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A STUDY OF SEISMIC RISK IN SOUTHWESTERN BRITISH COLUMBIA

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ABSTRACT

This paper presents results from seismic damage estimation studies for two major cities in south-western British Columbia; Victoria and Vancouver. Estimates of damage to buildings and lifelines used MMI-based damage probability matrices that were developed for Canadian construction types. The ground motion levels considered are due to crustal and subcrustal earthquakes with a probability of exceedance of 2% and 10% in 50 years. The corresponding seismic hazard in terms of peak ground acceleration for Vancouver and Victoria correspond to MMI levels of VIII and X for class C soils. The distribution of structural damage at these levels of MMI in Vancouver and Victoria were mapped on a block-by-block basis. A comparison of the damage estimates for these two levels of shaking is presented. In the second part of the paper, the contribution to seismic losses due to damage to non-structural components, site conditions and liquefaction potential are investigated for the levels of shaking considered. The "functionality performance" of buildings, taking into account the interdependency between buildings and lifelines, is investigated and discussed.

Seismic Hazard in Southwestern British Columbia

Southwestern British Columbia (BC) can be affected by crustal earthquakes in the continental crust overlying the North America plate (up to 30 km deep), deep (subcrustal) earthquakes within the subducting oceanic (Juan de Fuca) plate (about 50 km deep), and earthquakes at the interface between the two plate (Figure 1). With a population of approximately 2.5 million in the region, it is important to understand the possible damage and loss that could occur as the result of future earthquakes in order to reduce or eliminate the potential for catastrophic effects.

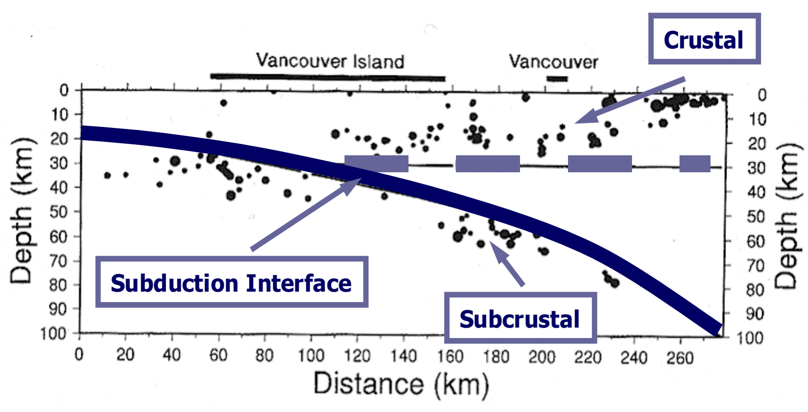

Figure 1. Seismicity in the Cascadia Region(after Rogers, 1998)

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Since the mid 1990 the authors have directed probabilistic seismic hazard analyses of southwestern BC using the seismic source zones and attenuation relationships that have been used to determine the design ground motions of the National Building Code of Canada (NBCC). Bell (1998) developed a classification system for buildings in British Columbia, based on construction practices in BC. Blanquera (1999) used a classification system and damage probability matrices (DPMs) to perform a seismic risk assessment for the City of New Westminster, BC. Cook (1999) studied non-structural component and building content damage. DPMs were applied to the City of New Westminster, (Blanquera, 1999). In 2001, a study by Onur (2001), estimated the potential damage and subsequent monetary losses that would result from seismic shaking in the Cities of New Westminster, Victoria and Vancouver. Structural damage was estimated using the damage probability matrices developed by Onur, Ventura and Finn (2005), and the results were mapped on a block by block basis using GIS software. Non-structural damage and monetary losses were also estimated for the study areas. Thibert, (2008) developed seismic damage estimations of buildings on the UBC campus so that realistic disaster simulations could be performed and critical infrastructure interdependencies could be identified. The authors and their students developed in 2009 an extensive building inventory for the cities of North Vancouver, West Vancouver and the District of North Vancouver and this database is being used for damage estimation studies of the North Shore of Metro Vancouver.

