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EFFECT OF EARTHQUAKE PROBABILITY LEVEL ON LOSS ESTIMATIONS

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SUMMARY

The ground shaking intensity used for calculating the quasi-static forces to be applied in building design according to the National Building Code of Canada (NBCC) is established by probabilistic seismic hazard analyses. The probability level for which the amplitudes of design motions are determined in the current building code, NBCC-1995, corresponds to a 10% chance of exceedance in 50 years. The insurance industry has funded loss estimation studies at the University of British Columbia for a number of cities in British Columbia, including the largest, Vancouver. This city has the highest seismic hazard among the three most populated urban centres in Canada. A major objective of the studies was to provide a rational basis for discussions with government on how to cope with catastrophic losses in the region. For this reason, it was considered appropriate to use the same probability of exceedance of shaking intensity as that used in NBCC-1995. The seismic provisions of the next edition of the code, NBCC-2005, will be based on a probability level corresponding to a 2% chance of exceedance in 50 years. This paper investigates the impact of this change on the loss estimations for Vancouver. The concepts and strategies used in the Vancouver study are of wide applicability and should be of interest to others engaged in risk assessment.

INTRODUCTION

Vancouver in the province British Columbia (BC) is the third largest city in Canada with a population of about 2 million people living in the Greater Vancouver metropolitan area (2001 census). It is located in one of the most seismically active regions in Canada, the Cascadia Subduction Zone, where the oceanic Juan de Fuca plate is subducting beneath the continental North America plate at a rate of 4-5 cm/year [1]. Vancouver is exposed to three types of earthquakes in this tectonic setting, shallow crustal earthquakes within the North America plate (up to 30 km deep), deep subcrustal earthquakes within the subducting Juan de Fuca plate (about 50 km deep) and "megathrust" (magnitude 8.0 or higher) earthquakes at the interface of the two plates (Figure 1). The average return period of Cascadia megathrust earthquakes is 500-600 years [2, 3] and the last one occurred about 300 years ago [4].

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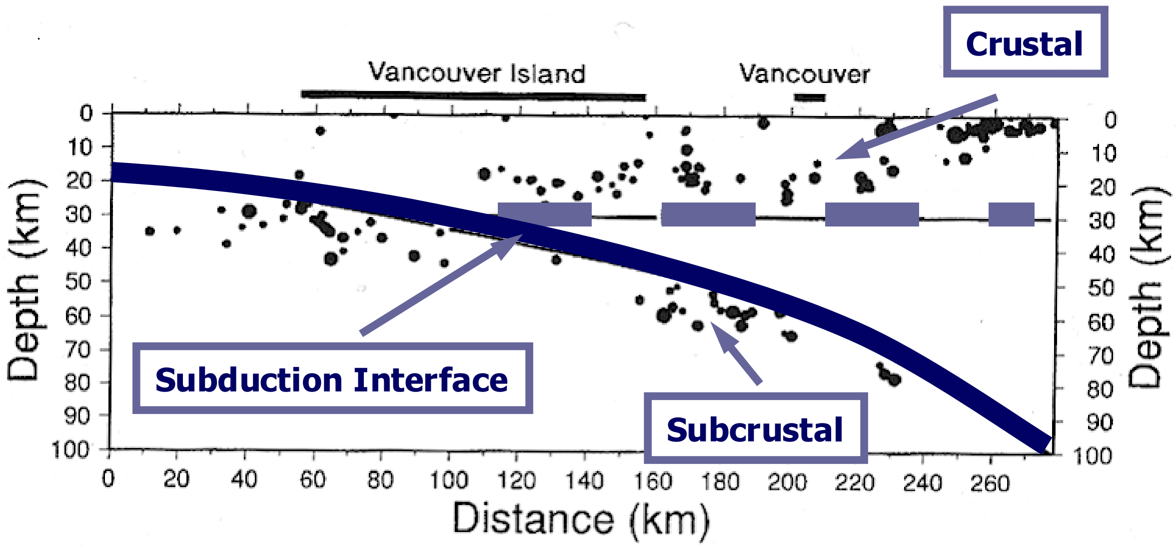

Figure 1. Seismicity in the Cascadia Subduction Zone (after Rogers [5])

The ground shaking intensities for the current National Building Code of Canada, NBCC-1995 and the upcoming NBCC-2005 were calculated by the Geological Survey of Canada (GSC) and documented in [6] and [7], respectively. Megathrust earthquakes are not included in the probabilistic calculations of ground shaking hazard for NBCC, rather they are treated deterministically [7].

