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ORIGINAL PAPER

Applying the HAZUS-MH software tool to assess seismic risk in downtown Ottawa, Canada

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Abstract The aim of this paper is to present earthquake loss estimations for a portion of downtown Ottawa, Canada, using the HAZUS-MH (Hazards United States Multi-Hazard) software tool. The assessment is performed for a scenario earthquake of moment magnitude 6.5, at an epicentral distance of 15 km, occurring during business hours. A level 2 HAZUS-MH analysis was performed where the building inventory, microzonation studies, and site-specific ground motion hazard maps (2% exceedence probability in 50 years) were all improved based on local information. All collected data were assembled into a set of standard geodatabases that are compatible with the HAZUS-MH software using a GIS-specific procedure. The results indicate that the greatest losses are expected in unreinforced masonry buildings and commercial buildings. Sensitivity studies show that soil classes, the vulnerability of schools, and the spatial scale of loss estimations are also important factors to take into account.

Keywords HAZUS · Eastern Canadian earthquakes · Loss estimations · Damage assessment · Casualty assessment · Eastern North American ground motions

1 Introduction

Global urbanization has increased significantly in recent decades. Bilham (1988) estimated that 40% of the world's major urban centers are located within 200 km of a tectonic plate boundary or in a region that has historically experienced a damaging earthquake. However, there has been an encouraging reduction of physical, social, and economical losses from

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earthquakes in developed countries for several reasons including strict and enforced building codes, and incentives to retrofit buildings (Spence 2004).

Mitigation is a sustained and cost effective approach to reduce or eliminate long term losses associated with a hazard. Mitigation involves the support and participation of experts across many disciplines. Historically, a breakdown in communication has existed between academia and policy makers (Wenzel et al. 2007); encouragingly, this is being rectified gradually with the introduction of user-friendly GIS (geographic information system) software packages like Hazards United States (HAZUS) and other similar tools. GIS software packages save valuable time and effort when managing geographically-sensitive information and databases. The use of GIS in disaster management is quickly becoming a standard operating procedure because the software can assess, compile, and display large amounts of data in a short period of time.

The basic earthquake loss estimation framework consists of: (1) evaluating seismic hazard for the given area; (2) collecting relevant and targeted data (e.g., in emergency response it is imperative to collect data pertaining to building and population characteristics; however, for recovery efforts the interest may shift to economical characteristics); (3) compiling and preparing data for input into the software tool performing loss estimation calculations; (4) analyzing the calculated losses for a specific or multiple scenarios; and (5) interpreting and incorporating projected losses into disaster response and mitigation plans.

HAZUS-MH, Hazards United States Multi-Hazard, is a comprehensive software tool developed by the Federal Emergency Management Agency (FEMA) of the United States through the National Institute of Building Sciences (NIBS), to determine multi-hazard loss estimations in the United States on a regional basis. Its three-tiered approach allows users to choose either default settings in a level 1 analysis or provide increasingly detailed user-supplied data to improve the level of detail of loss estimations in a level 2 or 3 analysis. In a level 1 analysis, results are based on default data for describing the hazard (regional earthquake hazard models), assessing soil amplification (generic amplifications for broad soil classes), and assessing vulnerability (default building inventory). Additions to default data that are implemented to upgrade from a level 1 to level 2 analysis include: the collection of a detailed building inventory, the development of site-specific earth science hazards maps, the compilation of data to model the economy, and the calculation of region-specific ground-motion parameters and site amplifications.

For earthquake loss estimations, once the inventories are updated and an earthquake scenario is specified, HAZUS-MH performs a series of operations to compute site-specific loss estimations. Typically, these operations utilize equations embedded within the program (outlined in FEMA and NIBS 2006b) and extract relevant information from corresponding databases to calculate losses. For example, physical damage to buildings for a specified ground motion is defined by capacity curves, which determine peak building response, and by fragility curves, which describe the probability of reaching or exceeding various damage states for a given building response (FEMA and NIBS 2006b). HAZUS determines the probability of slight, moderate, extensive and complete damage to the general building inventory, and then converts these probabilities into number of damaged buildings (see FEMA and NIBS 2006b for details). The loss estimation outputs include maps of seismic hazards, structural and non-structural damage probabilities to building and lifeline inventories, post-earthquake fire ignitions, inundated areas, debris generation, social losses, and both direct and indirect economic losses.

The aim of this article is to present earthquake loss estimations for downtown Ottawa, Canada, using the HAZUS-MH software tool. The assessment is performed for a scenario earthquake of moment magnitude (**M**) 6.5, at an epicentral distance of 15 km, occurring during business hours (2:00 pm). A challenge in implementing HAZUS-MH to a Canadian setting is that HAZUS-MH was designed for American applications. Our loss estimations will (1) focus on quantifying physical and social losses in terms of number of damaged buildings, amount of debris by weight and number of casualties, and (2) identify vulnerable characteristics of buildings and population. We will also briefly discuss the implications of our results for the entire City of Ottawa and outline future work needed. This article summarizes the graduate thesis of Ploeger (2008).

1.1 Study area

The City of Ottawa is an ideal candidate for an earthquake loss estimation study due to its status as the national capital of Canada and the threat that moderate-to-large earthquakes pose to the area (Adams et al. 2002). The study area for this article is centered on a limited sample in downtown Ottawa, bordered by Bronson Avenue, Cumberland Street, the Ottawa River and Gloucester Street. The area can be divided into two census tracts, the eastern and western census tracts, which can be further subdivided into ten dissemination areas as shown in Fig. 1. Comparatively, the study area is small and measures $\sim$2.5 km^2, while the City of Ottawa covers 2,796 km^2. However, the study area is densely populated relative to other parts of Ottawa.