Damage Estimation Methodology

In terms of natural disasters, risk refers to the expected losses from a given hazard to a given element at risk, over a specified future time. Seismic risk**,** therefore**,** refers to expected losses due to future earthquakes. Risk can be seen as the combination of four elements: hazards, location, exposure and vulnerability. In order for the seismic risk to exist, all four elements must be present. The Seismic Risk Assessment Methodology implemented by the authors and their collaborators incorporates all four elements of seismic risk. A detailed description of the most current version of this methodology has been presented by Thibert (2008). The main components are earthquake hazard, location, exposure, vulnerability, collateral hazards, direct damage, indirect damage, direct losses, downtime, indirect losses, consequence and the final risk level. Figure 2 presents a flow diagram of the methodology.

The four main components of risk assessment presented in the previous section are displayed in grey at the top of Figure 2. The assessment of collateral hazards (purple block) such as liquefaction, landslide and tsunami require separate assessment in order to account for their effects. The exposure includes inventory collection and a well established structural classification system. Currently there are 31 British Columbia building prototypes (Ventura, et al, 2005). The yellow block contains the estimation of direct damage to buildings and lifeline systems based on the vulnerability, exposure, hazard and location. The direct damage includes estimates of the damage sustained by the building structural components and non-structural components as well as damage to lifeline systems. Damage is expressed in terms of the mean damage factor (MDF)**,** which is calculated from the prototype damage probability matrices for a given instrumental intensity. The mean damage factor is defined as the ratio of the cost of damage to the current replacement value of the building. Details for determining the structural and non-structural damage sustained by a building are given by Thibert (2008).