In a past study by the authors [8, 9], an estimation of building damage was carried out for the City of Vancouver, BC based on the ground motions calculated at the probability level indicated in the current NBCC, i.e. 10% chance of being exceeded in 50 years. The building code probability level was of interest to the insurance industry as it formed a rational basis for discussions with government on how to cope with catastrophic losses due to earthquakes in the region. However, in the upcoming NBCC, the probability level is being reduced to 2% in 50 years for better and more consistent life-safety standards across the country. This study investigates the effect of this change on the estimated damage to buildings and the resulting direct monetary loss. The damage estimations are based on earthquake ground shaking intensities that are calculated probabilistically taking into account crustal and subcrustal earthquakes. The amount of damage in buildings due to a Cascadia megathrust earthquake was not estimated, because it is significantly influenced by the distinctive characteristics of this type of earthquake, especially long duration of strong shaking, quantification of which requires further research.

SEISMIC HAZARD, DAMAGE AND LOSS ESTIMATIONS

Probabilistic Seismic Hazard Models

In previous damage estimations [8, 9], the ground shaking intensities were calculated by probabilistic seismic hazard assessment (PSHA) procedures, using the hazard models developed by Adams et al. [10] for a probability level of 10% in 50 years. These calculations yielded a peak ground acceleration (PGA) of 0.23g for the City of Vancouver on firm ground [11], which corresponded to Modified Mercalli Intensity (MMI) VIII using an empirical PGA-MMI conversion relationship [12]. Although the PGA varied slightly across the city, the variation was not large enough to make a difference in MMI. The City of Vancouver lies almost entirely on glacial till, therefore amplification of ground shaking intensities is not expected.

The Adams et al. [10] hazard models form the basis for NBCC-2005 ground motions, and were updated with minor changes to calculate the final values to be listed in the code [7]. The updated models were used in calculating the ground shaking intensities in Vancouver at a 2%-in-50-year probability level. The resulting PGA is 0.48g, which corresponds to MMI IX [12].

Building Inventory and Estimation of Structural Damage

The building inventory was established by supplementing the building database obtained from the city by on-site building surveys and rapid visual screening of individual buildings [11]. It covers downtown Vancouver and surrounding neighbourhoods to the east and south, and includes roughly 20,000 buildings (Figure 2), which accounts for about one fifth of the City of Vancouver's total building stock. All building types that are common in BC are represented in the inventory.

