**Applying the HAZUS-MH software tool to assess seismic hazard and vulnerability
in downtown Ottawa, Canada**

By

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Abstract

The HAZUS-MH software tool, developed by the Federal Emergency Management Agency of the United States and the National Institute of Building Sciences, was manipulated to accept a Canadian setting to identify areas most physically and socially vulnerable to earthquake ground shaking and to present earthquake loss estimations for two census tracts (ten dissemination areas) in downtown Ottawa, Canada. The accuracy of loss estimations is dependent on the quality and quantity of data collection and preparation. In this study: 1) a detailed building inventory of downtown Ottawa was completed; 2) relevant census information was tallied; 3) microzonation studies were conducted to allow mapping of the study area by NEHRP (National Earthquake Hazard Reduction Program) site classes; 4) earthquake induced hazards were assessed, and 5) seismic losses were estimated for ground-motions given in the 2005 National Building Code of Canada for expected motions at a 2% exceedence probability in 50 years. 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 greatest amount of losses occurred 1) in scenarios with stronger ground shaking, 2) unreinforced masonry buildings, 3) commercial buildings, and 4) at 2:00pm.

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List of Abbreviations

AB95	Atkinson and Boore (1995)
AB06	Atkinson and Boore (2006)
CEUS	Central and Eastern United States
COM	Commercial
EDU	Education
FEMA	Federal Emergency Management Agency
FIPS	Federal Information Processing Standards
GCS	Geographic Coordinate System
GIS	Geographic Information System
GMPE	Ground-Motion Prediction Equation
GOV	Government
GPS	Global Positioning System
HAZUS	Hazards United States
HAZUS-MH	Hazards United States – Multi Hazards
IDW	Inverse Distance Weighting
K_M	Magnitude correction factor
K_w	Groundwater correction factor
Lat.	Latitude
Long.	Longitude
MATLAB	Matrix Laboratory
MR2	Maintenance Release
M	Moment magnitude
M_L	Richter local magnitude
MOE	Ontario Ministry of the Environment
M_s	Surface wave magnitude
NAD	North American Datum
NIBS	National Institute of Building Sciences
NBCC	National Building Code of Canada
NEHRP	National Earthquake Hazard Reduction Program
NRCan	Natural Resource Canada
NY1	New York default inventory
PESH	Potential Earth Science Hazards
PGA	Peak Ground Acceleration
PSA	Pseudo Spectral Acceleration
PGV	Peak Ground Velocity
P_{ml}	Proportion of study area
R_{CD}	Distance closest to fault
R_{epi}	Epicentral distance
RES	Residential
REL	Religious and non-profit
RLD	Subsurface rupture length
R_{hypo}	Hypocentral distance
RW	Downdip rupture width

Sa	Spectral Acceleration
SEV	Severity
SITEAMP	Boore's Site Amplification Program
UHS	Uniform Hazard Spectra
URM	Unreinforced Masonry
VBA	Visual Basic Application
V_s	Shear wave velocity
V_{s30}	Average shear wave velocity to a depth of 30 m
WUS	Western United States
WQU	Western Québec seismic zone

Chapter 1: Background information

1.0 Introduction

The City of Ottawa is the nation's capital and the fourth largest city by population in Canada. The original townsite was established in the 1820s, and since then has been a cultural, political and academic hub. However, due to a constant increase in population, zoning practices and a lack of education in disaster awareness, Ottawa has become dependent on a complex and aging infrastructure which is vulnerable to several natural hazards including earthquakes.

Most Canadians are ignorant of the seismic risk that surrounds them, but eastern Canadians, in particular, are at an increased risk because of their low awareness and preparedness for this type of natural disaster (Bruneau and Lamontagne, 1994; Multi Risk Strategies, 2003). The City of Ottawa was ranked third in the urban population most at seismic risk in Canada after Vancouver and Montréal (Adams et al., 2002), refer to Figure 1.1. The term risk can be defined as the product of hazard and vulnerability, therefore an urban centre located in or near a seismically active area (high hazard) and the exposure and unpreparedness of a large population (high vulnerability) will increase the inherent seismic risk. It is important that the government and municipal officials understand and identify the geotechnical and structural vulnerabilities in Canadian urban centres.

Figure 1.1. Distribution of urban seismic risk in Canada (Adams et al., 2002). Approximately 80% of total seismic risk in Canada is represented by 6 cities.

Eastern Canadian earthquakes also pose significant hazard and risk to the dense population centres of this region, because earthquakes in eastern North America shake a larger area due to lower attenuation (Adams, 1989a) from a relatively stable and unfractured crust, when compared to western events (Atkinson, 1989). A study commissioned by the City of Ottawa reported that its second largest public safety threat was an earthquake (Multi Risk Strategies, 2003).

The National Capital region is situated on a failed arm of a triple rift junction, called the Ottawa–Bonnechere Graben, created during the opening of the Iapetus Ocean in the late Precambrian. In effect, Ottawa is located in an area of increased seismic hazard due to a combination of very old pre-existing fault structures and rather young soft sediments deposited during and after the last glaciation. Ottawa is located within the western Québec seismic zone, and is the most seismically active area in Ontario (Eyles, 2002).

Seismic risk cannot be assigned uniformly across an entire city, since surficial geological deposits can either amplify or de-amplify incoming seismic waves. Microzonation studies can be performed across a city to determine regions with an increased vulnerability to ground shaking. Throughout the City of Ottawa, surficial geological deposits that tend to increase ground shaking are soft sediments, including the Champlain Sea sediments, also known as Leda clays (Hunter et al., 2007). Particular regions of increased vulnerability include Orleans where a team of researchers led by Dr. Jim Hunter from the Geological Survey of Canada and Dr. Dariush Motazedian from Carleton University have discovered

a buried bedrock valley filled with soft sediments (Motazedian and Hunter, 2008), and other unmapped buried valleys and gorges may exist in the Ottawa region (F. Michel, personal communication, 2008).

HAZUS-MH, Hazards United States Multi-Hazards, is a comprehensive software program developed by the Federal Emergency Management Agency (FEMA) through the National Institute of Building Sciences (NIBS) and designed 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 varying degrees of user-supplied data to improve the accuracy of loss estimations in a level 2 or 3 analysis. The City of Ottawa is an ideal candidate for an earthquake loss estimation study due to its status as the National Capital and its vulnerability to moderate-to-large earthquakes. According to Philip Schneider, director of the Hazard and Risk Assessment program at the NIBS and director of the HAZUS-MH methodology program, this research project will be the first time that the HAZUS-MH program has been applied in a Canadian setting (P. Schneider, personal communication, 2007).

1.1 Aim

The aim of this research project is to identify areas most physically and socially vulnerable to earthquake ground shaking and to present earthquake loss estimations for downtown Ottawa, Canada, using the HAZUS-MH software tool. HAZUS-MH is herein referred to as HAZUS.

The actions needed to be performed to achieve this broad objective are presented below and illustrated in Figure 1.2:

- To characterize seismic hazard and vulnerability for the City of Ottawa
- To establish and execute a set of procedures in data collection
 - To specify ground-motion parameters for a selected probability, adopted here as a response spectrum with a 2% chance in 50 years of being exceeded
 - To calculate and develop potential earth science hazard maps, including maps of liquefaction and landslide susceptibility, depth to water and soil classifications
 - To compile a building inventory of downtown Ottawa
 - To tally demographic data for residential and working populations at three times of the day in downtown Ottawa
- To prepare and input data into the HAZUS program using a GIS (Geographic Information System) as well as to manipulate the HAZUS program to accept a Canadian setting
- To present disaster projections for downtown Ottawa for selected scenarios

Figure 1.2. Flow chart illustrating the actions needed in determining earthquake loss estimations.

1.2 Study area¹

The study area for this research project is centered on Parliament Hill in downtown Ottawa, and bordered by Bronson Avenue, Cumberland Street, the Ottawa River and Gloucester Street. The area can be divided into two census tracts, which can be further subdivided into 10 dissemination areas, refer to Figure 1.3a.

The study area is underlain by Paleozoic sedimentary rock, predominantly limestone and shale; at a depth that ranges from 0 m to 40 m. Natural Resources Canada (NRCan) indicates that surficial sediment deposits consist predominantly of glacial till and post-glacial offshore marine sediments. NRCan engineering logs of boreholes reveal deposits of diamicton and numerous pockets of artificial fill ranging from sand and gravel to ashes and organic material. An important addition to the original NRCan surficial geological unit layer (NRCan, 2002) is the artificial fill located under Confederation Park, and across the Rideau Canal to Nicholas Street, refer to Figure 1.3b. In the early 1900s, a lay-over for ships existed in this area but was completely filled in the mid-1920s (Nagy, 1974).

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 background, the building inventory is

¹ The material presented in this section is adapted from Ploeger et al. (2008). Ploeger is the first author and the main contributor to the material in this paper.

Figure 1.3a. Map depicting the census units within the study area. There are 2 census tracts (in blue) which are divided by the Rideau Canal and 10 dissemination areas (in deep red). The inset shows the study area in relation to the city limits (GIS data sources: Natural Resources Canada (NRCan), City of Ottawa, Statistics Canada).

Figure 1.3b. Map of the study area illustrating the surficial geological units as well as a three-dimensional view of the building inventory (GIS data sources: NRCan, City of Ottawa, Statistics

dominated primarily by older masonry buildings in the eastern census tract. The western census tract is the central business district of Ottawa, and is dominated by both concrete and older masonry buildings. The study area is also of strategic importance as several key regional, national and international buildings are located here 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.

1.3 Disaster management in an urban setting²

Global urbanization has increased significantly in recent decades. In 2001, it was estimated that 50% of the world's population resided in urban centres, as opposed to 18% in the 1950s (Wenzel et al., 2007). Urban centres are generally academic, economic and political hubs. Due to this centralization, the effects of disturbances, including natural disasters, may affect entire regions or countries. Bilham (1988) estimated that 40% of major urban centres are located within 200 km of a tectonic plate boundary or in a region that has historically experienced a damaging earthquake. Dense population networks, complex and aged infrastructure, dependence on lifelines (various utilities and telecommunications) and limited awareness and preparedness programs are all factors which contribute to urban centre vulnerability (Wenzel et al., 2007). There has been an

² The material presented in this section is adapted from Ploeger et al. (2008). Ploeger is the first author and the main contributor to the material in this paper.

encouraging reduction of physical, social and economical losses from earthquakes in developed countries for several reasons including strict and enforced building codes, incentives to upgrade existing buildings and the development of natural hazard insurance (Spence, 2004). In the case of urban centres with older infrastructure, the potential to reduce the risk through retrofit programs exists. An accurate assessment of the hazard is the necessary first step to justifying and then implementing risk-reduction measures.

Traditionally, earthquake loss estimation studies focused on the numbers of casualties and the ability for authorities to provide emergency health care (FEMA and NIBS, 2006a). However, recent studies now also concentrate on the disruption of transportation networks and lifeline systems. These networks and lifelines are essential elements in post-earthquake emergency response (FEMA and NIBS, 2006a) because response planning depends on interagency communications and the deployment of emergency response personnel (Greene, 2002).

Mitigation is a sustained and cost effective approach to reduce or eliminate long term losses and risks associated with a hazard. Mitigation involves the support and participation of varying 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 software packages like HAZUS and other similar tools. HAZUS was developed originally for earthquake loss estimations, but has grown to model multi-hazard loss

estimations across the United States. HAZUS methodologies have also been used worldwide, for example HAZ-Taiwan was developed in 1998 to promote research in seismic hazard analysis, structural damage assessment and socio-economic loss estimations in Taiwan (Yeh et al., 2006).

GIS software packages are not only user-friendly but also 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 it can assess, compile and convey large amounts of data in a short period of time. Several user-friendly loss estimation software packages can be applied to many aspects of disaster management from mitigation proposals to immediately after a seismic event as a decision-making support tool (Yeh et al., 2006). Therefore software packages like HAZUS can link academia and politics, and are powerful and practical tools in disaster management.

1.4 HAZUS methodology

HAZUS is a state-of-the-art multi-hazard loss estimations program which uses the ArcGIS platform (ArcGIS is available from ESRI: www.esri.com). The HAZUS version used in this research thesis is HAZUS-MH MR2 (HAZUS-MH version 1.2), which was released in May 2006. For a detailed description of the HAZUS software and its capabilities, please refer to FEMA and NIBS (2006a, 2006b). A succinct description is

given here. The objectives of HAZUS are to develop guidelines for loss estimations and to enable the user to identify potential regions of vulnerability within their study area whether on a local or regional basis. This software program is applicable throughout the United States and was developed during a multi-year project involving numerous stakeholders and experts including earth scientists, engineers, social scientists, economists, and emergency planners. HAZUS is flexible and accommodating, and allows the user to select the scope and nature of the scenario disaster.

The HAZUS software program contains numerous default inventories that can be upgraded to obtain more accurate loss estimations. Inventories within this software program include building (general building stock, essential facilities, high potential loss facilities, etc.) and structure (lifelines, etc.) inventories, and demographics. These inventories can be upgraded by modifying the existing databases in Microsoft Access or with options embedded within the software interface. Upgrades to the software program also include the input of user-supplied hazard maps, because numerous default parameters within the program are too general. Three examples of user-supplied hazard maps are liquefaction susceptibility, landslide susceptibility, and ground-motion parameters. As a default, HAZUS assumes that no liquefaction and landslides will occur. A limited selection of seismic ground-motion prediction equations (GMPEs) for both eastern and western North America can be selected within the program in a dropdown menu when specifying an earthquake scenario. However, in many cases an updated or more site-specific representation of ground-motions is needed. In order to account for

Potential Earth Science Hazards (PESH) and GMPEs not available in HAZUS, user-supplied hazard maps can be constructed outside HAZUS in ArcGIS and later be imported into the program. A summary table of HAZUS inputs and outputs for earthquake loss estimations is presented in Appendices A1 and A2, respectively.