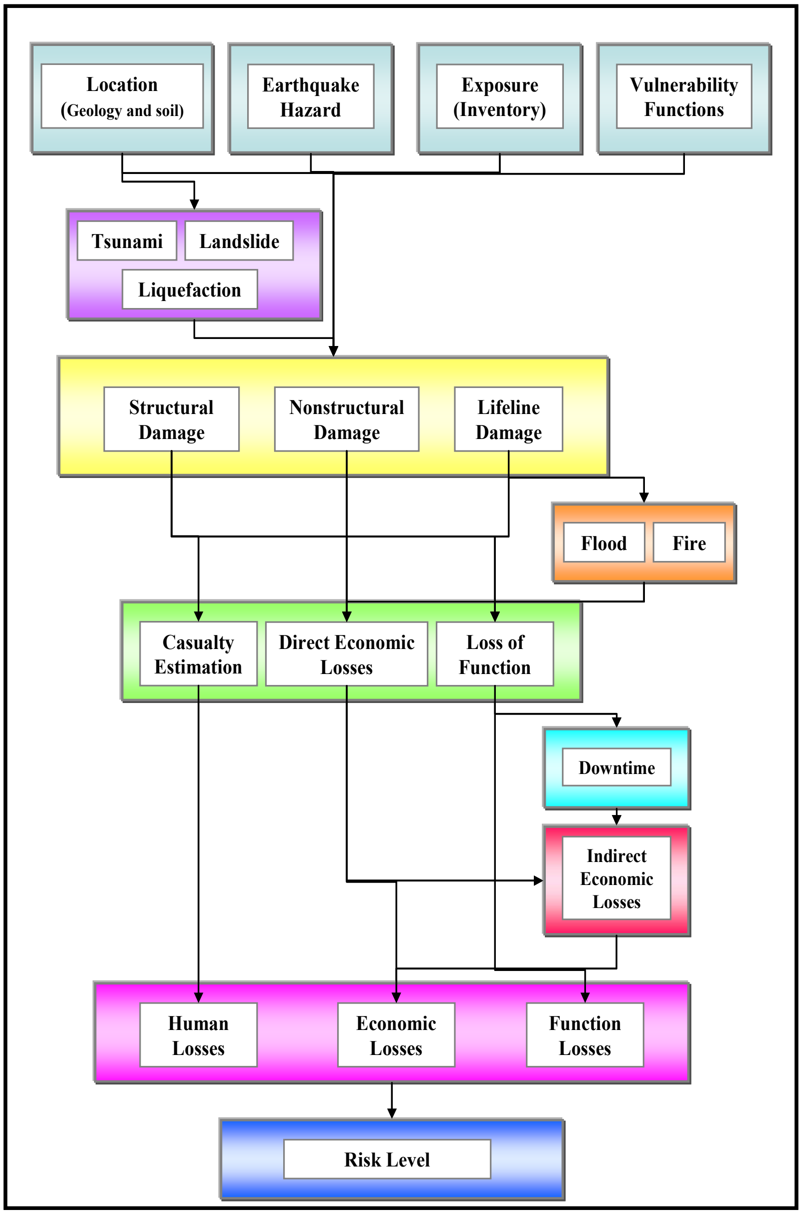

Figure 2. BC Seismic Risk Assessment Methodology

Indirect damage is the result of the additional hazard created by the direct damage sustained to the buildings and lifelines affected by the earthquake. Fires and flooding caused by the rupture of natural gas and water pipelines are common forms of indirect damage. Direct losses (green block) are the result of earthquake damage and include the estimation of human losses, monetary losses and the loss of building function. The BC seismic risk assessment methodology defines casualties as injuries and fatalities that result from earthquake building damage. The number of casualties is determined based on the level of structural damage suffered by a building and the number of occupants at the time of the earthquake. Direct economic losses are incurred from the repair and replacement of damaged building components. Monetary losses are determined based on the replacement value of the building and the damage to its structural and non-structural components.

Loss of function refers to the ability to conduct normal operations in the building given the level damage it has sustained from a seismic event. Buildings are placed into one of five functionality categories based on the structural and non-structural damage assessments. Indirect economic losses are the losses incurred due to business interruption and depend directly on the estimation of downtime.

The magenta block defines the final result of seismic risk assessment: the consequences of a given seismic event. The consequences include the total number of casualties, the direct and indirect economic losses and the loss of function. The consequences determine the level of risk associated with a particular seismic event. This risk level should be evaluated by policy makers and government officials to determine if the level is acceptable.

Ground motion intensity is usually estimated in terms of peak ground acceleration (PGA) and spectral acceleration (SA), or in term of damage potential, such as the Modifed Mercally Intensity (MMI), or the Instrumental Intensity (II). The MMI-based damage probability matrices have been commonly used to estimate damage (ATC, 1985). These matrices define the probability that a particular type of structure is in a specified damage state for a given level ground shaking intensity, expressed in terms of MMI. Each damage state is defined by a range in damage factors, which represent damage as a percentage of replacement cost. For example, moderate damage is defined as corresponding to 10%-30% of replacement cost, with an average factor called the Central Damage Factor (CDF) of 20%. Multiplying the CDFs by their probabilities as defined in the damage matrices and adding up the products gives the mean damage factor (MDF), which is the total level of damage as a percentage of replacement cost.

The FEMA damage estimation methodology incorporated in the software HAZUS (FEMA/NIBS 1997 and 2003) uses spectral parameters to define the level of ground shaking instead of MMI. In this method, the vulnerability of buildings is described by fragility curves, which are continuous versions of the damage probability matrices. While it is recognized that engineering parameter based vulnerability relationships are the current state of the art method for the assessment of seismic damage**,** at this time there is great uncertainty in the fragilities and insufficient data to develop these curves for BC. Damage probability matrices are already available for BC (Ventura, et al., 2005) and offer a more convenient and refined estimations for seismic risk studies of the region.

Building Inventory and Classification

The buildings in BC have been classified into 31 structural types in terms of their use, structural system, age and height. The most common building types in BC and a brief description of these building types are provided in Table 1. As an illustration, the distribution of prevalent building type in Vancouver is mapped in Figure 3.