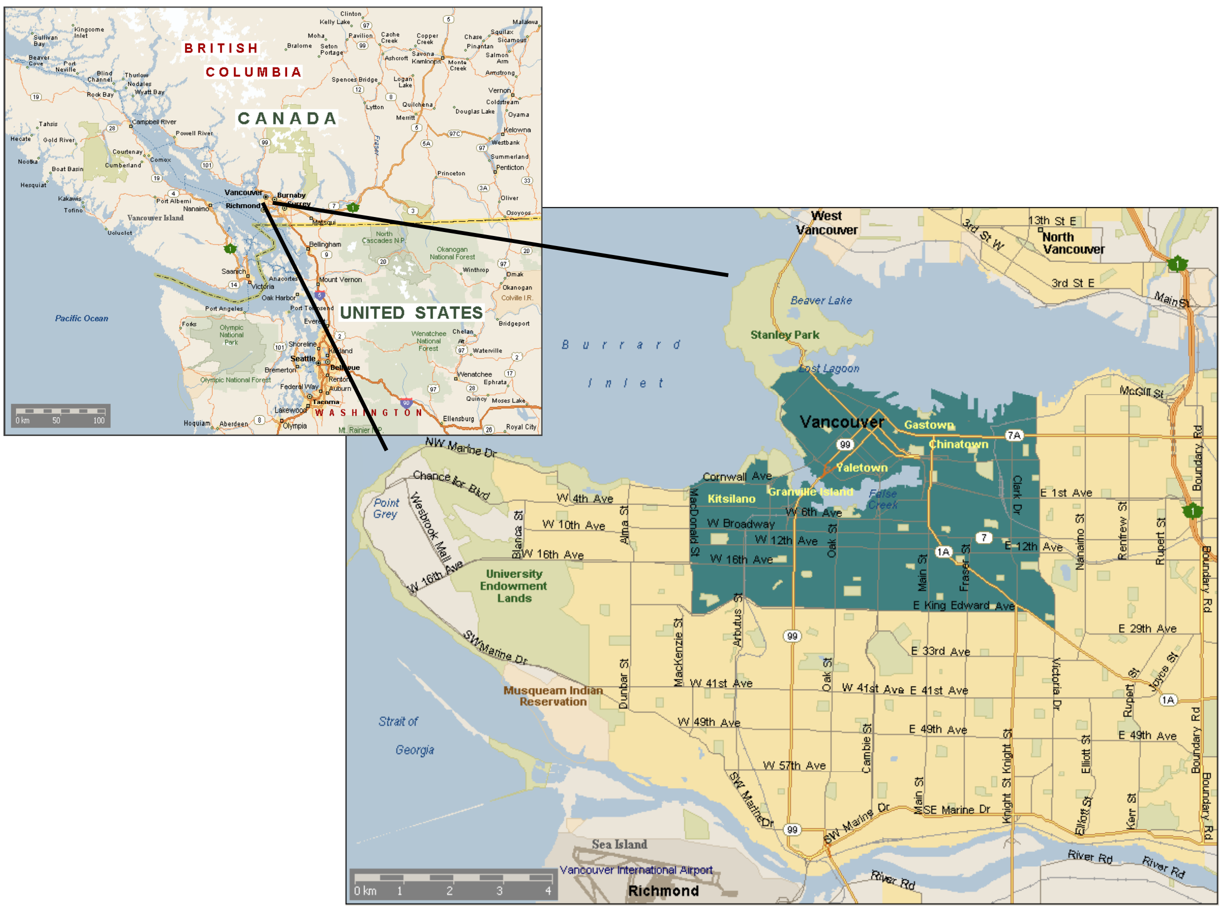

Figure 2. Building inventory coverage (in dark green) in the City of Vancouver

Damage estimation is based on damage probability matrices, which define the probability that a particular type of building is in a specified damage state for a given level of 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 CDFs by their probabilities as defined in the damage matrices and adding up the products gives the mean damage factor (MDF), which characterizes the total level of damage as a percentage of replacement cost.

This methodology, which was originally developed for buildings in California [13] and subsequently extended to non-Californian structures [14], was adapted to BC by developing a building classification scheme (Table 1) and damage probability matrices specific to BC buildings. This was achieved by consulting several professional engineers in BC on their judgement in building response taking into account the local construction practices [15]. Each building in the inventory was assigned one of the 31 building classes based on on-site rapid inspection of its lateral load bearing system, which was often exposed at the back of the building. The MDFs (Table 2) were calculated for each individual building and then averaged over each city block. The distribution of damage in the city was then plotted on a block-by-block basis [11] using Geographic Information Systems (GIS) software MapInfo®.

Table 1. BC building classes

	Material	Building Class Description	Code
1	Wood	Wood light frame residential (single family)	WLFR
2		Wood light frame low rise commercial/institutional	WLFCI
3		Wood light frame low rise (up to 4 stories) residential	WLFLR
4		Wood post and beam	WPB
5	Steel	Light metal frame	LMF
6		Steel moment frame low rise (up to 3 stories)	SMFLR
7		Steel moment frame mid rise (between 4 and 7 stories)	SMFMR
8		Steel moment frame high rise (8 stories and higher)	SMFHR
9		Steel braced frame low rise	SBFLR
10		Steel braced frame mid rise	SBFMR
11		Steel braced frame high rise	SBFHR
12		Steel frame with concrete walls low rise	SFCWLR
13		Steel frame with concrete walls mid rise	SFCWMR
14		Steel frame with concrete walls high rise	SFCWHR
15		Steel frame with concrete infill walls	SFCIW
16		Steel frame with masonry infill walls	SFMIW
17	Concrete	Concrete frame with concrete walls low rise	CFCWLR
18		Concrete frame with concrete walls mid rise	CFCWMR
19		Concrete frame with concrete walls high rise	CFCWHR
20		Concrete moment frame low rise	CMFLR
21		Concrete moment frame mid rise	CMFMR
22		Concrete moment frame high rise	CMFHR
23		Concrete frame with infill walls	CFIW
24	Masonry	Reinforced masonry shear wall low rise	RMLR
25		Reinforced masonry shear wall mid rise	RMMR
26		Unreinforced masonry bearing wall low rise	URMLR
27		Unreinforced masonry bearing wall mid rise	URMMR
28	Tilt up	Tilt up	TU
29	Precast	Precast concrete low rise	PCLR
30		Precast concrete mid rise	PCMR
31	Mobile	Mobile homes	MH