HAZUS uses a three-tiered approach to accommodate users of varying practical and theoretical expertise, refer to Figure 1.4. It comprises a comprehensive set of databases which have the option of being refined, to conduct its loss estimations. A level 1 analysis uses only the default inventory and parameter data, and requires no specialized user expertise in any given field. This analysis assumes average and uniform soil conditions across the study area, and ignores potential earth science hazards such as landslide and liquefaction susceptibilities. This analysis level also has a significant amount of uncertainty and is typically suitable for preliminary evaluations. A level 2 analysis incorporates moderate improvements to the inventories and parameters by the input of user-supplied data. Finally, a level 3 analysis incorporates substantial improvements to nearly all aspects of the inventories, and data from third-party studies not included within the HAZUS methodology. Level 2 and 3 analyses are highly dependent of the quality and quantity of updated inventories. A level 2 analysis was performed in this research project.

Results' accuracy improve significantly from a level 1 to a level 2 analysis as user-supplied data is input into the program. Additions to default data include: the collection of a detailed building inventory, development of potential earth science hazards maps, the

Figure 1.4. Tiered pyramid illustrating the various levels of HAZUS analysis.

compilation of data to model the economy, and the calculation of region-specific ground-motion parameters.

More specifically, for earthquake loss estimations, once the inventories are updated and an earthquake scenario specified, the program performs a series of complex operations to compute site-specific loss estimations. The loss estimation outputs include maps of seismic hazards, structural and non structural damage probabilities to the building and lifeline inventories, fire following an earthquake, inundated areas, debris generation, social losses and both direct and indirect economical losses.

1.4.1 HAZUS validation

In 2001, FEMA and NIBS released a validation report on an older version of HAZUS (FEMA and NIBS, 2001). This report compared predicted losses calculated from HAZUS to reported losses from previous earthquakes in California, and noted consistencies and inconsistencies of HAZUS predictions. The validation study scenarios used primarily a level 1 approach, but modified scenarios, created by refining the building inventory, soil classification and ground-motions, were also tested.

The most accurate estimates from the HAZUS program are direct economic losses including building repair and replacement costs together with loss of income. These estimations were within 50% of documented reports for the validation earthquakes.

The validation study found that HAZUS tended to overestimate physical losses which are expressed in the number of damaged buildings at various damage states. HAZUS calculated light damage (slight to moderate) reasonably well, but overpredicted heavy damage (extensive or complete) by 1 or 2 orders of magnitude. The report did not offer a clear explanation for these overpredictions. FEMA and NIBS (2001) reported, however, that losses estimated from scenarios with modified building inventories better agreed with documented data. It is important to bear these uncertainties in mind when evaluating the conclusions of this project.

User-supplied hazard maps (ground-motions, NEHRP site classes, and liquefaction) also reduced losses to more closely match documented data. In some validation scenarios, user-supplied ground-motions consistently resulted in a 30% and 50% reduction in calculated losses compared to default values. User-supplied maps of NEHRP site classes led to a 10% to 30% reduction in calculated losses. Liquefaction maps, however, increased predicted heavy damage by a factor of three in susceptible locations.

Functionality calculations, which cover initial loss-of-function and restoration times, were two-fold in the HAZUS study. FEMA and NIBS (2001) suggested that (1) most essential facilities performed well and did not experience significant physical damage as in documented data, while (2) utilities and lifelines functionality was not predicted reliably. The report did mention that although essential facilities did not experience significant damage and loss-of-functions, damage will likely be higher outside California

because California has higher seismic standards for new facilities. FEMA and NIBS (2001) also noted that the unreliability of predicted damage to utilities is expected due to a lack of a site specific utilities inventory.

HAZUS overpredicted the number of casualties by a factor of three for total casualties, and by less than a factor of two for fatalities. FEMA and NIBS (2001) suggested that many severity 1 and 2 casualties often go unreported in practice, leading to an overprediction of the HAZUS program. The report added that severity 3 casualties are transitional and are not always reported.

1.5 Geological and tectonic setting

Many geologists have studied the bedrock and Quaternary geology of the National Capital area (e.g. Kay, 1942; Wilson, 1964; Gadd, 1987). In a geological context, the National Capital area is located in the physiographic region of the Ottawa–St. Lawrence Lowlands which is a well-defined basin bounded by the Ottawa River and the Frontenac axis to the east and west, respectively, and the Canadian Shield and Adirondack Mountains to the north and south, respectively (Wilson, 1964; Chapman and Putman, 1966). A visual time series of the geological history of the Ottawa area is illustrated in Figure 1.5. The region consists of near-horizontal Paleozoic bedrock overlying a Precambrian crystalline basement and underlying unconsolidated Quaternary sediments (Kay, 1942; Gadd, 1987; Bélanger, 1998).

Figure 1.5. Geological time series illustrating major geological events (ages are in millions of years) in the Ottawa area.

The Precambrian basement, also known as the Grenville basement, was formed approximately 2,000 Ma (Forsyth, 1981) and underwent a major orogeny between 1,200 to 800 Ma (Bélanger, 1980). In the late Precambrian, approximately 750 Ma to 600 Ma, the supercontinent Rodinia began to breakup and the Iapetus Ocean opened (Kumarapeli, 1985; Eyles and Miall, 2007). Triple junction rifts are typically created during a continental breakup. Two of the three rifts open to form oceanic crust, while often a third remains as a failed arm, as exemplified by the contemporary East African Rift System (Sbar and Sykes, 1973; Kumarapeli, 1985). The Ottawa–Bonnechere Graben is characteristic of such a third failed arm generated during Iapetan rifting (Kumarapeli, 1985).

The Ottawa–Bonnechere Graben is the principal fault-related structure in the Ottawa area and is considered one of the major grabens in North America (Sykes, 1978). This structure transects 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). It is linked to the larger St. Lawrence rift system (Bent, 1996) and forms a 55 km by 700 km topographic low encompassing the majority of the Ottawa River valley (Bélanger, 1998; Rimando and Benn, 2005), refer to Figure 1.6.

Figure 1.6. A shaded relief map illustrating the extent of the Ottawa – Bonnechere Graben and the St. Lawrence Lowlands. (GIS data sources: GeoGratis, Ontario Geological Survey).

In the Cambrian and upper Ordovician, sedimentary rocks were deposited during marine invasions of the Iapetus Ocean which are present in the eastern section of the graben, but have been eroded into a patchy distribution in the western section (Kumarapeli, 1985; Gadd, 1987). The Iapetus Ocean began to close during the Ordovician, creating the Taconian orogeny, and then closed completely in the Devonian creating the Acadian Orogeny as ancestral North America and Africa collided (Kumarapeli, 1985, Rimando and Benn, 2005). During this continental collision, compression of the crust due to the Taconian and Acadian orogenies may have caused proximal faults along the rifted margin to become interlocked and sealed, and distal faults, including those delineating the Ottawa–Bonnechere Graben to be reactivated (Kumarapeli, 1985; Adams and Basham, 1989; Rimando and Benn, 2005).

The breakup of the supercontinent Pangea began during the middle Jurassic as North America and Africa broke apart to form the North Atlantic Ocean (Rimando and Benn, 2005). Crustal weaknesses created from the closing of the Iapetus Ocean and accompanying orogenies, were again reactivated during this continental breakup (Rimando and Benn, 2005). The current North Atlantic Ocean continued to open; new fault structures were generated by the compression of the North American plate (Rimando and Benn, 2005). A secondary set of faults in the Ottawa area was due to these tectonic forces (Ebel and Tuttle, 2002) and also due to stress relief along pre-existing weaknesses within the principal structure, the Ottawa–Bonnechere Graben (Wilson,

1964). All three classical fault types, normal, strike-slip and reverse faults are represented in the region (Wallach et al., 1995; Bélanger, 1998; Rimando and Benn, 2005).

An additional crustal weakness is observed trending north east of Ottawa, and is suggested to be the track of an ancient hot spot (Ma and Eaton, 2007). During the Mesozoic, the Great Meteor hotspot travelled parallel to the Ottawa – Bonnechere Graben, creating local uplift and crustal weaknesses (Adams and Basham, 1989; Ma and Eaton, 2007).

Numerous major faults are located in the National Capital area including the Gloucester, Eardley, and Hazeldean faults (Rimando and Benn, 2005), refer to Figure 1.7. The Gloucester fault system extends directly through downtown Ottawa, recording a vertical displacement of up to approximately 700 m and is thought to have originated during or before the Paleozoic (Wilson, 1964; Bélanger, 1998; Rimando and Benn, 2005). This fault system is characterized by a series of faults which trend north-south through the City of Ottawa and transect Old Ottawa South, the Carleton University Campus and Ottawa West / Tunney's Pasture (Ontario Geological Survey, 1984). The Gloucester fault system splays as it approaches the City of Ottawa from the south, where several faults jut through the study area: the first under Bank / Kent Street and another crossing Bank Street and Laurier Avenue. A third fault, not identified with the Gloucester fault system

Figure 1.7a) Map of major faults in the city limits of Ottawa and within the study area (GIS data sources: NRCan, City of Ottawa). b) A classic example of faulting in the area (at Hogsback Falls). Photograph taken by S. K. Ploeger.

but associated with the graben structure, also crosses the study area and joins the previous two faults just south of the Supreme Court of Canada (Ontario Geological Survey, 1984). Evidence of the Gloucester fault system can be seen from the exposure, via outcrops and borehole studies, of the uppermost unit of geological formations, for example, the Lindsay and Billings Formations, which have been up- or down-thrown due to seismic activity (Ontario Geological Survey, 1984). These secondary faults were typically created by three main methods; the closing of the Iapetus Ocean, the opening of the north Atlantic Ocean and post-Cretaceous compression of eastern North America (Rimando and Benn, 2005).

Statistical analyses performed by Daneshfar and Benn (2002) to investigate spatial associations between natural seismicity and faults in south eastern Ontario, suggested that due to the compression within the North American plate, several faults trending NW–SE may still be active. Additional evidence of deformation and seismic activity within the Ottawa area include (1) offset boreholes (Wallach et al., 1995), (2) slickensides (Saul and Williams, 1974) and (3) an infilling of calcite within fractures at the near-surface, with broken calcite and a considerable movement of groundwater at depth (F. Michel, personal communication, 2008).

Major erosion occurred between the Paleozoic and Cenozoic which is indicated by the absence of geological units between the Ordovician rocks and the unconsolidated Quaternary sediments (Bélanger, 1998). The National Capital area is dominated by two

major units of Quaternary sediments, glacial and marine deposits. Current glacial deposits were created and deposited in the Late Wisconsinian ice advance of the Laurentide ice sheet. Earlier glacial deposits were eradicated by the most recent glaciation (Gadd, 1987) which is dated at approximately 12,700 years ago from marine shell samples (Fulton and Richard, 1987). Dominant glacial tills in the National Capital area have sandy to gravelly textures and are either noncalcareous or variably calcareous depending on the distribution of Precambrian marbles transported from the north (Gadd, 1987; Kettles and Shilts, 1987). The weight of the ice sheet depressed the crust and allowed for the ponding of glacial meltwater and invasion of marine water that created the Champlain Sea between 12,100 and 11,100 years ago. Sediments deposited during this time are alluvial and post-glacial marine sediments. A large bulk of fine grained sediments were transported into the basin during deglaciation and deposited into thick sheets along the marine floor (Gadd, 1987). The high rate of sedimentation created deposit thicknesses in excess of 70 m (Bélanger, 1998); the thickest deposits occurred in bedrock valleys and along the north shore of the basin (Gadd, 1987). These marine clays deposited in a deep sea environment are known as the Leda Clays (Bélanger, 1998). As the ice sheet retreated and crust rebounded, the Champlain Sea gradually drained to the east (Bélanger, 1998).

1.6 Regional seismicity

Eastern Canada is located in an intraplate setting within the North American plate, where seismicity is clustered into four seismic zones: western Québec, Charlevoix, the lower St. Lawrence and the northern Appalachians (Adams, 1989a; Adams and Basham, 1989).

Most earthquakes within these zones occur in the Grenville basement at depths ranging from 5 to 25 km, and are suggested to be associated with the reactivation of the St. Lawrence rift system (Kumarapeli, 1985; Adams, 1989a; Adams and Basham, 1989). Evidence also suggests that some eastern Canadian earthquakes may be associated with postglacial faulting (Adams, 1989b) and isostatic rebound (Adams and Clague, 1993).

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 slightly more north, trending from Montréal through Mont Laurier to the Baskatong Reservoir, refer to Figure 1.8. 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 shield, weakening the bedrock (Kumarapeli, 1985; Ma and Eaton, 2007).