Table 1. Description of some common building types in BC

Building Type	Description
WLFR	One or two-storey single family detached homes and attached townhouses.
WLFCI	One or two-storey wood frame commercial/institutional buildings.
WLFLR	Residential apartment buildings usually up to four storeys high.
SFMI	Steel frame with masonry infill walls. Common prior to the 1950's (mainly offices).
CFLR,MR,HR	Concrete frame structures with shear walls (LR:1-3 stories, MR:4-7, HR: >8)
RCFIW	Reinforced concrete frame with infill walls. Common prior to 1950's.
RMLR	Reinforced masonry low rise (1-3 stories)
URMLR,MR	Unreinforced masonry (LR: 1-3 stories, MR: >3)

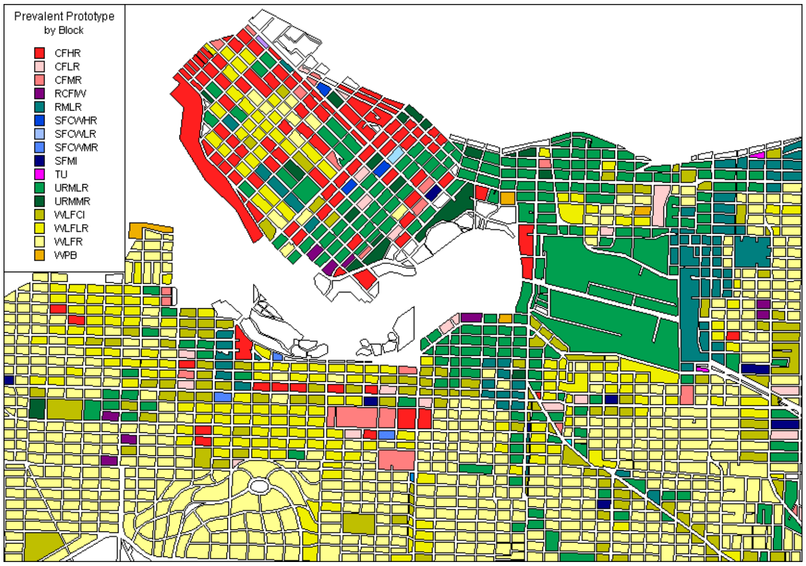

Figure 3. Building type distribution map for Vancouver.

Table 2 presents the Mean Damage Factors for all 31 prototypes as a function of the Instrumental Intensity.

The damage probability matrices were developed under the assumption that the buildings being assessed were "regular". A "regular" building is defined as one that has standard geometry, is without soft stories and short columns, is in good state of repair and has not been seismically retrofitted. Many buildings, however, are not regular and structural damage modification factors are required in order to account for the change in behaviour caused by these issues. Modification factors have been developed for plan and vertical irregularities, the current state of repair, pounding, soft stories, openings, short column effects, pre-code construction, construction after the benchmark code and retrofits. Each of the modifiers is described below in table 3. Note LFRS stands for Lateral Force Resisting System.

Thibert (2008) implemented a simple method to modify the damage factors of the "regular" buildings with appropriate factors to account for the possible situations in Table 3 encountered in the buildings included in the inventory. The modifiers, denoted as SM are the result of multiplying predetermined factors by the MDFs for the prototype. In mathematical terms, the damage estimate of the "idealized" building prototype and the "modifiers" are combined according to the following expression:

$$MDF_F = MDF + \sum SM$$

Where MDF_F is the final structural mean damage factor, MDF is the base mean damage factor and ΣSM is the summation of all of the applicable modifiers. Figure 4 shows how these modifiers are likely to affect the MDF for wood light frame commercial/institutional buildings (WLCI). In this figure, the "best case" is a building constructed post benchmark. The range of possible MDFs is bounded by best and worst cases of the building. Commercial buildings of this type tend to be grouped together in the form of streetscapes and corner buildings may be severely damaged by pounding. Also, many of these buildings have storefronts and suffer the effects of a soft storey. At low intensities, the modification factors have little effect on the total structural damage, but as the intensity increases they play a much more important role. For an intensity X earthquake, using the "base" mean damage factor only, the building is expected to have moderate damage (MDF = 27%). However, if the modifiers are included, the damage would be heavy (56%).