Table 2. Mean damage factors for structural components

Building Class	MDF (%) for MMI:		Building Class	MDF (%) for MMI:	
	VIII	IX		VIII	IX
WLFR	7.4	12.0	**CFCWLR**	5.0	13.9
WLFCI	9.1	14.5	**CFCWMR**	7.9	16.8
WLFLR	4.9	11.6	**CFCWHR**	11.3	22.9
WPB	11.8	18.9	**CMFLR**	13.8	21.0
LMF	4.1	7.0	**CMFMR**	13.6	22.3
SMFLR	5.0	6.3	**CMFHR**	15.7	25.5
SMFMR	5.1	8.7	**CFIW**	15.6	30.4
SMFHR	5.8	17.2	**RMLR**	5.9	16.6
SBFLR	6.9	12.3	**RMMR**	8.0	26.7
SBFMR	10.1	14.8	**URMLR**	23.4	34.9
SBFHR	10.5	16.0	**URMMR**	26.9	38.2
SFCWLR	6.2	15.6	**TU**	9.0	18.8
SFCWMR	7.7	19.3	**PCLR**	11.3	25.0
SFCWHR	9.3	22.8	**PCMR**	13.0	28.4
SFCIW	7.9	16.8	**MH**	13.5	18.8
SFMIW	16.5	36.2			

Estimation of Non-structural Damage and Direct Monetary Loss

In this paper, direct monetary loss refers to financial loss resulting from damage to structural and non-structural components of buildings due to ground shaking only, i.e. losses due to business interruption or collateral hazards such as fire, tsunami, liquefaction or landslides triggered by the earthquake are not included in the loss estimates.

After a number of recent earthquakes, it was observed that damage to non-structural components constitutes the largest portion of the monetary losses, which makes it essential to include non-structural damage in loss estimations. Non-structural components are divided into acceleration- and displacement-sensitive non-structural components, since their response to seismic forces is fundamentally different from each other. Displacement-sensitive non-structural components include non-load-bearing partition walls, wall panels, architectural finishing, veneer, and cladding. The amount of damage in these elements is largely controlled by drift. Acceleration-sensitive non-structural components include cantilever elements, parapets, mechanical and electrical equipment, suspended ceiling, elevators, racks and cabinets. Since these elements are typically much stiffer, the damage they suffer is largely controlled by high frequency accelerations. In this study, damage to non-structural components was estimated using a methodology similar to the one used for structural damage. Damage is estimated using separate non-structural damage probability matrices developed for acceleration-sensitive and displacement-sensitive components, and for each of the 31 classes of buildings [16]. For most building classes, expected damage to displacement-sensitive non-structural components are larger than damage to structural components. Expected damage to acceleration-sensitive components, on the other hand, is relatively lower.

Direct monetary losses are estimated by adding up losses from damage to structural and non-structural components of buildings. Since the amount of damage is expressed by MDF, i.e. the ratio of dollar loss to replacement cost, the monetary losses resulting from damage to these components were calculated by simply multiplying the MDFs by replacement costs. Construction costs for each of the 31 BC building classes were obtained from local construction companies (cost per square foot in Canadian dollars, 2001). Unreinforced masonry buildings were assumed to be replaced by reinforced masonry buildings of the same size, as the NBCC has required all masonry to be reinforced since 1973. Based on the judgement of local engineers, about 25% of these costs result from structural components and 75% non-structural components. The acceleration- and displacement-sensitive non-structural components were assumed to have equal costs.