Historic Ottawa is, for the most part, encompassed completely in the study area. The original Bytown townsite was established in the 1820s by Lt. Col. John By (Gordon and Osborne 2004). Due to the study area's historic character, the building inventory is dominated primarily by older masonry buildings in the eastern census tract. The western

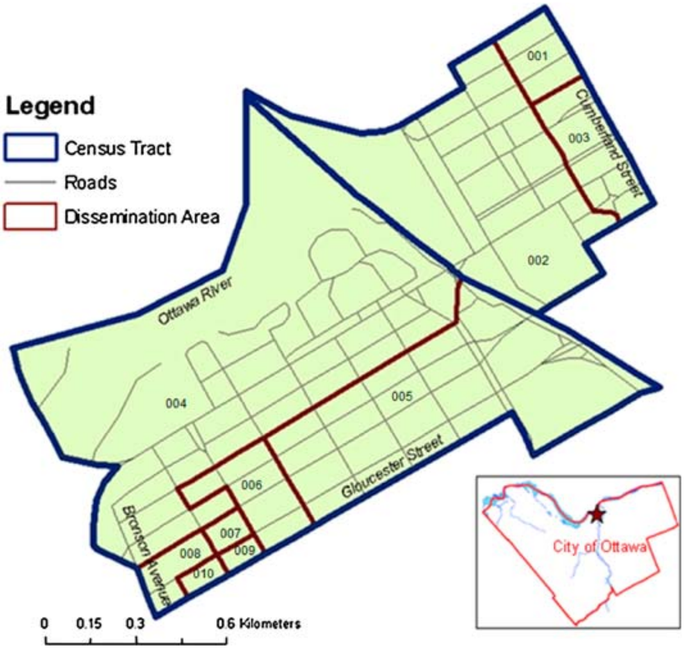

Fig. 1 Map depicting the census units within the study area (modified Ploeger 2008). (GIS data sources: Natural Resources Canada (NRCan), City of Ottawa, Statistics Canada)

census tract is the central business district of Ottawa, and is dominated by both recent concrete and older masonry buildings. Despite the study area's small sample size, it contains several key regional, national and international buildings including City Hall, various federal government agencies, Parliament Hill, and several embassies. The location of these key buildings makes this area of prime interest for emergency managers, planners, and engineers.

2 Overview of the seismic hazard

Ottawa is located in an intraplate setting within the North American plate, in the western Québec seismic zone. Seismicity in the western Québec seismic zone exists in two bands: (1) a northwest trending band following the Ottawa River and extending from eastern Ontario to the District of Timiskaming; (2) a parallel band to the north, trending from Montréal through Mont Laurier to the Baskatong Reservoir, as shown in Fig. 2. Forsyth (1981) showed that earthquakes within the first band may be associated with the Ottawa–Bonnechere Graben. The second band is suggested to be a result of the passing of the Great Meteor hotspot in the Mesozoic that caused crustal fractures and local uplift of the Canadian Shield, weakening the bedrock (Kumarapeli 1985; Ma and Eaton 2007).

Many geologists have studied the geology of the National Capital area (e.g., Kay 1942; Wilson 1964; Gadd 1987). The Ottawa–Bonnechere Graben is the principal fault-related structure in the Ottawa area and is considered as one of the major grabens in North America (Sykes 1978). The Ottawa–Bonnechere Graben is characteristic of a failed arm in a triple junction rift system that was generated during Iapetan rifting. This structure transects through the sedimentary rocks of the St. Lawrence Lowlands into the basement Precambrian rocks (Bélanger 1998), and is a zone of large, down-dropped blocks that extend from Montréal, north through Ottawa, and eventually branch north and west (Wilson 1964; Rimando and Benn 2005) as shown in Fig. 3. The Ottawa–Bonnechere Graben structure has been reactivated numerous times throughout geological time by compressional and extensional forces. These tectonic forces have created a secondary set

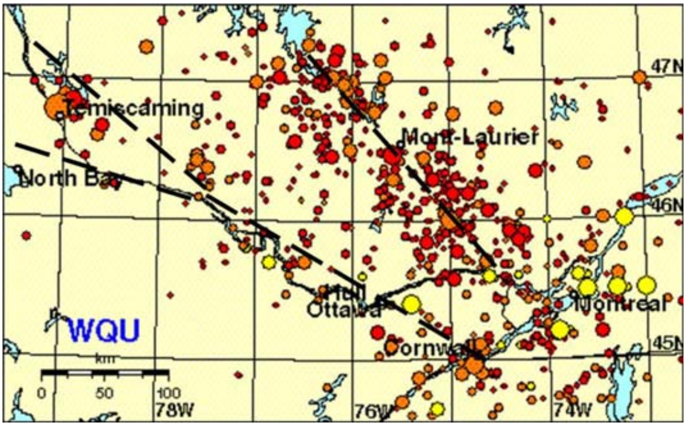

Fig. 2 Historic seismicity in the western Québec seismic zone. The graduated symbols and colors correspond to earthquake magnitude and year it occurred (*yellow* pre-1900, *orange* 1900–1965, *red* 1965–2001) (earthquakescanada.nrcan.gc.ca)

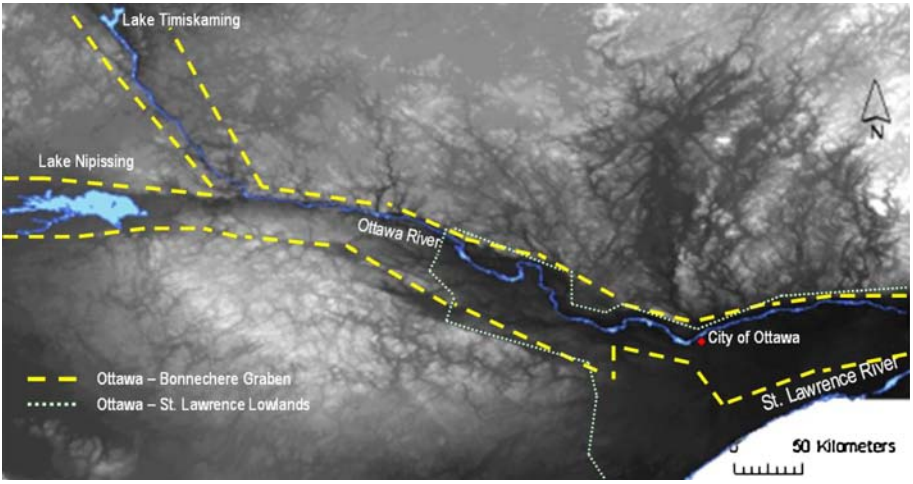

Fig. 3 A shaded relief map illustrating the extent of the Ottawa-Bonnechere Graben and the St. Lawrence Lowlands (Ploeger 2008). (GIS data sources: GeoGratis, Ontario Geological Survey)

of faults in the Ottawa area (Ebel and Tuttle 2002) in addition to stress relief along pre-existing weaknesses within the principal structure (Wilson 1964). Three major faults in the Ottawa area are the Gloucester, Hazeldean, and Eardley faults.