Table 2. BC Mean Damage Factors

		Mean Damage Factor (%)						
Number	**Prototype**	**II VI**	**II VII**	**II VIII**	**II IX**	**II X**	**II XI**	**II XII**
1	**WLFR**	1.2	4.1	6.2	12.0	22.7	28.4	37.7
2	**WLFCI**	1.2	5.5	9.1	14.5	27.4	36.9	44.1
3	**WLFLR**	1.0	3.8	4.9	11.6	18.8	28.1	37.4
4	**WPB**	1.4	6.4	11.8	18.9	31.6	39.1	45.9
5	**LMF**	0.5	2.7	4.1	7.0	18.8	23.9	36.7
6	**SMRLR**	0.6	3.2	5.0	6.3	17.3	23.4	36.1
7	**SMFMR**	0.7	3.7	5.1	8.7	20.6	31.7	42.8
8	**SMFHR**	0.7	4.5	5.8	17.2	23.6	37.4	44.8
9	**SBFLR**	0.9	2.6	6.9	12.3	22.4	31.4	40.6
10	**SBFMR**	1.6	4.5	10.1	14.8	22.1	32.5	38.3
11	**SBRHR**	1.6	5.9	10.5	16.0	23.8	39.6	48.4
12	**SFCWLR**	0.9	4.5	6.2	15.6	22.2	36.0	46.5
13	**SFCWMR**	1.3	4.7	7.7	19.3	29.1	42.2	51.1
14	**SFCWHR**	1.3	4.7	9.3	22.8	32.8	49.3	57.0
15	**SFCI**	1.1	4.6	8.5	18.4	30.3	47.9	53.4
16	**SFMI**	3.1	7.5	16.5	36.2	45.8	64.0	69.2
17	**CFCWLR**	0.9	4.7	5.0	13.9	21.0	36.9	49.4
18	**CFCWMR**	0.9	3.6	7.9	16.8	23.8	39.1	51.2
19	**CFCWHR**	1.1	4.0	11.3	22.9	30.4	43.2	54.2
20	**CMFLR**	3.0	5.5	13.8	21.0	37.9	48.9	54.5
21	**CMFMR**	3.0	5.8	13.6	22.3	41.0	55.3	60.3
22	**CMFHR**	3.4	4.9	15.7	25.5	41.6	60.1	67.4
23	**CFIW**	2.9	7.7	15.6	30.4	39.6	60.6	67.5
24	**RMLR**	0.7	4.0	5.9	16.6	31.5	43.4	58.3
25	**RMMR**	0.9	4.6	8.0	26.7	35.3	47.8	67.3
26	**URMLR**	2.8	10.2	23.4	34.9	51.7	65.8	80.0
27	**URMMR**	4.3	12.2	26.9	38.2	53.8	70.0	83.7
28	**TU**	0.8	3.7	9.0	18.8	34.0	50.5	65.6
29	**PCLR**	2.3	4.8	11.3	25.0	39.2	51.7	66.6
30	**PCMR**	2.7	6.1	13.0	28.4	38.0	53.0	69.1
31	**MH**	1.8	5.6	13.5	18.8	31.8	45.0	56.7

The building inventories in the areas investigated so far are as follows: New Westminster: 8,000; Victoria: 3,000; and Vancouver: 20,000 buildings, North Shore of Vancouver: 62,000, and UBC campus: 360. The building inventory for each city was established initially from the building database made available by the city. One of these databases contained a significant amount of structural information about the buildings, whereas others contained very little or none at all. These databases with no structural information were supplemented by building surveys, inference schemes, and by making use of data readily accessible in the Internet through Google Earth and Microsoft Bing Maps.

