot P(LS = ls \mid TE) \qquad (1)$$

where, ν_{te} is the mean annual rate of magnitude exceedance estimated from the Gutenberg-Richter (G-R) recurrence model for the *te*-th earthquake; *ls* is the level of shaking given in 10% increments (100% correspond to a 2475-yr return period earthquake); *dr* is the inter-storey drift of the structural system (damage measure); $P(LS = ls|\ TE)$ is the conditional probability of *ls* occurrence for the *te*-th earthquake. This probability is estimated from the temporal Poisson probability model of the annual frequency of exceeding *ls* (calculated from a Probabilistic Seismic Hazard Analysis, PSHA); $P(Dr>dr \mid LS, TE)$ is the conditional probability of drift exceedance given the *ls*-th level of shaking and for the *te*-th earthquake. This probability is obtained from a log-normal fitting of incremental dynamic analysis (IDA) results at *ls*-th level of shaking (Vamvatsikos and Cornell 2001).

Eq. 1 is valid for the hazard calculation of the single-source subduction earthquake. The seismic hazard of subduction earthquakes is indeed calculated deterministically with assigned probabilities of occurrence for each level of shaking, $P(LS = ls|\ TE)$. Previous studies (Adams and Halchuck 2003) have suggested a log-normal distribution of the hazard or levels of shaking with the 100% located at the 84-th percentile of the distribution, which is approximately equivalent to a 475yr return period earthquake.

The seismic hazard of crustal and subcrustal earthquakes is calculated probabilistically due to several possible earthquake sources. Sources are represented by different v_{te} values. By adopting these rates in the hazard calculations, Eq. 1 can be written as:

$$\lambda_{te} = \sum_{ls=10\%}^{250\%} P(Dr > dr \mid LS, TE) \cdot \lambda_{ls,te} \tag{2}$$

where, $\lambda_{ls,te}$ is the annual frequency of level of shaking occurrence for the *te*-th earthquake. This frequency is directly calculated from the PSHA of each location of interest.

The total annual frequency of drift exceedance is given by the summation of individual frequencies:

$$\lambda a = \sum_{te=1}^{nte} \lambda_{te} \tag{3}$$

The total probability of drift exceedance, *PDE*, is then calculated at any time interval, *T*, by:

$$PDE = 1 - \exp(-\lambda a \cdot T) \tag{4}$$

The risk tolerance limit can be either adopted in terms of annual frequencies or total probabilities. A usual threshold adopted by codes is given in probability terms as 2% exceedance in 50 years, which is equivalent to exceed the drift limit once every 2475 years.

Summary

The seismic risk procedure adopted in the school project can be summarized in the following steps:

Step 1 – Calculate the annual frequency of exceedance from a PSHA and derive the annual frequency of occurrence at each level of shaking;

Step 2 – Compute the conditional probability of drift exceedance for each level of shaking using incremental dynamic analyses, IDA;

Step 3 – Calculate the annual frequency of drift exceedance for crustal and subcrustal earthquakes with Eq. 2. For subduction earthquakes, assume an equivalent mean annual rate of one in 50 years (0.02) and calculate the annual frequency of drift exceedance with Eq. 1;

Step 4 – Calculate the total annual frequency of drift exceedance from Eq. 3;

Step 5–Set a time interval, T (e.g. 50years), and compute the total probability of drift exceedance with Eq. 4.

Illustrative Example

Description

The risk or PDE is calculated for a 2-storey plywood shear-wall building, W-2 prototype, (Hanson et al. 2009) located in Vancouver in firm soil. Ground motions recorded from crustal, subcrustal and subduction earthquakes were selected for this location (Pina 2010). PDEs were calculated for a 4 % inter-storey drift limit, for a wide range of prototype lateral resistance forces (given as a percentage of the building seismic weight, W). Crustal and subcrustal earthquake hazard was previously calculated for two models each, Historic (H) and Regional (R). This example describes the calculation process for a prototype lateral resistance force of 10 %W and specific numbers are for the R model only.