The largest historic earthquakes reported within approximately 350 km of the City of Ottawa are the 1732 **M**5.8 Montréal earthquake, the 1935 **M**6.2 Témiscaming earthquake, and the 1944 **M**5.8 Cornwall–Massena earthquake. The Témiscaming earthquake, e.g., was felt as far west as Minnesota, as far south as Virginia, and as far east as the Maritime Provinces, with damages reported as far as 320 km from the epicentre (Bent 1996). All three earthquakes would have shaken the City of Ottawa (Leblanc 1981; Natural Resources Canada 2006a; Natural Resources Canada 2006b; Lamontagne et al. 2008). Typically, eastern North American earthquakes have a larger felt area due to lower attenuation (Adams 1989) from a relatively stable and unfractured crust, when compared to western North American events (Atkinson 1989).

Prior to historic times, geological evidence presented by Aylsworth et al. (2000) supports that some of the massive paleo-landslides in the Ottawa River Valley were triggered by "two of the most geologically destructive earthquakes in eastern Canada" ~7,060 and 4,550 years ago; Aylsworth et al. (2000) suggest an approximate magnitude of seven for these events. There have been no damaging earthquakes (MMI $\geq$ VII) in the City of Ottawa since the 1944 Cornwall–Massena earthquake (Lamontagne et al. 2008), but evidence suggests that large earthquakes ($\mathbf{M} \approx 7.0$) may occur in the future.

3 Data collection

To obtain reliable loss estimates, a tremendous amount of data collection needs to take place beforehand. Data collection is typically the most resource-intensive step of the loss estimation process, but is a wise investment as the reliability of loss estimations is dependent on the quality and quantity of the data collected. A level 2 HAZUS analysis, such as the one performed for this paper, incorporates professional judgment and detailed information.

3.1 Ground motion

Ground motion parameters describing the expected earthquake shaking, including pseudo-spectral acceleration (PSA, 5% damped), peak ground acceleration (PGA) and peak ground velocity (PGV)—all for the horizontal component of motion—are fundamental input parameters to a seismic risk assessment. These parameters are specified by ground motion prediction equations, providing amplitude as a function of earthquake magnitude and distance. HAZUS does not contain the most recent ground motion prediction equations for eastern Canada, those of Atkinson and Boore (2006) [HAZUS contains the older Atkinson and Boore (1995) equations among its default set of choices]. However, they can be implemented using the input option of user-supplied ground motions.

Ground motion amplitudes for this study, for NEHRP A sites (hard-rock sites) (National Earthquake Hazard Reduction Program), were computed using the Atkinson and Boore (2006) equations, which are given as follows:

$$\begin{aligned}\mathrm{LOGPSA} = {} & c_1 + c_2\mathbf{M} + c_3\mathbf{M}^2 + (c_4 + c_5\mathbf{M})f_1 + (c_6 + c_7\mathbf{M})f_2 \\ & + (c_8 + c_9\mathbf{M})f_0 + c_{10}R_{\mathrm{cd}} + S\end{aligned} \tag{1}$$

where PSA is 5%-damped pseudo-acceleration (horizontal component); **M**, the moment magnitude; R_{cd}, the distance closest to the fault (km), $f_0 = \max(\mathrm{LOG}(R_0/R_{\mathrm{cd}}), 0)$; $f_1 = \min(\mathrm{LOG}R_{\mathrm{cd}}, \log R_1)$; $f_2 = \max(\mathrm{LOG}(R_{\mathrm{cd}}/R_2), 0)$; $R_0 = 10$ km; $R_1 = 70$ km; $R_2 = 140$ km; $S = 0$ for hard-rock sites (refer to Atkinson and Boore (2006) equations 7a and b for the values for soil sites); and '*c*' coefficients for NEHRP A are presented in Table 6 in Atkinson and Boore (2006).

In order to define a realistic earthquake scenario in terms of magnitude and distance from Ottawa, predicted ground motions according to the Atkinson and Boore (2006) (AB06) equations were plotted and compared with the expected ground motions presented in the 2005 National Building Code of Canada (NBCC) for an exceedence probability of 2% in 50 years. Details of the seismic hazard calculations for the 2005 NBCC are provided by Adams and Halchuk (2003). The Ottawa motions for 2% in 50 years from Adams and Halchuk (2003) were converted to equivalent values for NEHRP A (the site condition used in AB06). As shown in Fig. 4, the ground motions for a scenario **M**6.5 event at an epicentral distance of 15 km are very similar to the NBCC 2005 motions specified for Ottawa. We emphasize that the probability associated with these scenario motions is approximately 2% in 50 years, and that it is the ground motions that are important, not the magnitude and distance of the representative scenario that produces the target ground motions. Other representative magnitudes and distances could also be used. A focal depth of 10 km was assumed for the scenario, as the hypocenters of most earthquakes in eastern Canada are at depths ranging from 5 to 25 km (Adams 1989). The fault size was assumed to be as given by the empirical equations of Wells and Coppersmith (1994). It is noted that the scenario motions in Fig. 4 (**M**6.5 at 15 km) exceed the Adams and Halchuk (2003) target motions for frequencies above 5 Hz. However, most buildings do not respond to these higher frequencies. A control test was done to test the impact on the damage estimates of inputting a lower 10 Hz PSA (0.64 g from Adams and Halchuk (2003), rather than the 1.06 g scenario value) into HAZUS, while leaving all other ground motion spectral and PGA inputs unchanged. This confirmed that the damage estimates are not affected by the high value of the 10 Hz PSA.