Table 3. BC Modifiers

Modifier	Description
Plan Irregularity	The presence of irregularities and unsymmetrical layout of the building's plan geometry and LFRS
Vertical Irregularity	The presence of irregularities in the plan profile and LFRS at each storey
State of Repair	The overall condition of the building relating to pre-existing damage and deterioration
Pounding	Damage that is induced due to the relative displacement between adjacent buildings
Soft Story	The presence of a local reduction in stiffness of a particular storey of a building
Openings	The presence of large openings in LFRS shear walls
Short Columns	The presence of short columns which are the results of partial height infill walls or deep beams. The effect is a decrease in the shear resistance
Precode	A building constructed before the enforcement of seismic design provisions in the building code, 1967 for Vancouver
Post Benchmark	A building constructed after the benchmark code year, 1990 for Vancouver
Retrofit	A building that has had partial or full upgrading of its structural system

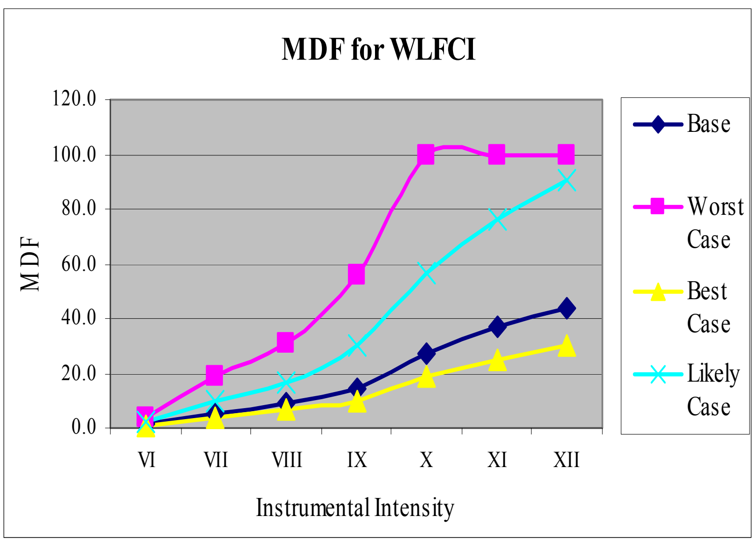

Figure 4. Effect of Modifiers on Mean Damage Factors for WLFCI

The impact of non-structural damage on monetary losses has been investigated as a function of the level of shaking. Figure 5 below shows the results for the damage estimates for the buildings at the UBC campus. The graphs are plotted using the logarithmic scale for clarity as the total losses are a thousand times higher than some of the component losses. The displacement sensitive losses are the most significant contributors for the lower intensities and the structural losses become more important for the higher intensities.

Another important component of the damage estimation methodology is the estimate of casualties as a function of the level of shaking and the time of the day when the earthquake occurs. The total number of casualties expected at UBC campus is presented for all seven levels of intensity in Figure 6 for three specific times of day.