10% IN 50 YEARS TO 2% IN 50 YEARS

Changing the probability level from 10% in 50 years to 2% in 50 years essentially increases the expected MMI levels from VIII to IX in Vancouver. Figure 3 presents the comparison of damage distributions for MMI VIII (Figure 3a) and MMI IX (Figure 3b) in the study area in City of Vancouver. The estimated damage increases from 20%-30% for MMI VIII to over 30% of the replacement cost for MMI IX in the older parts of the city where unreinforced masonry buildings are abundant. The residential neighbourhoods go up from 5%-10% damage (MMI VIII) to 10%-15% range (MMI IX). In downtown Vancouver, which is the commercial heart of the city with a high concentration of concrete high-rises, the expected damage goes up from 10%-20% range (MMI VIII) to 20%-30% range (MMI IX).

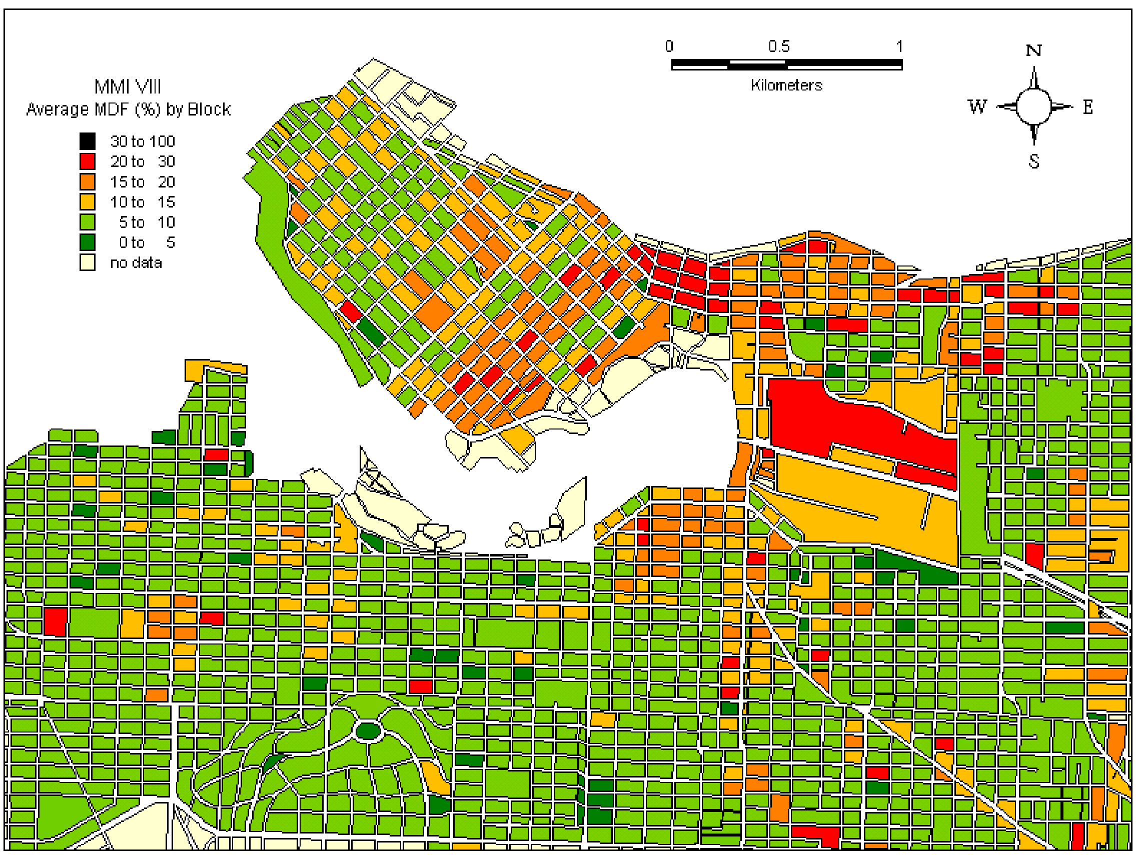

Figure 3a. Estimated structural damage distribution in Vancouver study area: MMI VIII – average MDF (%) by block