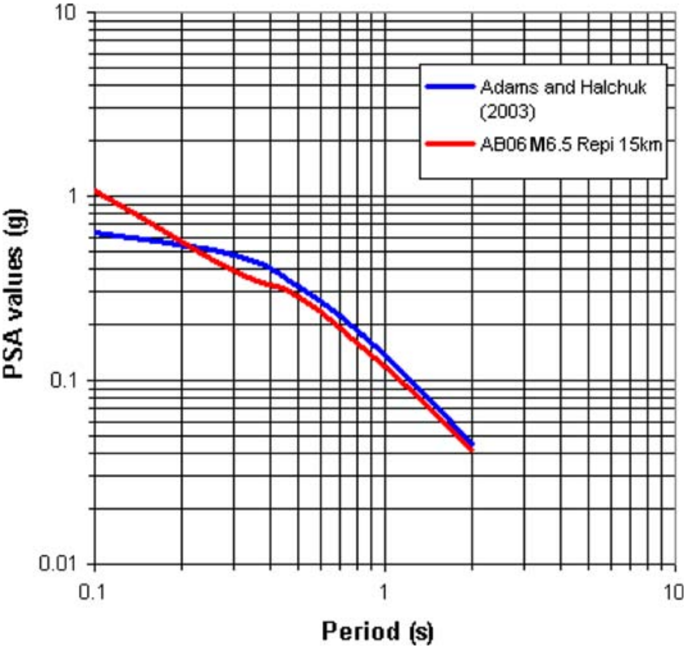

Fig. 4 Uniform hazard spectra for hard-rock sites in Ottawa (2%/50 years) from Adams and Halchuk (2003) (in *blue*) compared to Atkinson and Boore (2006) (in *red*) for a **M**6.5 earthquake at an epicentral distance of 15 km (modified Ploeger et al. 2008)

3.2 Soil conditions

Local soil conditions can influence the amplitude of incoming seismic waves, as observed dramatically during the 1985 Mexico City earthquake, and should therefore be incorporated in seismic risk assessment and design (Finn and Wightman 2003). Soil characteristics can be classified using the NEHRP classification system, which was initially an American classification system, but has been adopted by the 2005 NBCC. This classification system characterizes site conditions quantitatively and assigns a letter for specific soil classes.

NEHRP site classes are based on the measured travel-time-weighted average of shear wave velocity to a depth of 30 metres (Vs_{30}) and are divided into classes A (hard rock) to E (soft soils) based on shear-wave velocity, with F denoting problematic soils, as given in Table 1. In this study, Vs_{30} values were determined by performing seismic reflection and refraction surveys and borehole interpretations (Ploeger 2008). In the study area, NEHRP classes ranged from A to D as shown in Fig. 5.

Amplification factors reflect surficial geology. In order to calculate amplification factors to be applied to the AB06 ground motions for typical Ottawa soil profiles, the SITEAMP program developed by Boore (2005) was used. This program converts velocity and density models into site amplification factors at specific frequencies, based on the quarter-wavelength method of Boore and Joyner (1997). The SITEAMP program inputs velocity gradients and transforms them into a set of constant-velocity layers to calculate the amplification factors.

To account for soil nonlinearity effects, factors that were not considered in the SITEAMP program, the nonlinear amplification factors of Boore and Atkinson (2008) were

Table 1 NEHRP site classification (http://www.nerhp.gov/index.htm)

Site class	Description	Vs_{30} (m/s)	
		Minimum	Maximum
A	Hard rock	1500	
B	Rock	760	1500
C	Very dense soil and soft rock	360	760
D	Stiff soil	180	360
E	Soft soil		180
F	Problematic soil		

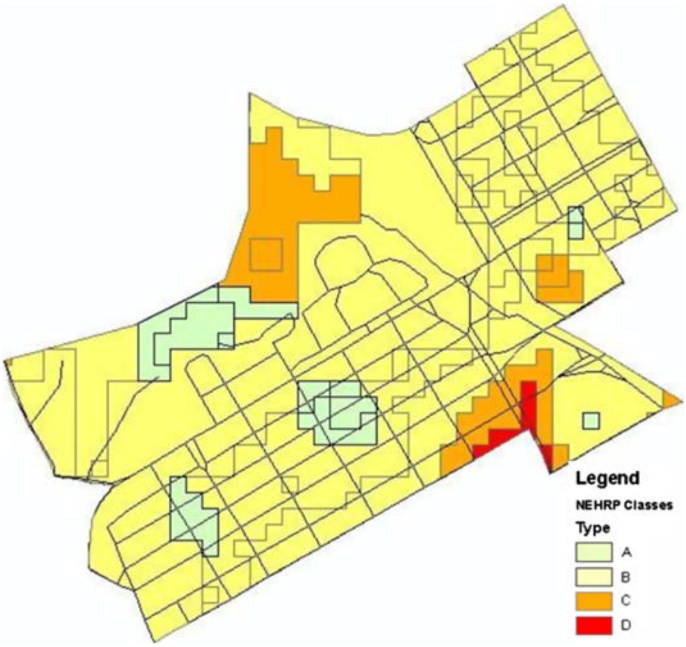

Fig. 5 NEHRP classes of the study area based on seismic surveys and borehole interpretation (Ploeger 2008). (GIS data sources: NRCan (Geological Survey of Canada), Statistics Canada)

included in our analysis. These factors were used to calculate by how much the calculated amplification should be reduced to account for nonlinearity effects, based on the input PGA of rock, and a typical shear-wave velocity for the site class (500 m/s for NEHRP C and 250 m/s for NEHRP D). The final amplification factors, including the effects of soil nonlinearity, were applied to the AB06 hard-rock (NEHRP A) ground motions to obtain the appropriate motions for NEHRP B, C, and D sites (all of which are amplified relative to A).

The susceptibility to liquefaction and landslide within the study area was also considered (Ploeger et al. 2008), but no additional losses were projected as a result of these earthquake-induced hazards, and they are therefore considered to contribute little or no risk in the study area.

3.3 Building inventory

A sidewalk survey of 597 buildings was conducted, during the summer months of 2007. Buildings were classified individually by visual inspection. Several characteristics were noted, the two most important are building type and occupancy classes (Ploeger et al. 2008).

HAZUS developers have created a building classification scheme to differentiate between buildings with varying potential damage characteristics, and behavior under strong ground motions. There are four main building types: wood, masonry, concrete and steel, which can be further subdivided into 36 classes. Occupancy type is also classified. There are seven main occupancy classes: residential, commercial, industrial, agricultural, religious and non-profit organizations, governmental, and educational. These occupancy classes can be further subdivided into 28 classes. The building inventory in the study area is dominated by masonry (45%) [42% unreinforced (URM) and 3% reinforced masonry] and concrete (36%) [34% concrete and 2% precast concrete] building types and commercial (60%) and residential (33%) occupancy classes, as listed in Table 2.