The largest reported historical earthquakes in the Ottawa area (within approximately 350 km of the city) are the 1732 M5.8 Montréal earthquake, the 1935 M6.2 Temiscaming earthquake, and the 1944 M5.8 Cornwall-Massena earthquake. The Temiscaming earthquake, for example, 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

Figure 1.8. Historical seismicity in the western Québec seismic zone. The graduated symbols and colours correspond to earthquake magnitude and year it occurred (yellow pre-1900, orange 1900-1965, red 1965-2001) (earthquakescanada.nrcan.gc.ca, 2006).

epicentre (Bent, 1996). All three of these large earthquakes were felt in the City of Ottawa (Leblanc, 1981; NRCan, 2006a; NRCan, 2006b; Lamontagne et al., 2008). Prior to historical times, geological evidence presented by Aylsworth et al., (2000) supports that the massive paleo-landslides in the Ottawa River Valley were triggered by “two of the most geologically destructive earthquakes in eastern Canada” approximately 7,060 and 4,550 years ago; Aylsworth et al (2000) suggest an approximate magnitude of 7 for these events. There have been no damaging earthquakes in the Ottawa area since the 1944 Cornwall–Massena earthquake, but evidence suggests that large earthquakes may occur in the future.

1.7 Potential earthquake–induced ground failure in the Ottawa area

The Ottawa–St. Lawrence Lowlands have substantial deposits of sensitive Champlain Sea sediments known locally as Leda Clays in the Ottawa River Valley (Chapman and Putman, 1966; Hugenholtz and Lacelle, 2004). These sediments are highly susceptible to deformation and failure due to human induced activities, active water undercutting (e.g. Gadd, 1987; Hugenholtz and Lacelle, 2004), climatological factors (e.g. Eden et al., 1971; Evans and Brooks, 1994) and earthquakes (e.g. Aylsworth et al., 2000). A map illustrating the extent of the Champlain Sea and the location of landslides in the Ottawa River Valley is presented in Figure 1.9.

Figure 1.9 Map depicting the extent of the Champlain Sea and the location of landslides in Leda clays in the Ottawa River Valley (modified from NRCan, 2008).

There are numerous trigger mechanisms of landslides in the Ottawa area. Trigger mechanisms of small modern landslides tends to be related to fluvial erosion and precipitation (Hugenholtz and Lacelle, 2004). Evidence suggests that in larger modern landslides for example the 1971 South Nation River landslide and the 1993 Lemieux landslide, the sediments were weak due to heavy saturation (Eden et al., 1971; Evans and Brooks, 1994). The South Nation landslide measured nearly 28 ha and not only did it occur during a heavy thunderstorm but also at the end of the snow-melting season (Eden et al., 1971). The Lemieux landslide occurred 4.5 km from the 1971 South Nation landslide and measured 17 ha, and occurred at the end of a near-record setting wet season (Evans and Brooks, 1994). Both of these landslides are categorized as rapid earthflows or lateral spreads in sensitive clay (Evans and Brooks, 1994).

Several paleo-landslides in the Ottawa–St. Lawrence Lowlands show evidence of a geological trigger (Aylsworth et al., 2000). Two clusters of landslides dating back to 4,550 and 7,060 years ago are suggested to have been triggered by large, destructive earthquakes (Aylsworth et al., 2000). As a lower limit of earthquake-induced landslides, Keefer (1984) found that the lowest magnitude was 5.2, but noted that some rock falls, rock slides, and soil falls were triggered by magnitudes as low as Richter local magnitude (M_L) of 4.0. A recent event to support Keefer's (1984) findings was a M4.2 earthquake located 6.4 km southeast of Bar Harbour, Maine, that triggered a small rock fall in Acadia National Park (Northeast States Emergency Consortium, 2006).

Chapter 2: Data Collection

2.0 Introduction

To successfully run loss estimation programs, a tremendous amount of data collection needs to take place beforehand. Data collection is typically the most expensive 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 comprehensive level 2 HAZUS analysis, such as the one performed in this research project, incorporates professional judgment and detailed information. For seismic risk assessment, this level of analysis requires information on ground-motion parameters (Section 2.1), potential earth science hazards including liquefaction and landslide susceptibility, water depth, soil classification (Section 2.2), building inventories (Section 2.3) and demographics (Section 2.4). These inputs are in the form of: (1) databases updated with local data rather than default parameters, and (2) user-supplied hazard maps designed specifically for the study area.

Data collection is a comprehensive and multi-disciplinary step which requires knowledge and skill in applied geomatics, seismology, geophysics, computational methods, civil engineering, city planning, land use practices, social sciences, and hydrology. Information sharing between government agencies, academic institutions and organizations may ease the challenge of data collection. In this research project, information was shared between multiple levels of government, including Natural Resources Canada, Ontario Ministry of the Environment and the City of Ottawa, as well

as various academic institutions including Carleton University, the University of Ottawa and the University of Western Ontario. Data collection may be a time consuming process but the connections made between agencies and organizations will ultimately lead to more accurate loss estimations and benefit the public.

2.1 Ground-motion parameters

Ground-motion parameters, 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 components needed in seismic hazard mapping for national building codes. An important aspect of seismic hazard analysis is to determine the level of ground shaking expected at a specific site. This can be in the form of a response spectrum, which gives the maximum response of a damped single degree of freedom oscillator to an input ground-motion record; where response may be expressed as the pseudo acceleration (displacement response * $(2\pi f)^2$). Periodic revisions to the National Building Code of Canada (NBCC) update seismic hazard maps to reflect the ongoing advancements in the understanding of seismicity and seismic hazard methodology (Adams and Atkinson, 2003). Particular advancements include additional years of recorded ground-motion data using broadband instruments, improvements to the definition and methodology of characterizing ground-motions and new approaches to modelling techniques (Atkinson and Boore, 2006).

Two alternatives to define input ground-motion parameters at the bedrock level were explored in this research project, with basic earthquake characteristics such as hypocentral depth and earthquake magnitude being the same for both approaches. The first approach was to use the ground motion prediction equations (GMPEs) proposed in Atkinson and Boore (1995) to define the motions as a function of magnitude and distance; these equations were used in the national seismic hazard maps in the 2005 National Building Code of Canada, and are a default option available in the HAZUS program. The AB95 equations can be selected directly in HAZUS using a dropdown list of ground-motion attenuation functions (for a given magnitude and distance). The second approach was to use the more recent ground-motion prediction equations of Atkinson and Boore (2006); AB06 is an update to the AB95 equations that includes more recent seismological information, and supplants the AB95 equations. These equations are not yet available on the HAZUS drop-down menus, but can be implemented in HAZUS using the user-supplied ground-motions option (after calculating the response spectrum and peak ground-motions for a given magnitude and distance, according to the equations). Atkinson and Boore (2006) parameters were selected for the user-supplied approach because compared to the Atkinson and Boore (1995) HAZUS options, they reflect advancements in ground-motion relations based on a larger and broader earthquake catalogue, include estimates of uncertainty and use stochastic finite-fault modelling techniques (Atkinson and Boore, 2006).

2.1.1 Earthquake scenarios

Basic earthquake characteristics include (1) hypocentral depth, (2) earthquake magnitude, and (3) earthquake distances which include epicentral (R_{epi}), hypocentral (R_{hypo}) and distance closest to the fault (R_{cd}). A sketch depicting earthquake distances is presented in Figure 2.1.

The hypocenters of most earthquakes in eastern Canada are at depths ranging from 5 to 25 km (Adams, 1989a); therefore a depth of 10km was selected.

In this study, the selected earthquake magnitudes for the HAZUS scenarios ranged from M5.0 to M7.0 in 0.5 increments and were considered at a range of distances. This magnitude range was chosen for three main reasons. First, M5.0 is the lower limit of earthquake-induced hazards, such as liquefaction (Obermeier, 1996). Second, historically, there has been no significant damage reported for eastern Canadian earthquakes measuring less than magnitude 5.0, with the exception of the 1973 Québec–Maine earthquake which registered a magnitude in the upper 4.9 range and damaged several chimneys in Québec (Lamontagne et al., 2007). Third, evidence presented by Aylsworth et al., (2000) indicated that the upper limit of expected magnitude was approximately M7.0 in the Ottawa area.

Figure 2.1. Sketch of a fault rupture showing the rupture plane, epicentral (R_{epi}), hypocentral (R_{hypo}), distance closest to fault (R_{cd}) and hypocentral depth.

Ground-motions for earthquake scenarios are calculated at spectral periods of 1.0s, 0.5s, 0.3s, and 0.1s to be consistent with those required in the hazard calculations used by the HAZUS program.

To place scenario earthquakes in the context of the motions used in the design of modern buildings, the response spectra according to the Atkinson and Boore (2006) ground-motion relations were plotted against the Uniform Hazard Spectrum (UHS) values presented in Adams and Halchuk (2003) for a 2% in 50 years probability of exceedence, as shown in Figure 2.2. A UHS is a plot that represents the spectral amplitude for each spectral period for a specified probability of exceedence (Adams and Atkinson, 2003). Scenarios, defined by earthquake magnitude, hypocentral depth and distance, which are reasonably consistent with the Adams and Halchuk (2003) UHS curve, are the focus for this study. It is noted that these UHSs also form the ground-motion design input parameters adopted in the 2005 NBCC (NRCC, 2005). From Figure 2.2, it can be inferred that an event of M6.5 with an epicentral distance of 15 km from Ottawa, provides median motions consistent with those in the 2005 NBCC (except at periods less than 0.3s). The implication is that modern buildings would provide life safety and collapse protection for such events, though modern buildings might sustain damage. For older buildings not designed to resist these earthquakes, damage would be expected to be more extensive.

Figure 2.2. UHS of hard rock values for Ottawa (2% / 50 years) from Adams and Halchuk (2003) compared to Atkinson and Boore (2006) values (labeled AB06). Scenarios are at a R_{cd} of 10 km and do not exceed the values presented in Adams and Halchuk (2003), with the exception of M6.0 (R_{epi} 10km) and M6.5 (R_{epi} 15km) at low periods ($< 0.25s$) and for M7.0 (R_{epi} 23km).

2.1.2 Ground-motions predicted by Atkinson and Boore (1995)³

There are a variety of options in HAZUS to model ground-motions within a study area, including deterministic hazard selections that include historical and arbitrary earthquakes, user-supplied information and probabilistic hazard selections. The Atkinson and Boore (1995) GMPE (ground motion prediction equation) is an option available in HAZUS. For this option, HAZUS requires the user to enter the earthquake magnitude, hypocentral depth and coordinates of the epicenter. These geographic coordinates were determined in ArcGIS using both a basemap and a map of faults of the Ottawa area. The coordinates of each epicenter were arbitrarily chosen so that they lie on or near an existing fault, though the epicenters could be placed anywhere, and there is no specific evidence to suggest that these surficial faults are more likely than others (either mapped or unmapped) to host earthquakes.

To determine the appropriate magnitude-distance combinations for the earthquake scenarios, for use with the AB95 equations, response spectra for various combinations were compared to the UHS values for Ottawa presented by Adams and Halchuk (2003). The spectra were constructed using the following three-step procedure. First, the PSAs must be converted into the same NEHRP site class. NEHRP is a soil classification system, based on near-surface shear-wave velocity, which will be further addressed in Section 2.2.3. The ground-motions (PSAs) presented in Adams and Halchuk (2003) are

³ The material presented in this section is adapted from Ploeger et al. (2008). Ploeger is the first author and the main contributor to the material in this paper.

given for NEHRP C (firm soil) while ground-motions in Atkinson and Boore (1995) are given for NEHRP A (hard rock). A conversion factor must be applied to convert the ground-motions from NEHRP C to A; results of converted ground-motions for Ottawa are shown in Table 2.1. The adopted conversion factors used for this purpose (for the AB95 equations) are those provided in Finn and Wightman (2003). These factors are also used in the 2005 NBCC and in the HAZUS methodology.

Second, the estimated Adams and Halchuk (2003) NEHRP A motions based on the conversion factors were used in conjunction with the Atkinson and Boore (1995) look-up tables (AB95) to obtain the appropriate hypocentral distance for a given magnitude.

Third, a spectrum for the Atkinson and Boore (1995) values was plotted against the NBCC UHS values presented in Adams and Halchuk (2003). Figure 2.3 shows the Adams and Halchuk (2003) spectrum for Ottawa (reduced to values for NEHRP A) in comparison to earthquake scenarios at a closest distance (to fault) of 10 km used in this study. The closest distance to fault (R_{cd}) is related to other distance measures such as epicentral and hypocentral distances in a manner described in Section 2.1.3. From Figure 2.3, it can be concluded that appropriate scenarios consistent with the 2005 NBCC motions are events of M5.5 to M6.5 at an epicentral distance of 15km. Other scenarios that are roughly consistent with the 2005 NBCC include M5.0 (R_{epi} 1km), M6.0 (R_{epi} 1km), M6.5 (R_{epi} 31km) and M7.0 (R_{epi} 38km). Once earthquake distances were established, appropriate geographic coordinates for each scenario event were entered into

Table 2.1. Summary of ground-motion parameters for Ottawa, presented in Adams and Halchuk (2003) for NEHRP C; equivalent values for NEHRP A are also shown, based on factors of Finn and Wightman (2003). PSA and PGA are measured in g.

NEHRP	Lat.	Long.	PSA(0.2)s	PSA(0.5)s	PSA(1.0)s	PSA(2.0)s	PGA
C	45.27	-75.75	0.660	0.320	0.130	0.044	0.420
A			0.528	0.192	0.065	0.018	0.294

Figure 2.3. UHS for Ottawa (2%/50 years) from Adams and Halchuk (2003) compared to Atkinson and Boore (1995) values (labeled AB95). Scenarios at a distance (R_{cd}) of 10 km do not exceed the values presented in Adams and Halchuk (2003), with the exception of M6.0 (R_{epi} 10km) and M6.5 (R_{epi} 15km) at low periods ($< 0.25s$) and for M7.0 (R_{epi} 23km).