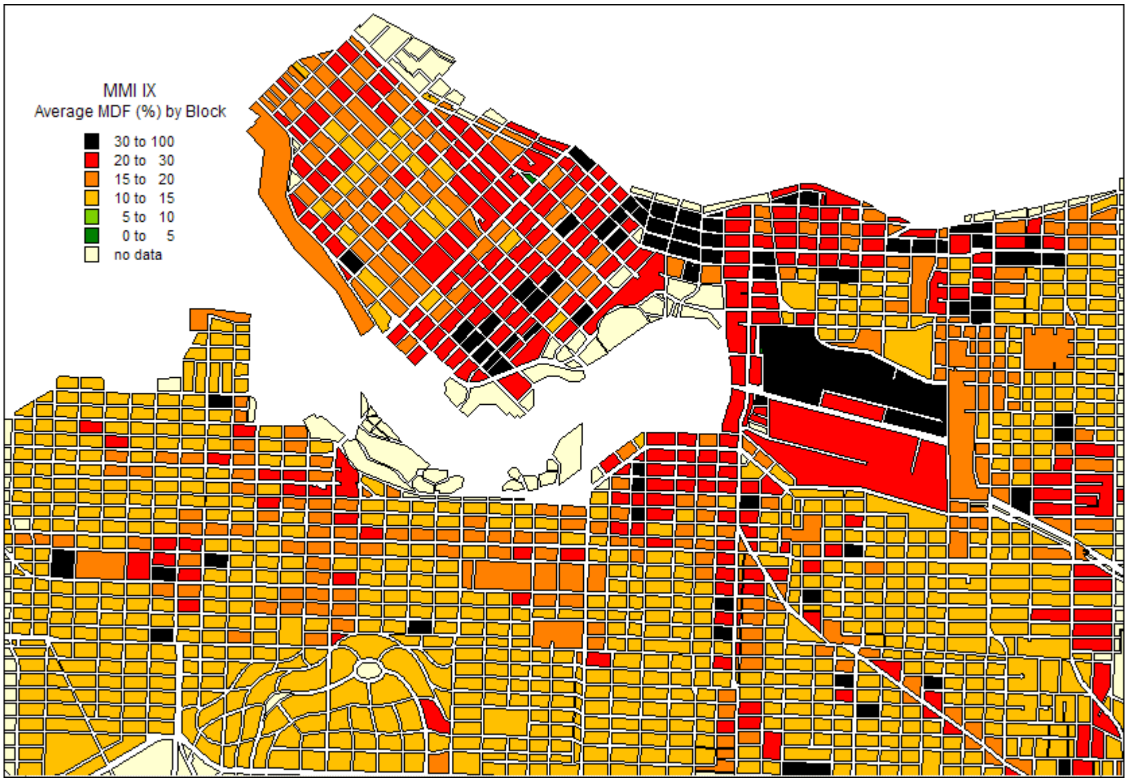

Figure 3b. Estimated structural damage distribution in Vancouver study area: MMI IX – average MDF (%) by block

The distribution of corresponding dollar loss for MMI VIII and MMI IX are presented in Figures 4a and 4b, respectively. Downtown Vancouver, where the high-rise buildings are concentrated is estimated to experience the highest economic loss, loss per block exceeding $1.0 million at most city blocks in the downtown core. The loss per block in primarily residential neighbourhoods is estimated to be lower than $500,000 in general for MMI VIII, whereas for MMI IX the loss per block exceeds $500,000 for almost all blocks.

The total direct loss expected in the study area in Vancouver is about $1.8 billion in Canadian dollars for a 10% probability of exceedance in 50 years (MMI VIII). For the same area, the estimate of total direct loss increases to $3.1 billion at a probability level of 2% chance of being exceeded in 50 years (MMI IX). These correspond to annualized losses of $3.8 million/year and $1.3 million/year, respectively. Thus, while increasing the earthquake shaking intensity from VIII to IX obviously increases the amount of total losses, the annual losses are greater for MMI VIII due to its higher likelihood of occurrence.

Two types of losses are identified above: **conditional expected loss** and **threshold loss**. The conditional expected loss is conditional on the seismic event occurring; hence it is defined as the total amount of loss given that the seismic event occurred. When the probability of exceedence for this event is taken into account and the associated loss reflects this probability, it is referred to as the threshold loss. In this study, the conditional expected loss is greater for the 2%-in-50-year ground shaking level while the threshold loss is greater for the 10%-in-50-year ground shaking. It is worthwhile to make this distinction between expected and threshold losses as it can help better understand the implications of the change in ground shaking intensity.