Table 2 Building type versus occupancy class, building height, and seismic design level for the study area

	Building type				
	Wood	Concrete	Steel	Masonry	Total
Occupancy class					
Residential	60	51	5	84	200
Commercial	23	153	28	153	357
Religious, non-profit	0	1	0	10	11
Governmental	1	7	0	15	23
Educational	0	2	0	4	6
Total	84	214	33	266	597
Building height					
Low-rise (1–3)	84	86	10	255	435
Medium-rise (4–7)	0	37	1	11	49
High-rise (8+)	0	91	22	0	113
Total	84	214	33	266	597
Seismic design level					
Pre-code	70	59	6	234	369
Low-code	10	138	12	31	191
Moderate-core	1	15	14	1	31
High-code	3	2	1	0	6
Total	84	214	33	266	597

Supplementary information collected for the building inventory was number of storeys, seismic design level, and square footage (estimated floor area). The number of storeys was determined by visual observation and categorized into low-, mid-, or high-rise or 1–3, 4–7 and 8+ storeys, respectively (Table 2). Seismic design level is classified into four groups: pre-, low-, moderate- and high-code, or pre-1950, 1950–1970, 1970–2005 and +2005, respectively (modified FEMA and NIBS 2006a) (Table 2). These levels are based on the United States code developments and practice, but Canadian practice has historically been closely tied to developments in the United States. Square footage was estimated by the use of high-resolution satellite and aerial photos, as well as field-based observations

Table 3 Population distribution of the eastern and western census tracts in downtown Ottawa (Ploeger 2008)

Time	Census tract	Population type		Total
		Residential	Working	
2:00 am	East	2,238	414	2,652
	West	3,718	217	3,935
2:00 pm	East	224	10,439	10,663
	West	372	65,688	66,060
5:00 pm	East	448	10,003	10,451
	West	744	18,033	18,777

3.4 Demographics

Modeling casualties requires specific information on demographics. HAZUS utilizes both residential and working populations at three times during the day; daytime, night time and commuting—or 2:00 pm, 2:00 am and 5:00 pm, respectively. The population distribution within the study area is summarized in Table 3; refer to Ploeger (2008) for details. Briefly, population data were collected from Statistics Canada (www12.statcan.ca), and the City of Ottawa. In some cases, simple ratios were used to calculate the population distributions at the dissemination area level. This paper focuses on a daytime (2:00 pm) scenario only, as this scenario is expected to generate the greatest amount of losses and better highlight areas of vulnerability. HAZUS distinguishes casualties by four classes of severity, 1 being minor injuries, 2 being serious but non-life threatening injuries, 3 being serious and life threatening injuries and 4 being fatalities.

4 Data preparation

HAZUS was originally designed for use in the United States. The general concept of HAZUS is that the program retrieves building inventory and other relevant information from accompanying databases to perform loss estimations. It is these databases that the user can upgrade. The possibility to modify these databases with non-American information therefore exists and is the basis for applying HAZUS to an international setting.

There are drawbacks to adapting HAZUS for an international setting. The most obvious drawback is that all inventories must be collected, prepared and input into the program; complete Canadian inventories for HAZUS are not available. The first drawback of HAZUS is that it provides only basic American databases which are the foundation of a level 1 analysis, the second is that the program uses a fixed and specific nomenclature to designate variables, and the third is that numerous inputs are based on American standards and imperial units; for example, the units of PGV are inches per second. Despite these challenges, the final outcome of HAZUS is equally useful in an international setting as in the United States: the user benefits from a proven methodology embedded in a software tool distributed free of charge from FEMA, and can at least perform a level 1 analysis of loss estimations at a local or regional scale anywhere in the world.

Using HAZUS for an international setting at a local scale requires a lengthy procedure. Many of these steps are presented in Hansen and Bausch (2007), a document that describes the HAZUS methodology for an international setting at a regional scale. In order to perform loss estimations for an international setting at a local scale, like downtown Ottawa, modifications and new steps are needed and are described in detail in Ploeger (2008).

5 Results

One of the overall objectives of the HAZUS methodology is to use earthquake loss estimations to project damages, disruptions, and consequences to a region that may result from an earthquake (FEMA and NIBS 2006a). Quantitative estimates of losses include the number of damaged buildings per building type and occupancy, quantity of debris, and casualties. The scenario used in this paper (**M**6.5 at an epicentral distance of 15 km) was selected because it was the most consistent with the 2005 NBCC ground motions and used in seismic-resistant design of modern structures.

5.1 Building losses

HAZUS determines the probability of damage to the general building inventory, and then converts these probabilities into number of damaged buildings. Analyzing the output in terms of the total number of damaged buildings for our chosen scenario, the building type and occupancy class with the greatest amount of damage are masonry and commercial buildings, respectively. The damage to these buildings is expected, as they both dominate the building inventory (Table 2), and URM is known to be seismically vulnerable. The building type and occupancy class with the least amount of damage are steel and educational buildings.

Analyzing the data in terms of vulnerability (measured by a percentage of number of damaged buildings to the total number of buildings for a given building type or occupancy), the most vulnerable building type and occupancy class are masonry, and religious buildings, see Fig. 6. Traditionally during eastern Canadian earthquakes, URM buildings experience the greatest amount of damage due to their lack of structural integrity (e.g., Bruneau and Lamontagne 1994). In the study area, 91% of the religious buildings are pre-code URM buildings which may offer an explanation to their vulnerability.

The least vulnerable buildings are steel and governmental buildings, as indicated in Fig. 6. Steel buildings, in particular, have durable and flexible frames which have performed well in past earthquakes (Roeder and Foutch 1996). Governmental buildings are similar to religious buildings and are dominated by pre-code masonry buildings; the low vulnerability of these buildings may thus be surprising. It is likely that the unexpected good performance of governmental buildings may be due to their location on NEHRP A and B site classes (22 of the 23 governmental buildings), where there is little to no soil amplification.

The dissemination area with the most damage is area 002, which contains 83 (36%) damaged buildings, while areas 004 and 005 contain 49 (21%) and 40 (17%) damaged buildings, respectively. It was expected that these three dissemination areas would generate the greatest amount of building damage, as they contain the majority of the building inventory. Areas 006 to 010 record the lowest amount of building damages with 7 (3%) damaged buildings.