Solution

Annual frequency of hazard occurrence

Step 1 applies to crustal and subcrustal earthquakes only. The annual frequency of level of shaking exceedance is obtained from a PSHA using computer program EZ-Frisk (Risk Engineering 2008) for the city of Vancouver. The annual frequency of occurrence is the derivative of the latter. The distributions of both frequencies to the level of shaking are shown in Figure 1.

Conditional Probability of Drift Exceedance

IDA is performed to the structural system using the selected suites of motions for crustal, subcrustal and subduction earthquakes. IDA results for each suite of motions have been discussed in other documents (Pina 2010, Hanson 2009). A log-normal distribution is assigned to each level of shaking for each suite. The distributions of resulting probabilities of drift exceedance for the W-2 model are shown in Figure 2 for the three earthquake types.

The conditional probabilities of drift exceedance differ considerably by the type of earthquake. At the 100% level of shaking (at the code-based design earthquake) the contribution from crustal earthquakes to the damage is much higher those from subcrustal and subduction earthquakes. Crustal and subcrustal effects in the structural system are comparable at levels of shaking larger than 140%. All earthquakes have similar contribution to damage at very large levels of shaking only. These observations are valid in terms of individual events regardless the frequency of occurrence of each level of shaking of each earthquake.

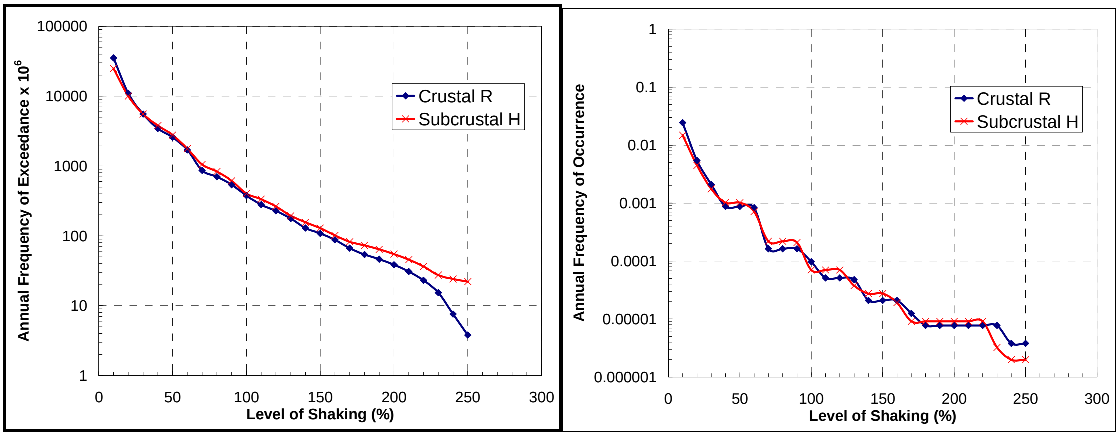

Figure 1. Annual frequencies of level of shaking exceedance (a) and occurrence (b) of crustal and subcrustal earthquakes for Vancouver.

The conditional probability of drift exceedance is an additional parameter to the PDE in the seismic retrofit stage of the overall seismic mitigation procedure. A target conditional probability has been defined in the project at the 100% level of shaking. Engineers must ensure that both the PDE and this conditional probability are below the defined targets. A more detailed explanation of this parameter can be found elsewhere (Taylor et al. 2009, Ventura et al. 2010).