HAZUS, which then uses AB95 to compute the expected ground-motions within the study area. Note that median motions for each scenario are consistently used throughout, though in reality motions for a given scenario may be either higher or lower than median, with higher-than-median motions tending to dominate hazard.

2.1.3 Ground-motions predicted by Atkinson and Boore (2006)

HAZUS does not contain the most recent ground-motion prediction equations for eastern Canada, those of Atkinson and Boore (2006). However, they can be implemented using the option of user-supplied ground-motion inputs.

PSAs for this purpose, for NEHRP A sites, were computed using the Atkinson and Boore (2006) equations, which are given as follows:

$$\begin{aligned} \text{LOG PSA} = & c_1 + c_2M + c_3M^2 + (c_4 + c_5M)f_1 + (c_6 + c_7M)f_2 \\ & + (c_8 + c_9M)f_0 + c_{10}R_{cd} + S \end{aligned} \quad [2.1]$$

Where M is moment magnitude, R_{cd} is distance closest to the fault (km), $f_0 = \max(\text{LOG}(R_0/R_{cd}), 0)$; $f_1 = \min(\text{LOG}R_{cd}, \log R_1)$; $f_2 = \max(\text{LOG}(R_{cd}/R_2), 0)$; $R_0 = 10$ km; $R_1 = 70$ km; $R_2 = 140$ km; ‘ c ’ coefficients for NEHRP A are presented in Table 6 in Atkinson and Boore (2006).

Earthquake distances for the selected scenarios, including R_{epi} , R_{hypo} and R_{cd} (see Figure 2.1) were determined using an earthquake depth of 10 km. The fault sizes are given by the empirical equations of Wells and Coppersmith (1994). The subsurface rupture length and downdip rupture width equations are (Wells and Coppersmith, 1994):

$$\text{LOG RLD} = a + bM \quad [2.2a]$$

$$\text{LOG RW} = a + bM \quad [2.2b]$$

Where RLD and RW are subsurface rupture length and width, respectively, M is earthquake magnitude, and a and b are regression coefficients found in Table 2A in Wells and Coppersmith (1994). The ‘ ab ’ coefficients used were for ‘all faults,’ since the Ottawa area is characterized by all three classical faults types (Wallach et al., 1995; Bélanger, 1998; Rimando and Benn, 2005). In comparison to the fault dimensions given by Wells and Coppersmith (1994), it is assumed that faults are significantly smaller in eastern North America for a given magnitude, by a factor of 0.6 ± 0.2 (Atkinson and Boore, 2006). Fault dimensions from Equations 2.2a and 2.2b were thus multiplied by 0.6 to account for a smaller fault area (Atkinson and Boore, 2006) due to higher average stress drops. A sketch of a fault rupture can be found in Figure 2.1.

A summary table of scenario earthquake magnitudes and distances, as well as arbitrary geographic coordinates that place the events an appropriate distance from Ottawa, is presented in Table 2.2; d_0 , d_1 , d_2 and d_3 are variables assigned to fixed R_{cd} distances.

Table 2.2. Earthquake distances (km) and arbitrary epicentre coordinates (decimal degrees) for the earthquake scenarios investigated in this study. Earthquake scenarios marked with an * are roughly consistent with the 2005 NBCC for Ottawa.

M	Distance label	Distances (km)			Epicentre coordinates	
		R _{epi}	R _{hypo}	R _{cd}	Lat. (°)	Long. (°)
5.0	d0	1.0	9.0	9.0	45.41	-75.72
	d1	5.5	10.5	10.0	45.38	-75.70
	d2					
	d3					
5.5	d0*	1.0	8.7	8.5	45.41	-75.72
	d1*	7.0	11.0	10.0	45.44	-75.62
	d2					
	d3					
6.0	d0*	1.0	8.0	7.5	45.41	-75.72
	d1*	10.0	12.5	10.0	45.39	-75.82
	d2	27.5	28.5	25.0	45.4	-75.35
	d3	53.0	53.5	50.0	45.54	-75.16
6.5	d0					
	d1*	15.0	16.0	10.0	45.48	-75.86
	d2*	31.0	31.6	25.0	45.36	-76.09
	d3	56.5	57.0	50.0	45.41	-76.02
7.0	d0					
	d1	23.0	23.5	10.0	45.29	-75.49
	d2*	38.5	38.5	25.0	45.54	-75.16
	d3	64.0	64.0	50.0	45.18	-76.43

Additionally, ground-motions determined by using the Atkinson and Boore (2006) equations can be found in Appendix B1. Note that a wide range of scenarios is considered, in addition to the scenarios identified to be consistent with the 2005 NBCC. Of the fourteen chosen earthquake scenarios presented in Table 2.2, seven are roughly consistent with the 2005 NBCC, while the remaining scenarios are included for sensitivity purposes.

It is important to note that there is no direct correspondence between the ground-motions implied by AB06 for various magnitude-distance combinations and the NBCC UHS, as the latter was based on AB95. Rather, the AB06 motions are believed to be more realistic median values for a given magnitude and distance, based on current knowledge. Also note that both AB95 and AB06 motions are given consistently in terms of a reference ground condition of NEHRP A (hard rock).

2.1.4 Site amplification

Local soil conditions can influence the amplitude of incoming seismic waves, as observed dramatically during the 1985 Mexico City earthquake for example, and should therefore be incorporated in seismic design (Finn and Wightman, 2003). Amplification factors reflect surficial geology. Soils have a lower density and shear wave velocity than rock. When an incoming seismic wave makes the transition from rock to soil, it slows down and its amplitude must increase to conserve energy.

In order to calculate amplification factors to be applied to the Atkinson and Boore (2006) ground-motions for typical Ottawa soil profiles, Boore's SITEAMP program was used. This program converts velocity and density models into site amplification factors at specific frequencies (Boore, 2005). SITEAMP is based on the square-root of impedance method, also known as the quarter-wavelength method; this method utilizes the square-root of the ratio between the seismic impedance averaged over a quarter-wavelength depth and the seismic impedance at the source depth to calculate amplification (Boore and Joyner, 1997). Amplification generally increases with increasing frequency due to the decrease in shear-wave velocity at shallow depths; however this increase is offset by high-frequency attenuation effects. Individual input files were prepared, consisting of data on the thickness, shear wave velocity and density of each unit to a depth of 13km. A total of 44 input files were created to reflect each polygon present on the NRCan sediment thickness map, refer to Figure 2.4.

Shear velocities at three various depths reflecting changes in the bedrock, from near-surface Paleozoic bedrock to the Grenville basement rock were input into Boore's (2005) SITEAMP program, in addition to the shear wave velocities of the overlying sediment units. The procedure to calculate the shear wave velocities (both the weighted shear wave velocity and the shear wave velocity to a depth of 30 m) is discussed in detail in Sections 2.2.3.1 and 2.2.3.2. Impedance contrasts (seismic impedance is the product of material density and velocity) affect the propagation of seismic waves. As the seismic wave propagates vertically to the surface, density of the rock and shear wave velocity decrease

Figure 2.4. Map depicting the various polygons of sediment thickness measured in metres. This map also depicts the locations of the boreholes and seismic survey sites (GIS data sources: NRCan, Statistics Canada).

leading to gradual amplification. The SITEAMP program will utilize velocity gradients and transform them into a set of constant-velocity layers to calculate the site response or amplification factors. Table 2.3 summarizes the fixed SITEAMP model inputs. Appendix C presents sediment/rock depth, density and V_s of each layer within each of the 44 soil polygons.

To account for soil nonlinearity effects, a factor that was not considered in the SITEAMP program, the nonlinear amplification factors of Boore and Atkinson (2008) were assumed to be applicable. 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 on 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 nonlinear reduction factor is the ratio of the actual amplification after accounting for nonlinearity to the linear amplification factor. These factors were calculated for all NEHRP C and D soil polygons, as NEHRP A and B are considered to be linear; Section 2.2.3 outlines the procedure to compute soil classification. The nonlinear reduction factor was then multiplied by the SITEAMP outputs, which resulted in the final site amplification factors.

Once site amplifications for the 44 polygons were determined, they were applied to each PSA, PGA and PGV value for a given magnitude and R_{cd} for the AB06 motions. Table 2.4 presents $V_{s(w,avg)}$, V_{s30} , depth and the amplification factors at each PSA for all 44 polygons. A map of the amplification factors at PSA 0.3s and polygon identifiers is

Table 2.3. Summary of SITEAMP fixed inputs for the Ottawa Region beneath the soil (see Table 2.4). Values indicated with an (*) were taken from Atkinson and Boore (2006), and (†) from Boore and Joyner (1991). An angle of incidence of 0° corresponds to seismic waves propagating vertically. Kappa diminishes amplitudes exponentially as frequency increases, where amplitude is proportional to $\exp(-\pi \text{ kappa } f)$.

Parameter/Input	Value
Shear-wave velocity (< 0.07 km depth)	2.2 km/s
Density (< 0.07 km depth)	2.5 g/cm ³
Shear-wave velocity (0.07 - 13km depth)	3.4 km/s
Density (0.07 - 13km depth)	2.75 g/cm ³
Shear-wave velocity (at 13 km depth)*	3.7 km/s
Density (at 13 km depth)*	2.8 g/cm ³
Angle of incidence	0.00°
Kappa (NEHRP A)*	0.005
Kappa (NEHRP B)*	0.010
Kappa (NEHRP C)*	0.020
Kappa (NEHRP D)†	0.040

Table 2.4. Shear wave velocities of overlying sediments (weighted average and average to a depth of 30 m) (measured in m/s), depth of the sediment, and amplification factors (as calculated from SITEAMP and MATLAB) at various spectral periods. Note that these amplification factors were applied only to the AB06 ground-motions.

Polygon Identifiers	Sediment Properties			Amplification factors			
	$V_{s(w.avg)}$	V_{s30}	Depth	Spectral Periods (s)			
				0.1	0.3	0.5	1.0
0	513.5	1478.0	5.0	1.688	1.269	1.169	1.106
1	329.6	960.6	6.8	4.874	1.423	1.214	1.119
2	206.4	690.8	6.8	3.129	1.355	1.165	1.093
3	294.7	1273.0	3.5	1.303	1.161	1.106	1.076
4	206.4	896.1	4.5	2.443	1.299	1.167	1.101
5	328.1	659.9	12.3	3.556	1.947	1.357	1.154
6	218.9	1518.0	2.4	1.309	1.162	1.106	1.076
7	444.5	1499.0	3.5	1.202	1.135	1.093	1.07
8	653.5	1155.0	11.5	1.575	1.211	1.129	1.085
9	653.5	781.7	23.0	2.255	1.455	1.224	1.122
10	513.5	1110.0	9.0	1.869	1.253	1.148	1.093
11	473.7	1452.0	4.3	1.233	1.136	1.094	1.07
12	387.8	1144.0	5.9	3.469	1.331	1.18	1.106
13	200.0	1916.0	0.5	1.351	1.183	1.122	1.084
14	675.0	1940.0	1.8	1.19	1.133	1.097	1.073
15	324.6	1611.0	1.9	1.427	1.201	1.131	1.088
16	206.4	409.4	13.6	3.123	2.625	1.487	1.186
17	532.8	969.6	12.2	3.477	1.444	1.221	1.121
18	532.8	569.9	36.6	3.164	3.841	2.1	1.286
19	532.8	757.1	18.3	3.471	1.633	1.26	1.126
20	175.0	1389.0	1.5	1.208	1.137	1.094	1.071
21	329.6	613.8	13.7	3.361	2.088	1.391	1.163

Table 2.4. (continued).

Polygon Identifiers	Sediment Properties			Amplification factors			
	$V_{s(w.avg)}$	V_{s30}	Depth	Spectral Periods (s)			
				0.1	0.3	0.5	1.0
22	354.8	1049.0	6.3	1.681	1.228	1.137	1.089
23	675.0	2022.0	1.2	1.172	1.127	1.093	1.071
24	675.0	1940.0	1.8	1.19	1.133	1.097	1.073
25	675.0	2111.0	0.6	1.154	1.121	1.09	1.07
26	675.0	2111.0	0.6	1.172	1.127	1.093	1.071
27	354.8	688.0	12.7	2.354	1.37	1.169	1.095
28	366.8	839.8	9.7	4.232	1.531	1.249	1.131
29	325.6	1139.0	4.9	1.733	1.238	1.141	1.09
30	675.0	1613.0	4.9	1.299	1.167	1.114	1.081
31	456.4	1849.0	1.5	1.213	1.141	1.101	1.075
32	219.2	317.9	19.7	2.074	4.815	3.352	1.318
33	675.0	1865.0	2.4	1.21	1.14	1.1	1.075
34	456.4	2013.0	0.8	1.173	1.127	1.094	1.072
35	200.0	1574.0	1.2	1.307	1.17	1.116	1.081
36	219.2	555.8	9.8	3.889	2.146	1.405	1.166
37	329.6	613.8	13.7	3.361	2.088	1.391	1.163
38	354.8	1423.0	3.2	1.208	1.144	1.098	1.072
39	200.0	426.0	12.5	3.135	2.326	1.44	1.175
40	200.0	629.1	7.5	3.135	1.46	1.196	1.105
41	495.6	1724.0	2.4	1.251	1.153	1.107	1.078
42	258.1	1306.0	2.7	1.356	1.172	1.111	1.078
43	204.7	1230.0	2.4	1.347	1.17	1.11	1.078

illustrated in Figure 2.5. It should be noted that some NEHRP B soil polygons (for example polygon 1, 12 17, etc.) have very high estimated PGA values after estimated soil amplification factors are considered. These motions may not be realistic, and thus for some cases the analysis may be overly conservative.