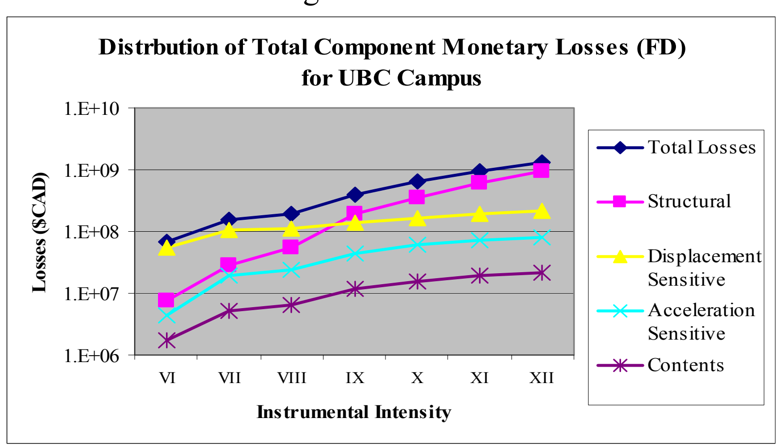

Figure 5. Monetary Losses for UBC Campus

Very few casualties are expected for intensities VI through VIII; however the number increases significantly from intensities IX through XII. The trend is similar to that of the expected structural damage. Since the casualty estimation depends on the structural damage and the number of occupants, this makes sense. For all levels of Instrumental Intensity, the time of 2:00 pm is the most critical earthquake time for UBC campus. This may differ in the case of a larger city.

The building functionally is determined taking into consideration the damage to the structural components and the damage to displacement-sensitive, acceleration-sensitive components and the building contents.

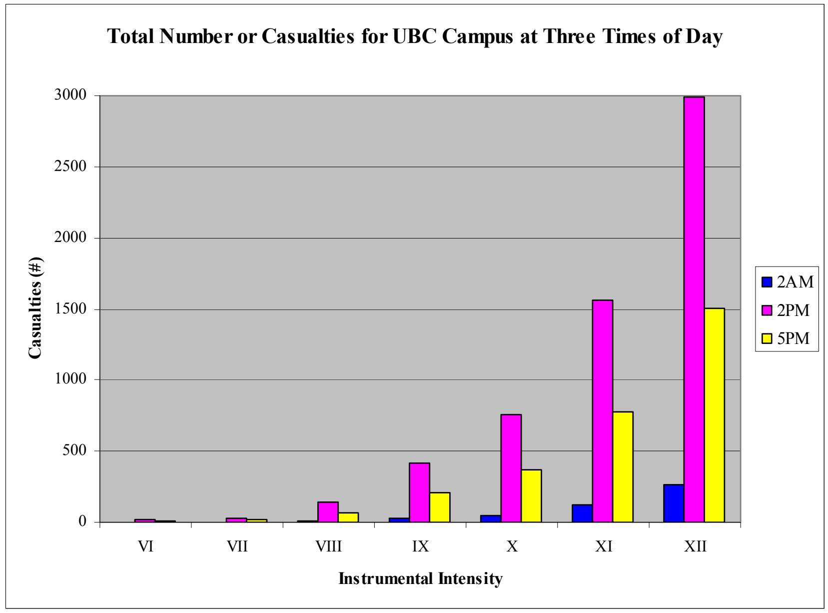

Figure 6. Expected Casualties for UBC Campus

Functionality categories were developed for British Columbia seismic risk assessment based on the PAHO seismic safety levels (2000) and the EERI standardized damage states (1994). There are five categories ranging from “Fully Functional” to “Near Collapse” and an estimate of the functionality in terms of percentage is presented for each. Table 4 lists the categories, their descriptions and functionality percentages.

Table 4. Functionality Categories

Category	Title	Description	% Functional
A	Fully Functional	The building remains in a suitable condition for normal use, perhaps with some limitations. No damage, but contents could be shifted. Only incidental hazard.	100
B	Operational	Very limited damage to the structure and non- structural components is seen. Contents are shifted. Clean up and inspection is a necessity. It is possible that repairs will have to be made before normal function can resume. Only incidental hazard. Important buildings, such as hospitals and fire stations, can operate. Less important buildings may be closed for a week for clean-up and minor repairs.	80
C	Moderate	Primarily Non-structural Damage and some minor structural damage. Repairs are required. Important buildings may be able to function, but at reduced capacity (~ 50%). Remote chance of lives threatened.	50
D	Life Safe	Extensive structural or nonstructural damage. Long term closure should be expected due to the amount of repair work or uncertainty of economic feasibility. Localized, life threatening situations would be common.	0
E	Near Collapse	Building may suffer total or partial collapse or structural or non-structural damage that is not economically repairable. Life threatening situations in every building in the category.	0

In order to determine the overall functionality of a building, the structural damage and all three forms of nonstructural damage must first be classified individually into functionality categories. Table 5 presents the damage thresholds for each functionality category for each type of damage. These thresholds are based on the damage state ranges for the structural components and for the nonstructural components and contents. Buildings are classified into functionality categories based on their final mean damage factors for each component. The overall functionality of the building is taken to be the worst case of the structural, displacement sensitive, acceleration sensitive or contents functionalities.