5.2 Debris

An estimate of the amount of debris generated during an earthquake is an important factor in emergency response and recovery efforts of a municipality. HAZUS measures only debris generated from the building inventory, which requires information on both building type and square footage. The two main sources of debris are structural and non-structural. Structural debris is created by partially or completely collapsed buildings. Non-structural debris is typically created by damaged ceilings, mechanical and electrical equipment,

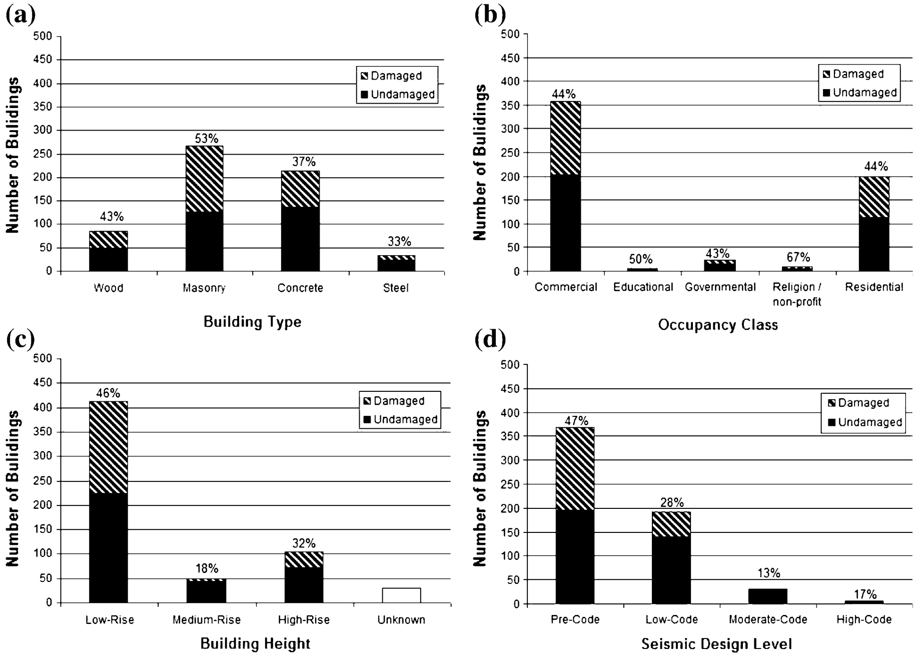

Fig. 6 Vulnerability versus **a** building type, **b** occupancy class, **c** building height, and **d** seismic design levels. The percentage of damaged buildings is presented over each *bar*

broken glass panes, damaged wall partitions, etc. There are two main types of debris: Type 1, consisting of wood, masonry and other material, and Type 2 consisting of concrete and steel. The primary difference between these two debris types is the mechanism by which they are removed. Type 1 can be removed with hand tools and bulldozers, while Type 2 requires specialized equipment to break long steel members and large concrete slabs.

The **M**6.5 scenario earthquake at an epicentral distance of 15 km creates 102,000 tonnes of debris, with a distribution of 39,000 and 63,000 tonnes for Type 1 and Type 2, respectively. Debris generation is influenced by not only building type and square footage, but also by NEHRP classes and the concentration of buildings within a dissemination area. Area 004 produces the most Type 1 debris, while area 005 produces both the most Type 2, and the largest total amount of debris. Area 005 has the largest square footage (due to the large number of high rises) and is located on the most sensitive NEHRP class in the entire study area (Fig. 7). A strong relationship also exists between debris generation and total amount of building damage in each area, as the areas with the most building damage are also the areas with the most debris. The dissemination area with the least amount of debris is area 010, which contains only four buildings.

5.3 Social losses

At 2:00 pm, HAZUS estimated 135 casualties (the sum of both fatalities and injuries) with the following distribution: 110 severity 1, 19 severity 2, 2 severity 3 and 4 severity 4. The greatest number of projected casualties occurs in URM and commercial buildings. Concrete building types also account for a significant portion of total projected casualties. The

Fig. 7 Building locations for dissemination area 005 with respect to NEHRP classes (modified Ploeger 2008). (GIS data sources: City of Ottawa, NRCan)

majority of concrete buildings not only have low-code seismic design levels (Table 2) but also contain a large percentage of square footage (Fig. 7). The combination of a dense working population located within concrete buildings, generate a greater number of casualties because there is more building material (concrete, glass panes, ceiling tiles, etc.) to incur social losses. The lowest number of projected casualties occurs in wood buildings. Wood buildings are primarily residential building types where the population is lowest during the day, hence the lowest number of casualties.

At 2:00 pm, dissemination area 004 is projected to have the greatest number of casualties, followed closely by area 005. The least number of casualties is projected in areas 008–010. A relation exists between the population of the dissemination areas at the time of the earthquake and the number of casualties.

6 Discussion

A benefit of HAZUS is that by anticipating the nature and scope of losses from earthquakes, development of emergency response plans and mitigation of potential consequences can proceed (FEMA and NIBS 2006a). In earthquake loss estimation studies, an important factor which influences losses in the urban environment is the building type. Building types differentiate building behavior during ground shaking; various building types have substantially different damage and loss characteristics (FEMA and NIBS 2006a).

The building type experiencing the greatest amount of projected losses is URM. URM buildings lack structural integrity, as they are generally not anchored to diaphragms and rely on friction to transfer various forces (Bruneau and Lamontagne 1994; FEMA and NIBS 2006b). During intense ground shaking, structural components may separate and behave independently. This behavior has been reported for several intraplate earthquakes including the 1989 Newcastle, Australia earthquake (Blong 2004), and several eastern Canadian earthquakes including the 1925 Charlevoix–Kamouraska, the 1935 Témiscaming and the 1944 Cornwall–Massena earthquakes (Bruneau and Lamontagne 1994). Chimney damage is also common in URM buildings, because chimneys experience the greatest amount of displacement, being located at the top of the building (Bruneau and Lamontagne 1994). Historically, the most observed earthquake damage in Ottawa is to URM buildings (Lamontagne et al. 2008).

The study area is dominated by URM and concrete commercial buildings (26% each). Given that URM buildings are the most vulnerable to ground shaking, a significant number of projected casualties in this study occurred in or near URM buildings. The number of casualties is not only influenced by partial or complete building failure, but also toppling of brick chimneys, out-of-plane failures of walls and collapsing gables and parapets.