It is important to note that the above procedure to calculate site amplifications for AB06 scenarios is entirely different, and more detailed than, the simple procedure used in HAZUS for the AB95 scenarios. The simple procedure used in HAZUS for AB95 scenarios is based on NEHRP factors consistent with a NBCC-type practice. The detailed procedure used for the AB06 scenarios is more site-specific and updated and therefore, user-supplied ground-motions use alternative methods that may be significantly different in terms of both input ground-motions at rock and site amplifications than the default HAZUS options.

2.2 Potential Earth Science Hazards (PESH)

HAZUS methodology accounts for: (1) hazards that may be induced during earthquake ground shaking, and (2) earth science features that may influence the intensity of ground shaking at the surface. In the first case, both liquefaction and landslides can be induced by an earthquake, and can increase both physical and social losses. In the second case, earth science features such as soil type can amplify or attenuate an incoming seismic wave.

Figure 2.5. Amplification factors for PSA at 0.3s, and soil polygon identifiers (GIS data sources: Statistics Canada, NRCan).

The HAZUS technical manual (refer to FEMA and NIBS, 2006b) presents a simple methodology to incorporate potential earth science hazards into the earthquake loss estimations. However, the user can choose various methodologies outside those presented in HAZUS to determine a PESH, provided that the input matches the format requirements of the HAZUS program. In this research project, the HAZUS methodology was used to determine both liquefaction and landslide susceptibilities; however, external, independent and comprehensive methodologies were used to determine soil classifications. Note that, when required, data used in earthquake scenarios defined in Section 2.1 - such as earthquake magnitude and PGAs - are used.

2.2.1 Liquefaction susceptibility⁴ and water depth

Intense ground shaking can cause various types of ground failure, including liquefaction. Liquefaction is the process by which water-saturated granular material transforms to a liquefied state due to a rapid change in pore pressure, as illustrated in Figure 2.6. Liquefaction susceptibility refers to the relative ease of a particular saturated geological unit to liquefy under intense shaking. Susceptibility can therefore be assigned qualifiers ranging from “very low” to “very high” (Youd and Perkins, 1978). Main factors affecting liquefaction include: (1) grain size distribution, (2) sensitivity of the sediments, (3) relative density, (4) depth of the water table, (5) depth, age and thickness of sediments, and (6) earthquake magnitude.

⁴ The material presented in this section is adapted from Ploeger et al. (2008). Ploeger is the first author and the main contributor to the material in this paper.

(a)

(b)

(c)

Figure 2.6. Sketches illustrating the process of liquefaction (Obermeier, 1996). During intense shaking, a) a breakdown of the original packing arrangement occurs due to change in pore pressure. b) This causes the grains to readily move with respect to each other and act as a liquid. c) The grains resettle and become densely packed causing ground deformation.

In this research project, the magnitude range that could potentially induce liquefaction and ground deformation is estimated to be from M5.0 (Obermeier, 1996) to approximately M7.0 (Aylsworth et al., 2000). Consequences of liquefaction include embankment slope failures (e.g. Lefebvre et al., 1992), sand boils, fissures (e.g. Tuttle et al., 1990), and ground subsidence.

The 1988 M5.8 Saguenay earthquake was the first earthquake in eastern North America for which ground-motion was recorded and liquefaction observed (Tuttle et al., 1990). Saguenay, Québec, and Ottawa, Ontario, are approximately 475 km from one another, but both sites share a similar Quaternary geological history and sediment units (Tuttle et al., 1990; Lefebvre et al., 1992; Aylsworth et al., 2000). Literature on liquefaction studies in the Ottawa area is limited; however, Aylsworth et al., (2000) did discover severely distorted sediments, suggesting that ground deformation is possible.

2.2.1.1 Liquefaction susceptibility methodology

In HAZUS, the default setting does not account for liquefaction susceptibility; therefore, data must be supplied by the user. In this study, ArcGIS was used to prepare the liquefaction susceptibility maps outside HAZUS. The HAZUS procedure to calculate the probability of liquefaction for a given susceptibility qualifier is presented in Equation 2.3. The relationships between liquefaction probability ($P[\text{Liquefaction}_{SC}]$) and peak ground acceleration (PGA) for each susceptibility qualifier are defined by Liao et al. (1988) as:

$$P[\text{Liquefaction}_{SC}] = \frac{P[\text{Liquefaction}_{SC} | \text{PGA} = a]}{K_M \cdot K_w} \cdot P_{ml} \quad [2.3]$$

Where $P[\text{Liquefaction}_{SC} | \text{PGA} = a]$ is the conditional liquefaction probability for a given susceptibility qualifier at a specified PGA, K_M is the moment magnitude correction factor, K_w is the groundwater correction factor and P_{ml} is the proportion of the geological unit susceptible to liquefaction. $P[\text{Liquefaction}_{SC}]$ is a probability factor and is therefore dimensionless. In order to calculate liquefaction susceptibility, HAZUS methodology requires: (1) a geological map containing information on the age, depositional environment and composition of the sediment units, (2) earthquake magnitude, and (3) depth of the water table.

On the geological map of the study area, presented in Figure 1.3b, each unit was assigned a susceptibility qualifier based on a classification system presented in Youd and Perkins (1978). In order to determine the approximate ages of these sediments as required by Youd and Perkins (1978), a geological map of the Ottawa area (Richard, 1978), and supplementary literature (e.g. Fulton and Richard, 1987; Holman et al., 1997) were utilized. Once qualifiers were assigned to each unit, $P[\text{Liquefaction}_{SC} | \text{PGA} = a]$ could be calculated, refer to Table 2.5.

Table 2.5. a) Susceptibility qualifiers assigned to the surficial geological deposits found in the study area, b) conditional liquefaction probabilities for a given PGA and the proportion of a geological unit to liquefy (FEMA and NIBS, 2006b).

(a)

Sediment Units	Susceptibility Qualifiers
Alluvial Sediments	Low
Artificial Fill	Very High
Offshore Marine Sediments	Very Low
Paleozoic Bedrock	None
Till	Very Low
Water	None

(b)

Susceptibility Qualifier	P[Liquefaction PGA=a]	Proportion of map unit
Very high	$0 \leq 9.09a - 0.82 \leq 1.0$	0.25
High	$0 \leq 7.67a - 0.92 \leq 1.0$	0.20
Moderate	$0 \leq 6.67a - 1.00 \leq 1.0$	0.10
Low	$0 \leq 5.57a - 1.18 \leq 1.0$	0.05
Very low	$0 \leq 4.16a - 1.08 \leq 1.0$	0.02
None	0.00	0.00

K_M is a dimensionless moment magnitude (M) correction factor, when $M \neq 7.5$, refer to Equation 2.4.

$$K_M = 0.0027M^3 - 0.0267M^2 - 0.2055M + 2.9188 \quad [2.4]$$

Depth of the water table is both a PESH input into the HAZUS program and a requirement to calculate liquefaction susceptibility. The depth of the water table was determined by analyzing 10 water well records, within a 1.5 km radius of Parliament Hill, that were obtained from the Ministry of the Environment (MOE) (Environmental Monitoring and Reporting Branch, personal communication, 2007). The water well database also contained ground elevations for each point that were compared with two other GIS elevation files for consistency. Depth of the water table and elevation values were interpolated individually using the inverse distance weighting (IDW) method to a resolution of 1 metre. IDW was the method of choice due to its simplicity and the relatively small number of available water well points for interpolation. The average depth of the water table was determined to be approximately 15 m (with well records ranging from approximately 3.5 m to 22.5 m). K_W is the groundwater correction factor, when depth of the water table (d_w) $\neq$ 1.5 m, and represents the depth to groundwater (Equation 2.5 is calibrated for depth measured in feet), refer to Equation 2.5.

$$K_W = 0.022d_w + 0.93 \quad [2.5]$$

P_{ml} is a dimensionless probability factor that quantifies the proportion of the geological unit susceptible to liquefaction, as the whole unit is unlikely to fail at once. Sediment units will have natural variation (grain size, deposit thickness, etc.) throughout individual deposits. Therefore a probability factor that quantifies the proportion of a geological unit or P_{ml} to liquefy is also accounted for and presented in Table 2.5b.

Once variables in Equation 2.3 have been determined ($P[\text{Liquefaction}_{SC} \mid \text{PGA} = a]$, K_M , K_W , and P_{ml}), the probability of liquefaction ($P[\text{Liquefaction}_{sc}]$) at any given location within the study area can be computed. HAZUS ranks the probability of liquefaction into 5 classes: 0 having no chance to 5 having a very high chance of liquefaction. The probabilities associated with each susceptibility class are presented in Table 2.6.

2.2.1.2 Results and implications of liquefaction

A positive correlation exists between PGA and liquefaction susceptibility. An increase in ground-motion, represented by larger PGAs, tends to increase the probability of liquefaction, represented by susceptibility qualifiers. The resulting susceptibility classes for each earthquake scenario ranges from 0 to 5, refer to Table 2.7. A graphical depiction of liquefaction susceptibility for an earthquake scenario of M7.0 (R_{epi} 23km) (also the same as M6.0 (R_{epi} 1km) and M6.5 (R_{epi} 15km)) is illustrated in Figure 2.7. The most susceptible geological unit is the artificial fill (for reference to the location of the artificial

Table 2.6. Relation between liquefaction probabilities and susceptibility classes.

P[Liquefaction_{sc}]	Susceptibility Class
< 0.01	0
0.01-0.20	1
0.21-0.40	2
0.41-0.60	3
0.61-0.80	4
> 0.80	5

Table 2.7. Resulting liquefaction susceptibility classes for each earthquake scenario for each of the representative susceptibility qualifiers (very low: glacial till and offshore marine sediments; low: alluvial sediments; and very high: artificial fill).

	Epi. Dist. (km)	AB95 scenarios			AB06 scenarios		
		Very Low	Low	Very High	Very Low	Low	Very High
M5.0d0	1.0	0	0	1	0	1	2
M5.0d1	5.5	0	0	1	0	1	1
M5.5d0	1.0	0	1	2	1	1	3
M5.5d1	7.0	0	1	2	0	1	2
M6.0d0	1.0	0	1	3	1	1	5
M6.0d1	10.0	0	1	3	1	1	4
M6.0d2	27.5	0	0	1	0	0	1
M6.0d3	53.0	0	0	0	0	0	0
M6.5d1	15.0	0	1	3	1	1	5
M6.5d2	31.0	0	0	1	0	1	1
M6.5d3	56.5	0	0	1	0	0	0
M7.0d1	23.0	0	1	2	1	1	5
M7.0d2	38.5	0	0	1	0	1	2
M7.0d3	64.0	0	0	1	0	0	1

Figure 2.7. Liquefaction susceptibility map for earthquake scenario M7.0 (R_{epi} 23km) (also the same as M6.0 (R_{epi} 1km) and M6.5 (R_{epi} 15km)) (GIS data sources: NRCan, Statistics Canada).

fill, refer to Figure 1.3b). It is expected that artificial fill would have a higher probability of liquefaction because it tends to be very loosely packed.

Additional ground deformation may occur due to the presence of a depression in the underlying bedrock. Aylsworth et al. (2000) noted that depressions in bedrock-topography tended to have disturbed overlying soil. This suggests that the pre-existing bedrock-topography, not accounted for in Equation 2.3, may increase the probability of liquefaction in the study area.

2.2.2 Landslide susceptibility⁵

Aylsworth et al. (2000) has reported several prehistoric landslides in the Ottawa area, however these landslides occurred within Champlain Sea sediments. No literature on historic landslides (rockslides) occurring in downtown Ottawa has been found, however several deadly rockfalls have been documented in Quebec City, which has similar Quaternary geology but differing bedrock geology to Ottawa. Rockfalls in Quebec City were influenced by the dip, slope angle and erodibility of the bedrock; bedrock in downtown Ottawa is relatively horizontal, but the slope is steep and susceptible to erosion. It should be noted that concrete passages have been built along Ottawa bike paths by the Ottawa River for safety precautions.

⁵ The material presented in this section is adapted from Ploeger et al. (2008). Ploeger is the first author and the main contributor to the material in this paper.

2.2.2.1 Landslide susceptibility methodology

In the study area, there are pockets of Leda clays, but none of these are located near a slope. Adjacent to the Ottawa River, located atop of a Paleozoic bedrock unit which stands up to 47 m above the river bed, is an area that may be vulnerable to a landslide; refer to Figure 2.8.

In order to calculate landslide susceptibility, HAZUS methodology requires: (1) a surficial geological map, (2) depth to the water table (3) elevation, (4) PGAs defined in the earthquake scenarios, and (5) critical accelerations of the susceptibility classes. Landslide susceptibility classes range from 0 to X, with 0 being no chance and X being a very high chance of a landslide. HAZUS methodology only considers landslides initiated during earthquakes and not due to inertial instability.

First, the rock unit underlying the study area, in this case Paleozoic bedrock, is categorized into one of three geologic groups: “A” for strongly cemented rocks; “B” for weakly cemented rocks, or “C” for argillaceous rocks (FEMA and NIBS, 2006b), refer to Table 2.8. The geologic groups have varying landslide susceptibilities due to their different degree of cementation. The slopes in the study area are underlain by late Ordovician sedimentary rock from the Verulam formation which consists of interbedded fossiliferous limestone and calcareous shale (Sharma et al., 2003). This formation is considered a strongly cemented rock, and ranks in geologic group A, although locally

Figure 2.8. Three dimensional figure illustrating topography from Parliament Hill to the base of the Ottawa River. Three dimensional buildings of Parliament Hill and the Supreme Court of Canada have been added for geographic reference (GIS data sources: City of Ottawa).