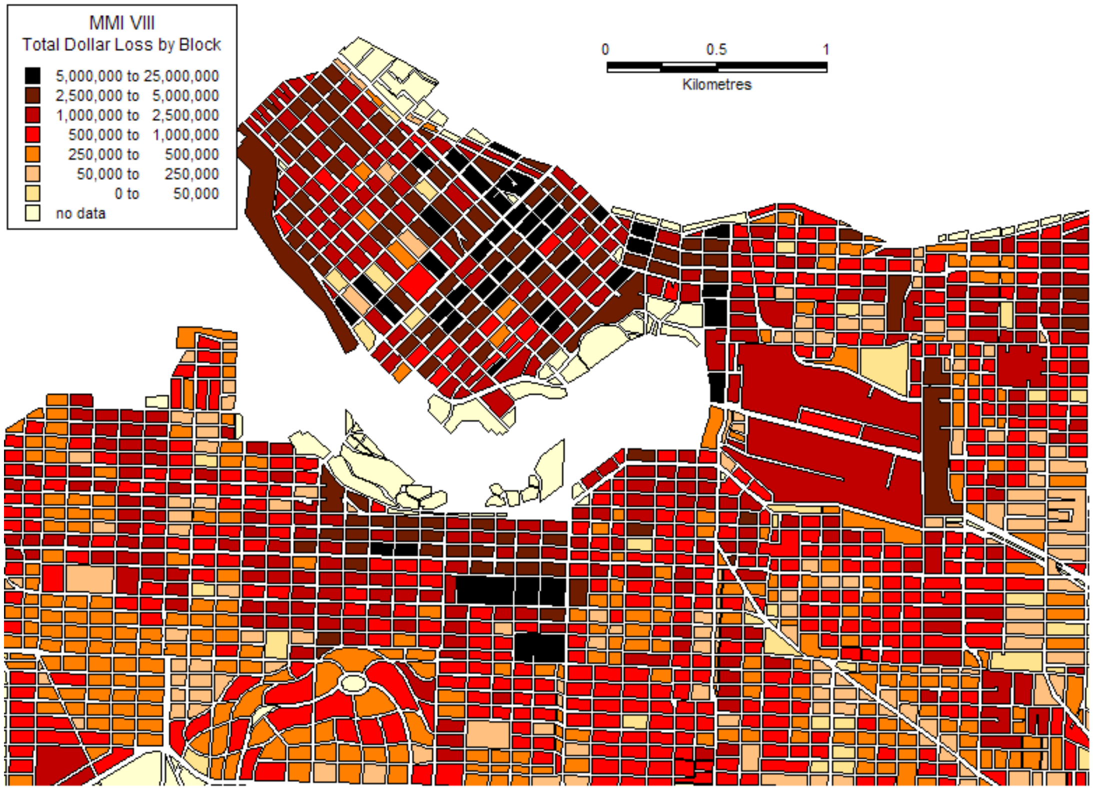

Figure 4a. Estimated loss distribution in Vancouver study area: MMI VIII – total loss ($) by block