The majority of concrete buildings in the building inventory are commercial (26%) and have seismic design levels that are pre- or low-code (92%). Concrete buildings comprise 64% of calculated square footage in the study area and therefore have a greater exposure to losses in terms of total area. Older buildings are more vulnerable to partial or complete failure due to their frame design (FEMA and NIBS 2006b), and in some cases these buildings may fail in a 'pancake' fashion (FEMA and NIBS 2006a). Architectural features on concrete buildings can also spell off during ground shaking. The above aspects can account for the high number of casualties in commercial and concrete buildings recorded in the chosen earthquake scenario.

Wood and steel buildings are the two building types which experience the least amount of damage. Wood-frame buildings have large structural redundancies and can readily dissipate energy, thus making them more resistant to damage from ground shaking (Bruneau 1990). There are few casualties reported in wood buildings for two primary reasons: (1) the satisfactory performance of the wood frames during earthquakes, and (2) the low population residing or working in wood buildings, as wood buildings tend to be single family dwellings. Steel-frame buildings have traditionally behaved well during earthquakes for several reasons, including their light and flexible frame (Roeder and Foutch 1996) and overstrength in their seismic design (Rahgozar and Humar 1998). The low number of casualties projected in steel buildings is likely due to the reliability of the steel frame during ground shaking.

Building height also plays a role in physical losses. Buildings have natural periods which are partly dependent on building height. If the natural period of the building is similar to the period of the incoming seismic waves, then the building can be subjected to amplified vibrations due to wave resonance. The fundamental period (T_a) of a building can be calculated using the following equation:

$$T_a = 0.1N \tag{2}$$

where N is the number of storeys (Saatcioglu and Humar 2003). High-rise buildings (>8 storeys) are sensitive to long-period shaking (>0.8 s), while low-rise buildings (<3 storeys) are sensitive to short-period shaking (< 0.3 s). In this study, low-rise buildings experience greater projected damage than buildings that are medium- and high-rise, which is consistent with what is expected for the **M**6.5 earthquake studied.

Debris generation should also be considered in this discussion, as this factor becomes an obstacle experienced by the emergency responders en route to the scene(s) as roadways may be impassable. In the study area, it is estimated that ~102,000 tonnes of debris will be produced, of which 38% will be Type 1 and 62%, Type 2. The average size dump truck can carry a maximum of 17.5 tonnes. This amounts to ~2,200 and 3,600 truckloads of Type 1 and Type 2 debris, respectively.

Occupancy class does not affect building damage, as occupancy is the designation of building use. It does, however, affect the number of casualties. The greatest damage is projected for masonry and concrete buildings which dominate commercial occupancies. It can therefore be deduced that the population in these buildings would incur the most casualties. The results support this deduction as at least 90% of projected casualties occur in URM and concrete buildings. The number of casualties are greatest during the daytime, when a working population of >76,000 is in the study area.

6.1 Vulnerable regions

Identifying areas most physically and socially vulnerable to earthquake ground shaking at a regional or local scale, is one of the many benefits of the HAZUS software. The ability to recognize areas most vulnerable to losses will aid planners to develop more focussed mitigation measures and also aid emergency responders to target areas with high potential losses.

After interpreting results generated for this study, the most vulnerable areas are 005, 004, and 002, as illustrated in Fig. 8. The most vulnerable areas were determined by a simple ranking system of various loss estimations. The area with the most vulnerability is 005, which had the highest number of fatalities and debris generation. The second most vulnerable area is 004, which had the highest number of injuries. The third most vulnerable area is 002, which had the greatest number of damaged buildings.

This study suggests that the vulnerable areas, in terms of building characteristics, will be (1) older neighborhoods containing URM buildings, and (2) areas with low-code concrete buildings. Local site conditions also play a significant role in loss estimations, as softer and deeper sediments will amplify incoming seismic waves. NEHRP C and D soils are found in a portion of area 005 which is considered to be the most vulnerable area within the study area (Fig. 7). Bruneau and Lamontagne (1994) noted that in historic eastern Canadian earthquakes, high amounts of physical losses were associated with not only older URM buildings, but also softer sediments.

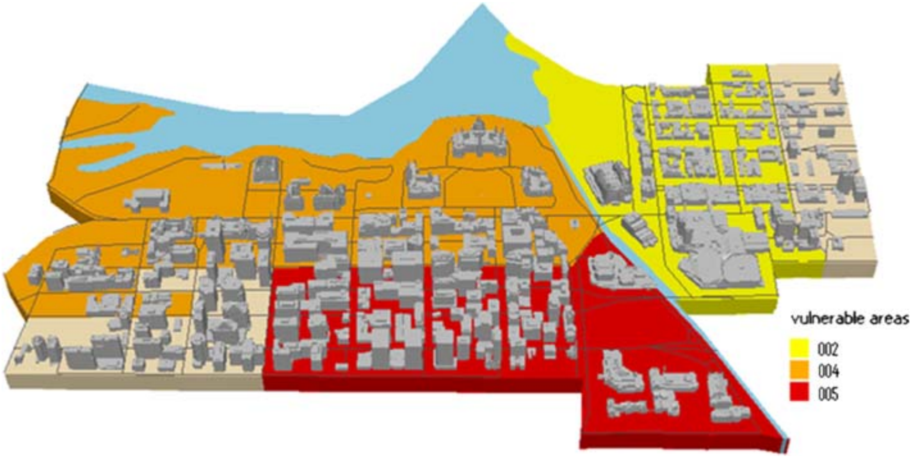

Fig. 8 Three most socially and physically vulnerable dissemination areas in the study area (Ploeger 2008). (GIS data sources: City of Ottawa, NRCan)

7 Implications and future work

The results gathered from this study are a beneficial preliminary step in disaster management. However, there are implications that require further attention. The two most important of these are (1) the influence of NEHRP classes on losses and (2) the vulnerability of educational buildings (schools).