Table 2.8. Landslide susceptibility of “dry” geologic groups as a function of slope angle (FEMA and NIBS, 2006b). Note that landslide susceptibility reaches X with “wet” geologic groups.

Geologic group		Slope angle, degrees					
		0 - 10	10 - 15	15 - 20	20 - 30	30 - 40	> 40
DRY (groundwater below level of sliding)							
A	Strongly cemented rocks	None	None	I	II	IV	VI
B	Weakly cemented rocks	None	III	IV	V	VI	VII
C	Argillaceous rocks	V	VI	VII	VII	IX	IX

some shale deposits may be considerably weaker.

Second, HAZUS requires that the depth to the water table is classified as either above or below level of sliding, where susceptibility increases if the groundwater level is above the level of sliding (FEMA and NIBS, 2006b). The depth to the water table was ascertained by the interpolation of borehole and well water depths, and used against the height of the slope. The depth to the water table was generally found to be below the level of sliding or “Dry” as indicated in Table 2.8. A cautionary note is that fracturing in the bedrock may aid water to reach below the level of sliding (F. Michel, personal communication, 2008).

Third, there is a strong correlation between slope angle and landslide susceptibility; hence the collection of the elevation data to calculate the slope angle in degrees, as presented in Table 2.8.

Finally in HAZUS methodology, landslide susceptibility is a function of critical acceleration. Landsliding occurs at times when PGA within a slide mass exceeds critical acceleration. HAZUS defined the lower bound of critical acceleration for Geologic Group “A” to be 0.20 (g), therefore any PGAs below this value will not likely cause a landslide. The table of critical accelerations for each susceptibility class is presented in Table 2.9. To determine the final landslide susceptibility classes, from 0 to X, as required by HAZUS, PGA values for each earthquake scenario were used against the critical

Susceptibility Category	None	I	II	III	IV	V	VI	VII	VIII	IX	X
Critical Acceleration (g)	None	0.60	0.50	0.40	0.35	0.30	0.25	0.20	0.15	0.10	0.05

Table 2.9. Critical accelerations by susceptibility class (FEMA and NIBS, 2006b).

accelerations. For a Geologic Group “A” falling in the “dry” slope category, to be assigned a susceptibility class, PGAs must exceed the listed critical acceleration.

2.2.2.2 Landslide susceptibility results

Results suggest that only a small region of the study area is susceptible to a landslide. This region extends from behind the Supreme Court of Canada and stretches eastward to the Alexandra Bridge, and contains susceptibility values as high as VI. Notably, the only region with a susceptibility class of VI is adjacent to Parliament Hill, refer to Figure 2.9. Table 2.10 presents the final susceptibility classes. To be conservative, HAZUS methodology indicates that only a percentage of each slope area is susceptible to a landslide; these percentages are presented in Table 2.11. It should be noted that HAZUS methodology to determine landslide susceptibility is very simple and does not consider the dip of the layers and the degree of fracturing.

2.2.3 Soil classification

Soil amplification is dependent on soil type, its properties and thickness. Soil characteristics can be classified using the National Earthquake Hazards Reduction Program classification system (NEHRP), which was initially an American classification system, but has been adopted recently by the 2005 NBCC. This classification system characterizes site conditions quantitatively, and not only assigns a letter for specific soil

Figure 2.9. Landslide susceptibility classes for the study area. (GIS data sources: City of Ottawa). Note that the lighter pastel colours are a reflection of surficial geological deposits (Figure 1.3b).

Table 2.10. Landslide susceptibility classes for each earthquake scenario. For example, an AB95 M5.0d0 earthquake scenario may trigger a landslide only on a slope of strongly cemented rocks with a slope angle greater than 40° (listed as susceptibility class VI). AB95 and AB06 refer to the different set of ground-motion scenarios.

	Susceptibility Classes	
	AB95	AB06
M5.0d0	VI	0
M5.0d1	VI	0
M5.5d0	IV, VI	IV, VI
M5.5d1	IV, VI	VI
M6.0d0	II, IV, VI	I, II, IV, VI
M6.0d1	II, IV, VI	IV, VI
M6.0d2	0	0
M6.0d3	0	0
M6.5d1	II, IV, VI	I, II, IV, VI
M6.5d2	0	0
M6.5d3	0	0
M7.0d1	IV, VI	I, II, IV, VI
M7.0d2	0	0
M7.0d3	0	0

Susceptibility Classes	None	I	II	III	IV	V	VI	VII	VIII	IX	X
Study Area	0.00	0.01	0.02	0.03	0.05	0.08	0.10	0.15	0.20	0.25	0.30

Table 2.11. Percentage of study area having a geological unit susceptible to landslides (FEMA and NIBS, 2006b).

classes (Finn and Wightman, 2003), but also provides a reference ground condition which is comparable across Canada. NEHRP site classes are based on the measured travel-time-weighted average of shear wave velocity to a depth of 30 metres (V_{S30}) and are divided into classes A (hard rock) to E (soft soils) based on shear-wave velocity, with F denoting problematic soils, refer to Table 2.12. V_{S30} can be determined by several methods including borehole shear wave velocity measurements (e.g. Hunter et al., 2007), shear wave reflection Landstreamer technology (e.g. Pugin et al., 2007), and shallow seismic reflection / refraction surveys (e.g. Motazedian and Hunter, 2008).

The process of soil classification is sometimes referred to as microzonation, as it provides finely detailed maps of ground conditions within a small area like a city. In Canada, microzonation studies have been performed in Vancouver, Victoria, Montreal and Ottawa (Adams and Halchuk, 2004; Chouinard and Rosset, 2007; Hunter et al., 2007; Pugin et al., 2007; Motazedian and Hunter, 2008).

In this study, two approaches were used to determine average shear wave velocity, the first approach was by seismic surveys (Section 2.2.3.1) and the second approach was based on borehole interpretations (Section 2.2.3.2).

Table 2.12. NEHRP site classification (FEMA and NIBS, 2006b).

Site Class	Site Class Description	V _{s30} (m/s)	
		Minimum	Maximum
A	Hard rock	1500	
B	Rock	760	1500
C	Very dense soil and soft rock	360	760
D	Stiff soils	180	360
E	Soft soils		180
F	Problematic soils		

2.2.3.1 Seismic reflection and refraction surveys⁶

Six sites within the study area were surveyed using seismic reflection / refraction: 259 (Parliament Hill), 341 (Ottawa Tech), 365 (Confederation Park), 366 (the Supreme Court of Canada), 367 (National Archives of Canada), and 371 (Major Hill Park), see map in Figure 2.10. These survey sites represent the few available green spaces in the downtown core which meet specific survey criteria, including site dimensions, accessibility and traffic.

Seismic field data were acquired by using a seismic array geometry developed by Motazedian and Hunter (2008). The seismic array consisted of 24 horizontal low frequency (4.5 Hz) geophones, and a Geometrics Geode seismograph, activated by a hammer with an electronic trigger. This energy source produced a downward signal to penetrate and image the sub-surface layers. The number and location of shot points at each site was dependent on the available green space. Each survey site had shots at 3.0 m and 4.5 m off each end of the array and space permitting, 30 m shots were also recorded. Refer to Figure 2.11 for a sketch of the array orientation at survey site 366, the Supreme Court of Canada. All sites within the study area were affected by traffic noise to some degree; therefore each shot was stacked 8 times to enhance the signal-to-noise ratio.

⁶ The material presented in this section is adapted from Ploeger et al. (2008). Ploeger is the first author and the main contributor to the material in this paper.

Figure 2.10. Location of six seismic surveys (GIS data sources: NRCan).

Figure 2.11. Sketch (to scale) of the seismic acquisition layout at site 366 (Supreme Court of Canada). The triangles represent the 24 geophones and are numbered from 1 (south end of the spread) to 24 (north end of the spread). The forward and reverse endshots are at 3.0 m and 4.5 m spacing off each end, no 30m shots were performed due to space restrictions.

To determine V_{s30} and sediment depth, data were interpreted using methods from the Geological Survey of Canada (GSC) (H. Crow, personal communication, 2007). First, data were plotted to determine best-fit linear trendlines and their related equations, as shown in Figure 2.12. The slope of each trendline was inverted to determine the shear wave velocity of that particular layer. Two dominant layers existed, the first a thin low-velocity surface layer and the second, a bedrock refractor.

The results of V_s for both layers were input into a BASIC program called “refract”. The output of this program provides the depth of the interface between the surface layer and the bedrock. These results were then input into a customized spreadsheet to determine the V_{s30} in 5 m intervals to a depth of 30 m.

2.2.3.2 Borehole interpretation

The lack of availability of green space within the study area, and the reasons outlined below meant that a second approach, borehole interpretation, was required to determine the shear wave velocity over the entire study area. The six seismic surveys described in the previous section were conducted in regions with less than 15 m of sediment cover; however, unsurveyed regions within the study area show drift accumulations of up to 25 to 40 m (NRCan, 2002). Pockets of softer sediments are expected to have lower V_{s30}

Figures 2.12. Plot to determine V_s showing the two distinct layers, the first trendline (open circles) represents the thin surface layer, while the second trendline (solid circles) represents the bedrock refractor.

values than the surveyed sites and this may have serious implications on potential wave amplification during an earthquake (Eyles, 2002). These pockets are located under a major shopping centre and commercial area, and this specific area may be more at risk due to the lower V_{s30} (higher hazard) and higher population density (higher vulnerability) (Adams, 1989a).

A total of 48 NRCan borehole engineering logs located within the study area were used. Each log recorded the total thickness of sediment, as well as the composition of each layer of sediment found within each borehole. Using the NRCan sediment thickness map (Figure 2.4) as a guide, information from the 48 boreholes was used to assign a shear wave velocity to each of the 44 polygons on the map.

The first step to determine the average shear wave velocity of each polygon was to collect information on each borehole. Individual borehole logs were examined and each sediment unit within the log was generalized into 5 categories (fill, till, sand, clay and diamicton), as these were most abundant.

Second, to determine the average shear wave velocity of each sediment category, results from Hunter et al. (2007) were utilized. For example, the shear wave velocity profiles contain numerous velocity measurements within a particular unit; by recording the velocity of each measurement, an average shear wave velocity of that entire sediment unit

can be determined. These average shear wave velocities were then assigned to the 5 sediment categories (fill, till, sand, etc.) from the borehole logs.

At this point, each borehole had the following information: (a) the depth of the sediment–bedrock interface, (b) the thickness, and (c) the shear wave velocity for each sediment unit. The next step, for a more accurate calculation of shear wave velocity of each borehole log, was to determine the weighted average of each unit based on its thickness: for example, polygon 32 (borehole 1881) contained approximately 17 m of clay and 2 m of diamicton. In this case, the average shear wave velocity would not be adequate because of the disproportionate amount of clay relative to diamicton.

Third, the data collected on the sediment thickness, weighted average of shear wave velocity of the sediments and the shear wave velocity of bedrock, were input into the same customized spreadsheet used for the seismic reflection / refraction approach. A comparison of the shear wave velocity profile from surface measurements and the average shear wave velocity to a depth of 30 m profile for borehole 1881 is illustrated in Figure 2.13. Surface measurements of the near-surface sediments will provide a better indication as to the behaviour of an incoming seismic wave. In cases where more than one borehole existed in a particular polygon, both borehole logs were taken into consideration.

Figure 2.13. Sediment units, shear wave velocities for each unit and average shear wave velocities in 5 m intervals for borehole 1881.

2.2.3.3 Results of soil classification

A graphical depiction of the resulting NEHRP classes within the study area is presented in Figure 2.14. It should be noted that the artificial fill deposit indicated in Figure 1.3b may not be adequately represented in the soil classifications as only one borehole was present on this deposit. The results show that the majority of the polygons were class B. Due to the shallow underlying bedrock, NEHRP classifications of A and B were expected. NEHRP C was found in the area in and around Confederation Park (site 365), in a small pocket in the eastern census tract, and below a section of the Ottawa River. These results reflect the presence and depth of clay, till and fill deposits. For polygons with NEHRP C and D, the majority of boreholes contained at least 7 m of clay and/or fill deposits. Additionally, almost all polygons with NEHRP C and D had total sediment thicknesses greater than 10 m. It should be noted that this area of the city has in general excellent soil conditions (NEHRP A to C) and that this is a significant factor in mitigating seismic hazard.

2.3 Building inventory⁷

A sidewalk survey of 597 buildings was conducted, during the summer months of 2007. The inspections were performed by a fourth year graduate of Civil Engineering (R. O'Connell), who also completed the HAUZS training course. The building stock was classified individually by visual inspection. All buildings were catalogued using a digital

⁷ The material presented in this section is adapted from Ploeger et al. (2008). Ploeger is the first author and the main contributor to the material in this paper.

Figure 2.14. NEHRP classes of the study area based on seismic surveys and borehole interpretation (GIS data sources: NRCan, Statistics Canada).

camera and GPS. In regions where tall buildings interfered with the GPS satellite signal, the buildings were catalogued by ArcGIS. Additionally, building type, occupancy class, number of stories and other information were collected.

HAZUS developers have compiled building type classifications to differentiate between buildings with varying potential damage and loss characteristics, and behaviour under strong ground-motions. There are four main building types: wood, masonry, concrete and steel, refer to Figure 2.15. These building types can be subdivided into 36 classes. An example of a subdivision of building type would be S1, steel moment frame, which is characterized by having a frame of steel columns and beams (FEMA and NIBS, 2006b).