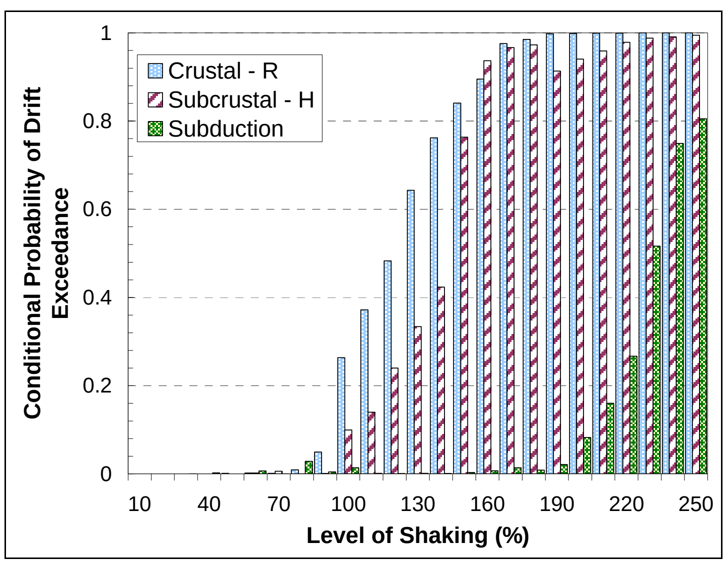

Figure 2. Conditional probabilities of 4% drift exceedance for the three earthquakes for a W-2 located in Vancouver with 10%W resistance

Annual frequency of drift exceedance

Annual frequencies of drift exceedance were calculated for crustal and subcrustal earthquakes using Eq. 2 and for subduction earthquakes using Eq. 1; values for the R model being 4.06×10^{-4}, 1.37×10^{-4} and 1.89×10^{-4}, respectively. We can observe a higher frequency of the 4% drift being exceeded by crustal earthquakes in this particular case.

Figure 3 shows the contribution to the annual frequency of drift exceedance from each type of earthquake (models H and R), for a wide range of W-2 resistance forces. The contribution to the total annual frequency is higher for crustal motions using the R hazard model and for subcrustal motions using the H hazard model, though the frequencies in the H model are much lower. Contribution from subduction motions is important for very low lateral resistance buildings, say resistances less than 8 %W. In general, we can observe that for all the resistance levels crustal earthquakes contribute mostly to drift exceedance or damage.

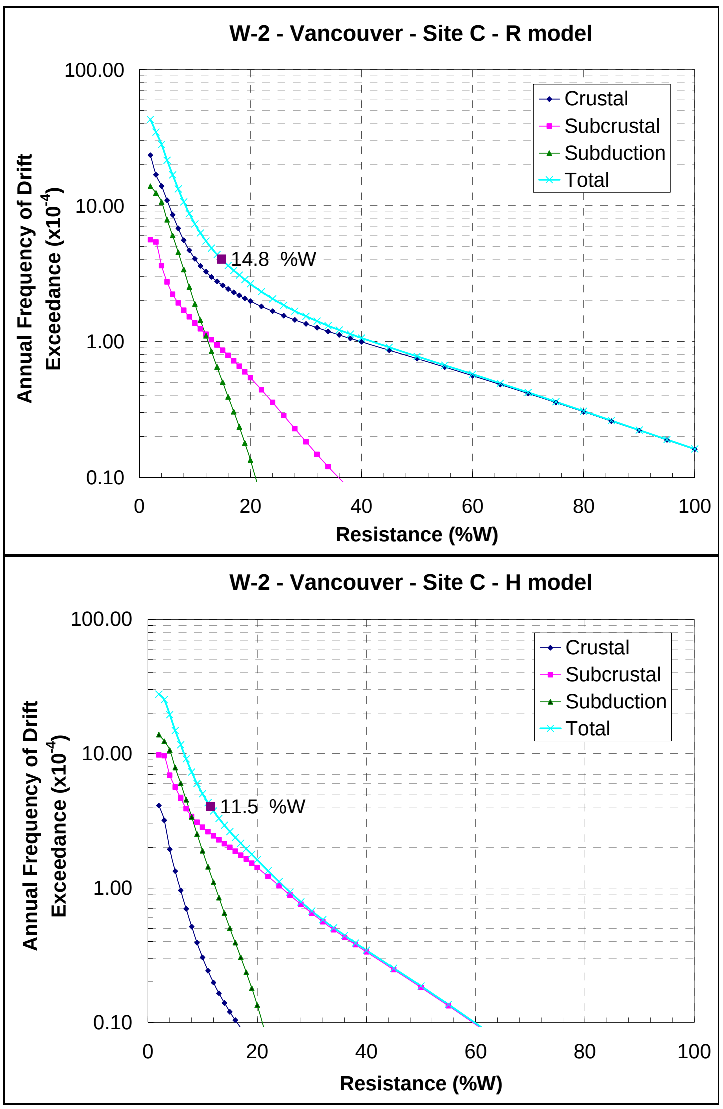

Figure 3. Annual frequencies of 4% drift exceedance of the W-2 prototype located in Vancouver