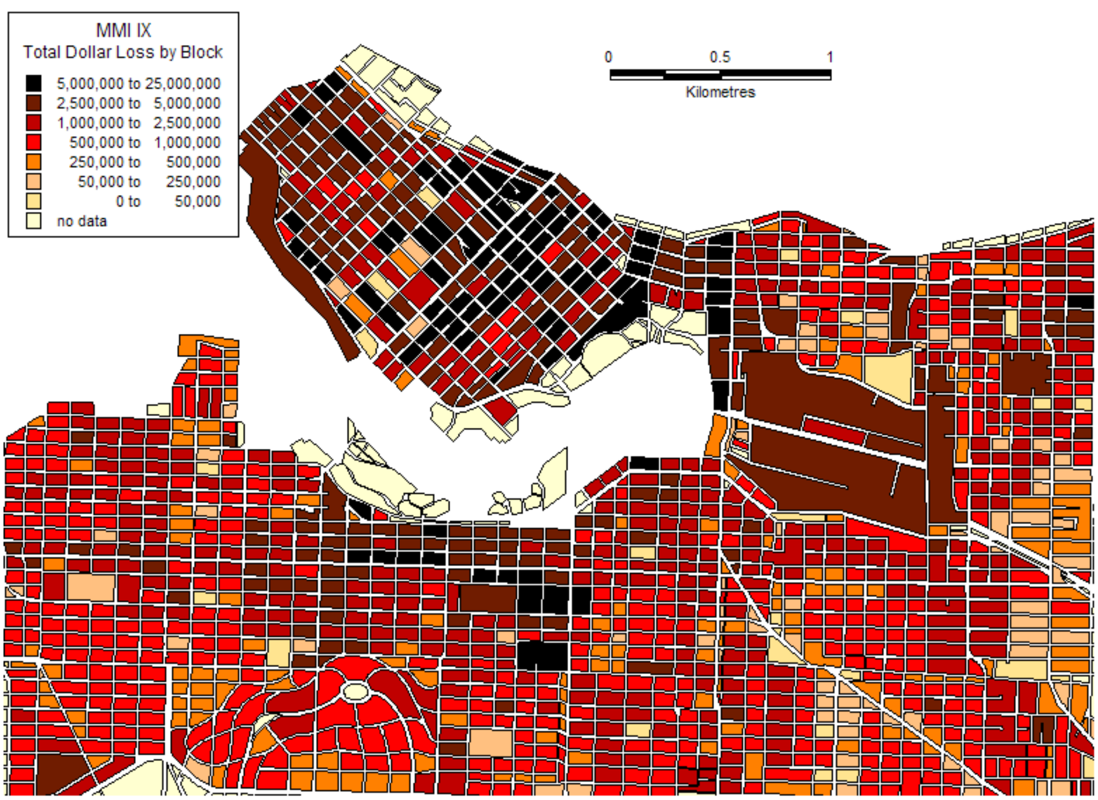

Figure 4b. Estimated loss distribution Vancouver study area: MMI IX – total loss ($) by block

CONCLUSIONS

This paper investigates the impact of the change in building code probability level on the loss estimations for Vancouver. The concepts and strategies used are of wide applicability and should be of interest to others engaged in risk assessment.

In theory, loss estimations can be carried out for any probability level of interest, e.g. 20% chance of being exceeded in 50 years (return period: 225 years) or 1% in 50 years (return period: 5000 years). In practice, selecting a non-arbitrary probability level is often a challenge, and in the absence of any other rational basis, the common practice is to use the probability level stated in the relevant seismic design code. The code provides a point of reference, an upper boundary for the seismic resistance of existing building inventory.

The current building stock in Vancouver was designed to 10%-in-50-year ground motions or lower. Figure 3a shows expected damage for the current building code level ground shaking while Figure 3b presents expected damage for the upcoming building code level ground shaking. It should be noted that single-family homes and some types of multi-family homes and commercial construction are not required to comply with any seismic code, which exacerbates the potential losses from these types of construction.

The estimate of structural damage at a 2%-in-50-year probability level in Vancouver varies across the study area: 10%-15% in residential neighbourhoods, 20%-30% in downtown, and over 30% in older parts of the city. Note that these estimates are for earthquake ground shaking hazard only, and do not reflect effects of secondary hazards such as liquefaction, landslides, tsunami, fire or aftershocks that may be caused by the main event. Total direct monetary loss in the study area at this probability level is estimated at $3.1 billion (in 2001 Canadian dollars).

The probabilistic approach presented in this study shows that while the total loss increases as the shaking from the expected event increases from MMI VIII to MMI IX, the annualized losses are greater for MMI VIII as its probability of occurrence is higher. In other words, larger events have lower probabilities of occurrence, but their potential damaging effects are greater.

The case study presents, quantitatively, how the probability of exceedance of certain ground shaking intensities affects the expected economic loss. The insurance industry has commonly used the building code level ground shaking for their earthquake loss estimations. The change from 10% in 50 years to 2% in 50 years may provide incentive to revise their models and estimates. This study was intended to provide alternative analysis tools to the insurance industry and other interest groups for making reliable judgements regarding the loss exposure they are willing to assume.

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