Occupancy classes are also classified. There seven main occupancy classes: residential, commercial, industrial, agricultural, religion / non-profit organizations, governmental and educational. These occupancy classes can be subdivided into 28 classes. An example of a subdivision of an occupancy class would be COM9 which is classified as theatre (FEMA and NIBS, 2006b). A summary of building types and occupancy classes can be found in Appendices D1 and D2, respectively. The building inventory was 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, refer to Figures 2.16 a and b. A summary table of building type and occupancy classes is presented in Table 2.13a.

Figure 2.15. Photographs of the four main building types (upper left: wood, upper right: masonry; lower left: concrete, lower right: steel). Photographs taken by S.K. Ploeger and R. O'Connell.

Figure 2.16. a) Distribution of building types, b) Distribution of occupancy classes, c) Distribution of building heights, and d) Distribution of building seismic design levels.

Table 2.13. a) Building type against occupancy class, b) Building type against building height, c) Building type against seismic design level.

	Building Type and Occupancy Class				
	Wood	Concrete	Steel	Masonry	Total
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 Type and Building Height				
	Wood	Concrete	Steel	Masonry	Total
Low-Rise	84	86	10	255	435
Medium-Rise	0	37	1	11	49
High-Rise	0	91	22	0	113
Total	84	214	33	266	597

	Building Type and Seismic Design Level				
	Wood	Concrete	Steel	Masonry	Total
Pre-Code	70	59	6	234	369
Low-Code	10	138	12	31	191
Moderate-Code	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 stories, seismic design level, square footage and cost per square footage. The number of stories was simply determined by visual observation and categorized into low-, mid-, or high-rise or 1-3, 4-7 and 8+ stories, respectively. 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). 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. Design level was inferred by the use of fire insurance records (Underwriter's Survey Bureau, 1963), City of Ottawa aerial photographs and visual observation. The distribution of building height and seismic design level was dominated by low-rise buildings (73%) and buildings built pre-code (62%), refer to Figures 2.16 c and d. Summary tables of building type and building height, and seismic design levels are presented in Tables 2.13 b and c, respectively. Square footage was calculated using both building footprints on high resolution aerial photographs and information collected in the field, and is presented in Table 2.14 by building type. The cost of each building (not including content cost) was calculated per square foot based on a default table of subdivided occupancy classes presented in the HAZUS technical manual. These values should be considered a minimal structural replacement cost, as all buildings were treated without consideration of their intrinsic or downtown real estate market values.

The New York default building inventory in HAZUS, entitled NY1, was also examined. In HAZUS, the NY1 inventory is generalized for use in all parts of New York State when an actual inventory is not available.

The NY1 default building inventory was dominated by wood (33%) and steel (31%) building types, refer to Figures 2.17 a. The distribution of building height and seismic design level was dominated by low-rise buildings (100%) and buildings built pre-code (60%), refer to Figures 2.17 b and c. The most substantial differences between the actual downtown Ottawa and the NY1 building inventories are that the NY1 inventory (1) underestimated the presence of concrete and masonry buildings, (2) overestimated the number of steel and wood buildings, and (3) there were building types listed as unknown. Additionally, the NY1 building inventory used only low rise buildings at pre- and low-code buildings, while the actual downtown Ottawa building inventory contained a distribution of all heights and codes.

Information on critical facilities and utilities was also collected. Critical facilities in the study area included essential facilities (schools, medical clinics, and emergency centres), and high potential loss facilities (military installations); while utilities included electrical plants, communication facilities and transmitters. Unique and specific types of data were required by HAZUS for each critical facility. For example, schools required the number of students and telecommunication facilities required broadcast transmitter type.

Table 2.14 Square footage of the different building types at the dissemination area level (see Figure 1.3a) measured in thousands of square feet.

Area	Building type				Total
	Concrete	Steel	Masonry	Wood	
001	200.8	9.3	192.2	62.6	464.9
002	1085.3	109.8	232.3	51.5	1479.0
003	3686.3	122.1	2196.7	174.6	6179.7
004	4643.8	1794.8	3412.2	30.0	9880.7
005	11391.1	2293.5	757.7	1.3	14443.6
006	2098.1	2215.3	12.2	0.0	4325.6
007	493.4	107.4	13.2	0.0	614.0
008	490.9	0.0	10.6	0.0	501.4
009	466.7	226.2	38.2	0.0	731.0
010	649.9	0.0	0.0	0.0	649.9
Total	25206.2	6878.4	6865.2	320.2	39270.0

Figure 2.17. NY1 default inventory. a) Distribution of building types, b) Distribution of building heights, and c) Distribution of building seismic design levels.

2.4 Demographics⁸

Modelling casualties requires specific information on demographics. HAZUS utilizes both residential and working populations at three time periods during the day; daytime, night time and commuting or 2pm, 2am and 5pm, respectively. The study area is located in the central business and tourist district in Ottawa where populations change drastically between day and night. For example, in the western census tract or the central business district, there is a working population of 217 during the night, and over 65,000 during the day, refer to Table 2.15. Demographics on a dissemination area level regarding night time residential populations were collected from Statistics Canada (www12.statcan.ca). Demographics for the remaining residential and working populations at the required time periods were collected from the City of Ottawa (I. Cross, personal communication, 2007). Simple ratios were used to calculate the remaining population distributions at the dissemination area level, refer to Table 2.16. HAZUS uses these populations to calculate the number and type of casualties. Visitor populations were not considered in this project. 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.

⁸ The material presented in this section is adapted from Ploeger et al. (2008). Ploeger is the first author and the main contributor to the material in this paper.

Table 2.15. Populations of the east and west census tracts in downtown Ottawa.

Time	Census Tract	Population Type		Total
		Residential	Working	
2 AM	East	2,238	414	2,652
	West	3,718	217	3,935
2 PM	East	224	10,439	10,663
	West	372	65,688	66,060
5 PM	East	448	10,003	10,451
	West	744	18,033	18,777

Table 2.16. Populations at the dissemination area level (see Figure 1.3a) at 2:00pm.

Area	Population Type	
	Residential	Working
001	35	1,107
002	114	7,328
003	75	2,004
004	103	28,574
005	8	31,530
006	20	3,613
007	78	328
008	68	329
009	56	657
010	39	657
Total	596	76,127

Chapter 3: Loss estimation interpretation and analysis

3.0 Introduction

HAZUS computes loss estimations for a variety of hazards including earthquakes. For international settings, default information is supplemented with local data. Appendix E provides an in depth, step-by-step guide for supplementing local data into the HAZUS program. Upon the calculation of loss estimations, it is the responsibility of the user to record and interpret results in order to identify areas most physically and socially vulnerable to earthquake ground shaking. Loss estimation results for downtown Ottawa, Canada (Section 3.1) and a comprehensive discussion (Section 3.2) are presented below.

3.1 Results

One of the overall objectives of the HAZUS methodology is to use the earthquake loss estimations to project damages, disruptions, and consequences to a region that may result from an earthquake (FEMA and NIBS, 2006a). To deduce this, HAZUS outputs the following information: (1) quantitative estimates of losses, (2) functionality losses and (3) extent of induced hazards. Quantitative estimates of losses (Section 3.1.1) include the number of damaged buildings for general and specific building types and occupancies, casualties, and quantity of debris. Functionality losses (Section 3.1.2) include loss-of-function and restoration times for both critical facilities and utility lifeline systems. The extent of induced hazards (Section 3.1.3) includes damage incurred due to liquefaction and landslides.

Results from the earthquake loss estimations performed for fourteen earthquake scenarios (see Table 2.2) for the ground-motion prediction equations of Atkinson and Boore (1995) and Atkinson and Boore (2006), with the NEHRP based and site-specific amplifications, respectively, are presented in the subsequent sections. The ground-motion prediction equations of Atkinson and Boore (1995) and Atkinson and Boore (2006) are herein referred to as AB95 and AB06. Additional scenarios were run to (1) investigate whether the extra effort devoted to the sidewalk survey (actual inventory) was justified in comparison to the NY1 default inventory (the NY1 inventory is the default inventory generalized for use in all parts of New York State) and, (2) explore a simple validation exercise to check the reasonableness of HAZUS loss estimations in eastern Canada. These will be discussed in Section 3.2. Note that only some of the scenarios are consistent with the 2% exceedence probability in 50 years motions in the 2005 NBCC (Table 2.2). The most consistent scenario for the NBCC is the AB95 motions for the M6.5 (R_{epi} 15km). However, a more realistic interpretation of losses for such a scenario is based on the updated AB06 motions, in conjunction with site-specific amplification factors based on microzonation studies. Therefore, this scenario will be focussed on in the discussion of losses.

3.1.1 Quantitative estimation of losses

Quantitative estimation of losses is the most straight forward output from HAZUS as these estimations can be applied to most aspects of earthquake losses including: (1)

physical (Section 3.1.1.1), (2) social (Section 3.1.1.2) and (3) direct economical losses (Section 3.1.1.3). Note that all losses at the dissemination area level discussed here are based on an AB06 M6.5 (R_{epi} 15km) scenario (best estimate of median ground-motions from an event of M6.5 at a R_{epi} 15km (R_{cd} 10 km)); Appendix F contains these results. Additionally, dissemination areas are herein referred to as area ### (for example dissemination area 001 is simply area 001).

3.1.1.1 Physical losses

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. 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). Details on building design and response, as well as fragility and capacity curves are beyond the scope of this research. Briefly, however, a description these damage curves are given below.

Capacity curves characterize building response as they represent the nonlinear behaviour of a building under an increasing spectral displacement or load, as illustrated in Figure 3.1a (ITS Group, 2004). Capacity curves are typically overlain with seismic design curves, where the intersection of the two curves is the peak building response, which then

Figure 3.1. Capacity curve showing damage for different levels of seismic demand. a) Nonlinear building behaviour curve depicting various damage states using base shear (the total lateral force at the base of the building), and roof displacement. b) An example of building capacity curves and seismic demand curves, where seismic demand is commonly expressed in the form of the response spectrum (ITS Group, 2004). Note that the peak building response variable to be used with the fragility curve can be found at the intersection of the capacity curve and response spectra.

controls the likely damage state of the building, depicted in Figure 3.1b (ITS Group, 2005; FEMA and NIBS, 2006b). The intersection point of the capacity curve and response spectra is used with the fragility curves to estimate damage state probabilities.

Fragility curves determine the probability of a building being in, or exceeding a damage state (none, slight, moderate, extensive, complete) for a given building type. To determine this probability, uncertainties are considered. Uncertainties are expressed in terms of probabilistic distributions on both the median seismic demand curve, and the capacity curves. These curves are plotted as a function of ground-motion (PSA), and are illustrated in Figure 3.2a (ITS Group, 2004; FEMA and NIBS, 2006b). Based on these curves and their associated uncertainties, fragility curves are constructed and correspond to a damage state as illustrated in Figure 3.2b. The HAZUS-MH Technical Manual (FEMA and NIBS, 2006b) can be consulted for further explanation. Note that in this study HAZUS uses damage functions specific to the United States which were not modified to Canadian Engineering Practice and may not be entirely applicable. HAZUS does have the option however, to modify default damage functions.

In this presentation of results, the amount of damage is measured by the total number of damaged buildings, while overall building vulnerability is measured by a percentage – number of damaged buildings to the total number of buildings for a given building type or occupancy. Refer to Section 2.3 for the distribution of the 597 buildings within the study area.

Figure 3.2. Fragility curves and their probabilistic distribution (median). a) Examples of a capacity curve and seismic demand curve showing the probabilistic distribution to account for uncertainty. b) Fragility curves for each damage state (ITS Group, 2004). Note that the cumulative probability is the conditional probability of being in, or exceeding a damage state for a given PSA (in this case spectral displacement).

Tables 3.1 and 3.2 present the number of damaged buildings and building vulnerability. Appendix G presents a breakdown of the number of damaged buildings into damage states (none, slight, moderate, extensive and complete) for building types (G1) and occupancy classes (G2) for AB06 scenarios. Table 3.3 defines each damage state with respect to building type.

Building inventory – ground-motion

The number of damaged buildings in each scenario is dependent on the amplitude of ground shaking; therefore, the closer the distance to the earthquake and the larger the earthquake magnitude, the greater the amount of damage. This is depicted in Figure 3.3. The least amount of damage occurs in scenario M5.0 (R_{epi} 5km), where the total number of damaged buildings was 14 and 1 for the AB95 and AB06 scenarios, respectively. The greatest amount of damage occurs in scenario M7.0 (R_{epi} 23km), where the total number of damaged buildings was 390 and 395, with 15 of those buildings being completely damaged, for AB95 and AB06 scenarios, respectively.

In all scenarios, AB95 building damages were greater than AB06 building damages with the exception of the M7.0 (R_{epi} 23km) scenario (Figure 3.3). AB95 losses exceed AB06 losses because AB95 ground-motion is richer at short periods. Short period motions tend to affect low-rise buildings, while long period motions tend to affect high-rise buildings. The study area is dominated by low-rise buildings which would then experience a greater

Table 3.1. Number of damaged buildings and building vulnerability (in brackets) for AB95 scenarios.