The total annual probability (Eq. 3) is 0.7‰, which is equivalent of having one drift exceedance in the next 1365 years. In terms of probabilities (Eq. 7), there is a 3.6% chance of exceeding the 4% drift in the next 50 years. Figure 4 shows the PDE values for other resistance forces for the two models. Robust values have been adopted in this project as the total PDEs. In this example, 17%W resistance is equivalent to a frequency of exceedance of 1 in 2475 years or to a PDE of 2% in 50 years.

The limit on risk will depend on the owner or decision-makers. A uniform 2% probability of exceedance has been recommended for the school project for very large inelastic deformations in the structural systems. This number is part of a consensus and has been mainly based on the 2% hazard exceedance in 50 years defined in the NBCC 2005 (NRCC 2005).

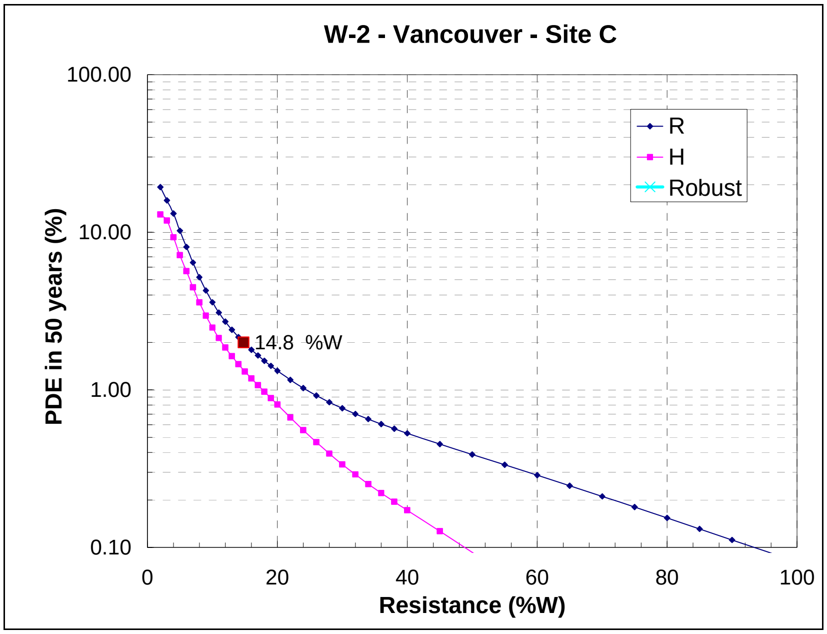

Figure 4. Total probabilities of 4% drift exceedance of the W-2 prototype located in Vancouver

Final remarks

Summary

This paper presented a tri-hazard incremental probabilistic non-linear dynamic analysis methodology for the seismic risk assessment of low-rise British Columbia school buildings. The methodology uses a comprehensive hazard analysis that includes deaggregated crustal, deaggregated sub-crustal and subduction ground motions. Risk is given by the probability of excessive damage in a school building over a specified duration. The excessive damage is associated to large inelastic deformation of structural systems. Probabilities are based on annual frequencies of exceeding the damage state for each earthquake type individually and calculated from a temporal probability model. The principal features of this methodology are:

- rational quantitative method of assigning risk;
- insight into the mechanics of earthquake damage;
- deaggregated tri-hazard risk estimation;

- probabilistic measurement of risk and performance;
- incremental probabilistic non-linear dynamic analysis; and
- ability to mitigate earthquake damage to the performance requirements of the owner;

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