The majority of the study area is located on NEHRP B, as depicted in Fig. 5, a particular firm soil where little amplification is anticipated. The loss estimations generated for the study area provide a false impression of optimism for the Ottawa region, in that soils present in other wards of Ottawa are poorly-consolidated, (e.g., Crow et al. 2007) and are classed as NEHRP C, D and E. Figure 9 shows the increase in losses from a site classification of NEHRP B, the dominant site classes of the study area, to NEHRP E for our chosen earthquake scenario. Note that heavy losses (extensive and complete damage levels) increase dramatically when NEHRP classes shift from rock to soft soils. Although no specific earthquake loss estimation studies have been performed in other areas of Ottawa, Fig. 9 is an inferred representation of losses when only NEHRP classes are altered (the remaining variables are identical to those used in the study area: demographics, building inventory, etc.). It should be noted that the study area comprised of ten dissemination areas, while the National Capital Region comprised over 1,700 dissemination areas; thus this study considers damage potential for a very limited sample of the city.

Worldwide, schools experience a disproportionate amount of damage during earthquakes (Monk 2007). Numerous examples of school collapses exist for both occupied and unoccupied schools during an earthquake. For example, the 1933 Long Beach, California, earthquake severely damaged 120 schools including 70 collapses, the 1952 Kern County, California, earthquake damaged 20 schools including 1 complete collapse, and the 1944 Cornwall–Massena earthquake damaged the local high school when a fallen masonry wall destroyed the gymnasium (Bruneau and Lamontagne 1994; Monk 2007). In the 2002 Molise, Italy, earthquake the only building that collapsed was a school, and in the 1935 Helena, Montana, earthquake the single building which incurred the most damage was the local high school. North America, however, has never experienced a damaging earthquake

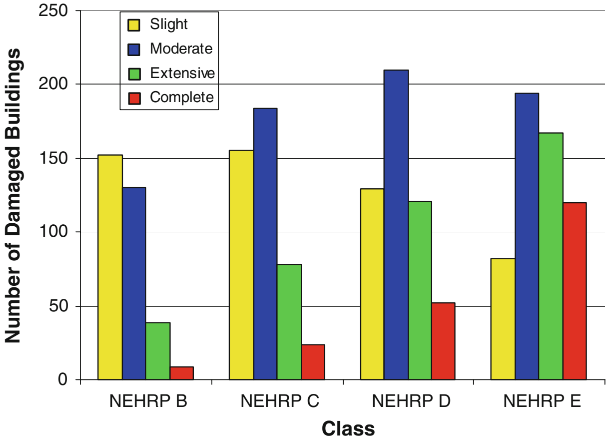

Fig. 9 Histogram comparing building damage for NEHRP classes B to E for a **M**6.5 earthquake at an epicentral distance of 15 km (Ploeger 2008)

during school hours. This has led to a sense of complacency among North American engineers and other key officials (Monk 2007). In this study (earthquake scenario of **M**6.5), is it estimated that half the educational buildings in the study area would incur physical losses.

Additional implications should also be considered: (1) casualties could increase when factoring in the number of visitors, especially since the study area is a large tourist district within the City of Ottawa; (2) economical losses will increase substantially when considering the real estate value of buildings and content costs, most notably Parliament Hill; (3) building damage to the Parliament Buildings may increase as they are reported to be in poor condition (Cook 2007), though it should be noted that the Parliament Buildings are currently being upgraded; and (4) the relative likelihood of a moderate-to-large earthquake (**M**6.0–7.0) increases with the considered distance from Ottawa (simply because the area within which it could occur is increasing, and the occurrence rate scales with area). Ploeger (2008) shows that even at large distances (>50 km), both physical and social losses still register in the study area. However, it is acknowledged that as the distance of the scenario event is increased, the amount of damage in Ottawa will be decreased.

In summary, this article presented earthquake loss estimations for downtown Ottawa, using the HAZUS-MH software tool for a specific earthquake scenario of **M**6.5 at an epicentral distance of 15 km. The study area consists of two census tracts, which can be further divided into ten dissemination areas, and contains 597 buildings, including the Canadian Federal Parliament Buildings. This study was accomplished by: (1) characterizing seismic hazard and vulnerability for the City of Ottawa, (2) establishing and executing a set of procedures in data collection, (3) preparing and inputting data, and adapting HAZUS, (4) interpreting loss estimations. Results from this study provide a means to evaluate the nature and scope of potential losses due to a moderate-to-large earthquake in the Ottawa area, and assess HAZUS' applicability to Canadian settings at a local scale. This study was successfully able to produce earthquake loss estimations for the study area; however, future work is needed to create larger scale and more comprehensive loss estimations. Specific recommendations for future work are as follows:

1. Some NEHRP B calculations within the study area have very high estimated PGA values after estimated soil amplification factors are considered (see Sect. 3.2). These motions may not be realistic, and thus for some cases the analysis may be overly conservative. Further research is needed to refine these NEHRP B amplification factors.
2. The majority of the study area is located on firm soil. Given the importance of soil conditions, scenarios should be run in regions of Ottawa underlain by poorly-consolidated soils. In this study, a scenario was run for an area of Ottawa built on firm soils with an aged building inventory; while other neighborhoods of Ottawa are built on poorly-consolidated soils with a modern building inventory (e.g., Orleans, a neighborhood located in the eastern part of the City of Ottawa). Extrapolations of the results to other areas of Ottawa with poorly-consolidated soil are likely to show a significant increase in losses.
3. The modified HAZUS-MH program should be run with its full capabilities for an entire Canadian urban area (municipality). This will ensure that HAZUS-MH can be used to its fullest potential in Canada and that specialized neighborhood plans (as some neighborhoods are more vulnerable to losses than others) can be well integrated into a municipal emergency plan.

4. This study has not addressed modification of the engineering functions (fragility and capacity curves) to reflect Canadian practice, which would improve applicability of HAZUS to Canada.
5. According to FEMA and NIBS (2001), uncertainty in loss estimations is large, perhaps as much as an order of magnitude. However, upgrades to information on soil classification, ground motions and amplifications, and building inventory are shown to produce results closer to documented data. This research provides an important stepping stone in the implementation of HAZUS in Canada and provides a good indication into the vulnerable areas within downtown Ottawa.
6. Historic scenarios should be performed on previous eastern Canadian earthquakes. This will enable Canadian users of HAZUS-MH to measure the accuracy of the modified HAZUS-MH program (with or without user-supplied maps) in an eastern Canadian setting. Note that the HAZUS-MH program is calibrated against past earthquakes in California, where several ground motions and loss estimation methodology differs from those used in eastern North America. Also needed, is to test whether the PGA-based economical calibrations are pertinent to eastern North American scenarios.

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