Table 5. Functionality Category Thresholds

Category	Structural	Displacement Sensitive Components	Acceleration Sensitive Components	Building Contents
A	0 to 1%	0	0	0
B	1 to 10	0 to 5	0 to 5	0 to 2
C	10 to 30	5 to 20	5 to 20	2 to 10
D	30 to 60	20 to 80	20 to 80	10 to 40
E	60 to 100	80 to 100	80 to 100	40 to 100

Figure 7 displays the overall functionality of buildings in the UBC campus for all seven levels of intensity. The functionality is plotted in terms of the number of buildings in each category. For intensities VI through VIII, the majority of buildings fall into category C. The number of buildings in category D increases dramatically at intensity IX and continue to be the most common category through intensity XII. Category E buildings begin to emerge at intensity IX. The number of buildings in this category increase steadily to intensity XII, where they account for one third of the buildings in the study area.

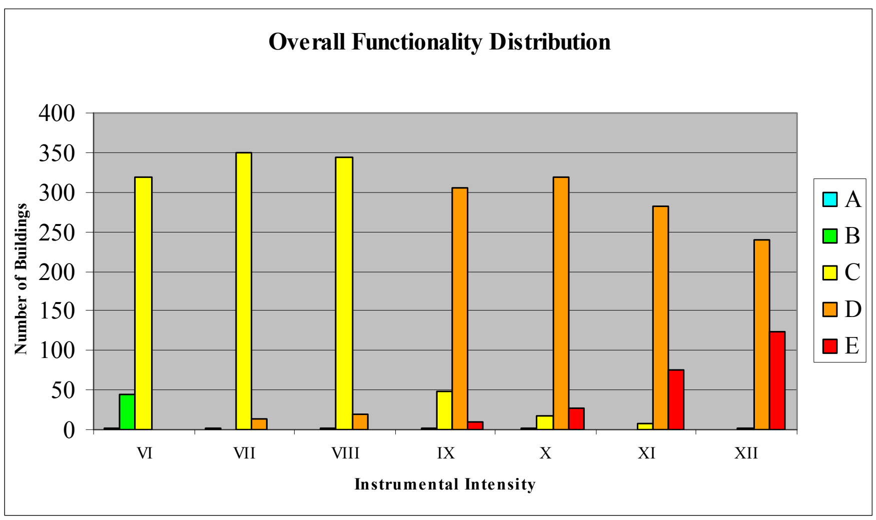

Figure 7. Building Functionality for UBC Campus

CONCLUSIONS

A detailed study of seismic risk was conducted for the various cities in the Vancouver region and Victoria in British Columbia, Canada. Risk was assessed in terms of casualties, structural and non-structural damage, monetary losses and loss of functionality. The assessments were conducted using MMI based damage matrices for BC construction. HAZUS technology could not be used because fragility curves are not yet available for BC construction. Each building was assessed initially on the assumption that the building was regular. The resulting mean damage factor was then modified to account for any deviations from regularity using specially developed modifiers. A novel feature of the process was the development of a simple procedure for estimating post-earthquake functionality of buildings. Different levels of functionality were defined and these levels were linked to mean damage factors.

Future development of the damage estimation procedure envisages two major improvements, one related to data presentation using multi-information layers attached to Google maps and the other related to handling the effects on damage due to the interdependencies between the structure and associated services such as lifelines.

Acknowledgements

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