Scenario	Epi. Dist. (km)	Building Damage - AB95					Total Damaged Buildings
		None (%)	Slight (%)	Moderate (%)	Extensive (%)	Complete (%)	
M5.0d0	1.0	583	11	3	0	0	14
		(97.7)	(1.8)	(0.5)	(0.0)	(0.0)	(2.3)
M5.0d1	5.5	583	11	3	0	0	14
		(97.7)	(1.8)	(0.5)	(0.0)	(0.0)	(2.3)
M5.5d0	1.0	513	56	24	4	0	84
		(85.9)	(9.4)	(4.0)	(0.7)	(0.0)	(14.1)
M5.5d1	7.0	513	56	24	4	0	84
		(85.9)	(9.4)	(4.0)	(0.7)	(0.0)	(14.1)
M6.0d0	1.0	354	129	87	23	4	243
		(59.3)	(21.6)	(14.6)	(3.8)	(0.7)	(40.7)
M6.0d1	10.0	361	126	85	21	4	236
		(60.5)	(21.1)	(14.2)	(3.5)	(0.7)	(39.5)
M6.0d2	27.5	545	37	14	1	0	52
		(91.3)	(6.2)	(2.3)	(0.2)	(0.0)	(8.7)
M6.0d3	53.0	585	9	3	0	0	12
		(98.0)	(1.5)	(0.5)	(0.0)	(0.0)	(2.0)
M6.5d1	15.0	266	152	131	39	9	331
		(44.6)	(25.5)	(21.9)	(6.5)	(1.5)	(55.4)
M6.5d2	31.0	459	86	44	7	1	138
		(76.9)	(14.4)	(7.3)	(1.2)	(0.2)	(23.1)
M6.5d3	56.5	541	39	15	2	0	56
		(90.6)	(6.5)	(2.5)	(0.4)	(0.0)	(9.4)
M7.0d1	23.0	207	155	160	60	15	390
		(34.7)	(26.0)	(26.8)	(10.0)	(2.5)	(65.3)
M7.0d2	38.5	359	127	86	21	4	238
		(60.1)	(21.3)	(14.4)	(3.5)	(0.7)	(39.9)
M7.0d3	64.0	474	78	38	6	1	123
		(79.4)	(13.1)	(6.3)	(1.0)	(0.2)	(20.6)

Table 3.2. Number of damaged buildings and building vulnerability (in brackets) for AB06 scenarios.

Scenario	Epi. Dis. (km)	Building Damage - AB06					Total # of Damaged Buildings
		None (%)	Slight (%)	Moderate (%)	Extensive (%)	Complete (%)	
M5.0d0	1.0	595	2	0	0	0	2
		(99.6)	(0.4)	(0.0)	(0.0)	(0.0)	(0.4)
M5.0d1	5.5	596	1	0	0	0	1
		(99.8)	(0.2)	(0.0)	(0.0)	(0.0)	(0.2)
M5.5d0	1.0	567	22	7	1	0	30
		(95.0)	(3.7)	(1.2)	(0.2)	(0.0)	(5.0)
M5.5d1	7.0	577	16	4	0	0	20
		(96.6)	(2.7)	(0.7)	(0.0)	(0.0)	(3.3)
M6.0d0	1.0	429	100	55	11	2	168
		(71.9)	(16.7)	(9.2)	(1.8)	(0.4)	(28.1)
M6.0d1	10.0	485	73	33	5	1	112
		(81.2)	(12.2)	(5.5)	(0.9)	(0.2)	(18.8)
M6.0d2	27.5	583	11	3	0	0	14
		(97.7)	(1.8)	(0.5)	(0.0)	(0.0)	(2.3)
M6.0d3	53.0	595	2	0	0	0	2
		(99.6)	(0.4)	(0.0)	(0.0)	(0.0)	(0.4)
M6.5d1	15.0	333	139	97	24	4	264
		(55.8)	(23.3)	(16.2)	(4.0)	(0.7)	(44.2)
M6.5d2	31.0	537	42	16	2	0	60
		(89.9)	(7.0)	(2.6)	(0.4)	(0.0)	(10.0)
M6.5d3	56.5	583	11	3	0	0	14
		(97.7)	(1.8)	(0.5)	(0.0)	(0.0)	(2.3)
M7.0d1	23.0	202	159	162	59	15	395
		(33.8)	(26.7)	(27.1)	(9.9)	(2.5)	(66.2)
M7.0d2	38.5	448	91	48	9	1	149
		(75.0)	(15.2)	(8.0)	(1.5)	(0.2)	(25.0)
M7.0d3	64.0	556	30	10	1	0	41
		(93.1)	(5.0)	(1.7)	(0.2)	(0.0)	(6.9)

Table 3.3. Descriptions of damage states for each building type (FEMA AND NIBS, 2006b).

	Building Type			
	Wood	Steel	Concrete	Masonry
N o n e	No structure damage.	No structure damage.	No structure damage.	No structure damage.
S l i g h t	Small cracks in plaster, gypsum-boards, masonry chimneys and masonry veneer.	Minor deformations or hairline cracks in connections, welds, shear wall surfaces or infill walls; minor stretching, buckling or sagging of brace members.	Hairline cracks in beams, columns or shear or infill walls; minor separation of walls.	Diagonal or hairline cracks in masonry wall surfaces or parapets; minor separation of walls from floor and roof.
M o d e r a t e	Large cracks in plaster, gypsum-boards, and brick chimneys; diagonal cracks in wall panels; small cracks in stucco and gypsum wall panels; toppling of tall masonry chimneys.	Observable and permanent rotation, stretching, buckling, sagging or crushing of brick at connections or brace members; few major cracks, broken or enlarged bolts in welded connections, wall ends, or infill walls.	Larger cracks in beams, columns, or shear or infill walls; crushing of brick at connections; some walls may have visibly pulled away from roof.	Large diagonal cracks in masonry wall surfaces or parapets; some walls may have visibly pulled away from roof.

Table 3.3. Continued.

E x t e n s i v e	Large diagonal cracks in wall panels, and plywood joints; permanent lateral movement of floors and roofs; toppling of most brick chimneys; cracks, splits of slippages in the foundations; partial collapses of soft-story configurations.	Permanent lateral deformation of structure; permanent rotation, buckling, sagging or failure at connections, welds, braces or frames; large diagonal cracks or bulges in walls; stretched anchor bolts, and broken brace rods; partial collapse of portions of structure	Large cracks or bulges in infill walls; shear failures or bond failures at splices; broken or buckled columns; partial collapse of roof.	Large through-the-wall cracks; visibly buckled wall reinforcement; partial collapse of roof; parapets or gables may fall; beams or trusses may move relative to their supports.
C o m p l e t e	Potential permanent lateral displacement, building collapses or imminent danger of collapse; slip off foundations; large foundation cracks.	Permanent lateral displacement, deflection, partial collapse or complete collapse of the building;	Structure collapse or imminent collapse.	Structure collapse or imminent collapse.

Figure 3.3. Number of damaged buildings with respect to epicentral distances for five earthquake scenarios.

amount of damage when exposed to short period motions. Appendix B summarizes the AB95 and AB06 ground-motions used in, and computed from, HAZUS.

Figure 3.4 shows the various damage states projected for five AB06 earthquake scenarios in order of increasing magnitude from the left to right. In all cases, the number of buildings with slight and moderate damage exceeds the number of buildings with extensive and complete damage. These results predict that earthquake building damage is biased towards a large number of buildings suffering slight and moderate damage. Another important factor that influences the difference in loss estimates is that NEHRP-based factors have been used to amplify the AB95 input motions, while site-specific amplifications were used with AB06.

Building inventory – building type and occupancy class

Analyzing the data in terms of the total number of damaged buildings for all scenarios, the general building type (wood, steel, concrete, masonry) and occupancy class (commercial, educational, governmental, residential, religious) with the greatest amount of damage are masonry and commercial buildings, respectively, as shown in Figures 3.5 and 3.6. The damage to this type and class of building is expected, as they both dominate the building inventory (Figure 2.16 a and b), and masonry is known to be seismically vulnerable. Note that the study area contains both reinforced (7%) and unreinforced

Figure 3.4. Damage states for five AB06 earthquake scenarios at approximate epicentral distances of 5km (M5.0), 7km (M5.5), 10km (M6.0), 15km (M6.5) and 23km (M7.0).

Figure 3.5. Number of damaged building types for five AB06 earthquake scenarios.

Figure 3.6. Number of damaged buildings by occupancy classes for five AB06 earthquake scenarios.

masonry (93%) buildings, and both sustained significant damages. The building type and occupancy class with the least amount of damage are steel and educational buildings, as illustrated in Figures 3.5 and 3.6.

Analyzing the data in terms of vulnerability, the most vulnerable building type and occupancy class are masonry, and religious buildings. Traditionally during eastern Canadian earthquakes, masonry buildings experience the greatest amount of damage due to their lack of structural integrity (e.g. Bruneau and Lamontagne, 1994). The quality, strength, and performance of older masonry buildings are poor, as these building types are generally not anchored (Bruneau and Lamontagne, 1994). In the study area, 91% of the religious buildings are pre-code masonry buildings which may offer an explanation to their vulnerability.

The least vulnerable buildings are steel and governmental buildings. 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 results are surprising. In the absence of other evidence, it is suggested that the unexpected good performance of governmental buildings may be due to their location on shallow bedrock, where there is little to no soil amplification. Figure 3.7 and Figure 3.8 depict building type and occupancy class vulnerability based on the number damaged building types to the total

Figure 3.7. Building type vulnerability for five AB06 earthquake scenarios.

Figure 3.8. Occupancy class vulnerability for five AB06 earthquake scenarios.

number of those types (or classes) in the study area for five AB06 earthquake scenarios. A detailed discussion of building vulnerability is presented in Section 3.2.2.

Building height and seismic design levels were also examined. In all scenarios, low rise and pre-code buildings are the most vulnerable and experience the most damage. The natural frequency of a building is partly dependent on building height. Low-rise building damage is biased to short periods, hence their vulnerability; Section 3.2.2 provides a detailed discussion on the relationship between building height and damage. Pre-code buildings were not designed to withstand earthquake ground shaking in comparison to low-to-high code buildings. This provides an explanation for their vulnerability. Figure 3.9 and Figure 3.10 depict vulnerability according to building height and seismic design level for an M6.5 (R_{epi} 15km) scenario.

Building inventory – dissemination areas

Table 3.4 and Table 3.5 summarize building damages by damage state and building type on a dissemination area basis for the M6.5 (R_{epi} 15km) scenario; refer to Figure E.2 for the location of the ten dissemination areas within the study area. 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

Figure 3.9. Vulnerability according to building height for an AB06 M6.5 (R_{epi} 15km) scenario. HAZUS uses probabilities to determine a building count, the unknown slice represents intermediate damage probabilities.

Figure 3.10. Vulnerability according to seismic design level for an AB06 M6.5 (R_{epi} 15km) scenario.

Table 3.4 Building damage by damage state, with percent of the total inventory in brackets, for the AB06 M6.5 (R_{epi} 15km) scenario.

Area	None (%)	Slight (%)	Moderate (%)	Extensive (%)	Complete (%)	Total (%)
001	31 (5.2)	14(2.3)	7 (1.2)	1 (0.2)	0 (0.0)	22 (3.7)
002	113(18.9)	42(7.0)	33 (5.5)	7 (1.2)	1 (0.2)	83(13.9)
003	43 (7.2)	16(2.7)	11(1.8)	2 (0.3)	1 (0.2)	30(5.0)
004	65 (10.9)	27(4.5)	17(2.8)	4 (0.7)	1 (0.2)	49 (8.2)
005	58 (9.7)	21(3.5)	16(2.7)	3 (0.5)	0 (0.0)	40(6.7)
006	9 (1.5)	3 (0.5)	1 (0.2)	0 (0.0)	0 (0.0)	4 (0.7)
007	4 (0.7)	1 (0.2)	0 (0.0)	0 (0.0)	0 (0.0)	1 (0.2)
008	4 (0.7)	1 (0.2)	0 (0.0)	0 (0.0)	0 (0.0)	1 (0.2)
009	4 (0.7)	1 (0.2)	0(0.0)	0 (0.0)	0 (0.0)	1 (0.2)
010	3 (0.5)	0 (0.0)	0(0.0)	0 (0.0)	0 (0.0)	0(0.0)

Table 3.5. Building damage by building type, with percent of the total inventory in brackets for the AB06 M6.5 (R_{epi} 15km) scenario.

Area	Wood (%)	Concrete (%)	Steel (%)	Masonry (%)	Total (%)
001	8 (1.3)	0 (0.0)	0 (0.0)	14 (2.3)	22 (3.7)
002	18 (3.0)	18 (3.0)	0 (0.0)	47 (7.9)	83 (13.9)
003	7 (1.2)	3 (0.5)	0 (0.0)	20 (3.3)	30 (5.0)
004	1 (0.2)	9 (1.5)	1 (0.2)	38 (6.4)	49 (8.2)
005	0 (0.0)	20 (3.3)	3 (0.5)	17 (2.8)	40 (6.7)
006	0 (0.0)	3 (0.5)	1 (0.2)	0 (0.0)	4 (0.7)
007	0 (0.0)	1 (0.2)	0 (0.0)	0 (0.0)	1 (0.2)
008	0 (0.0)	1 (0.2)	0 (0.0)	0 (0.0)	1 (0.2)
009	0 (0.0)	1 (0.2)	0 (0.0)	0 (0.0)	1 (0.2)
010	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)	0 (0.0)

record the lowest amount of building damages with 7 (3%) damaged buildings.

Graphical representations of building damages on a dissemination area basis are presented in Figure 3.11 and Figure 3.12.

Debris generation

An estimation 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. In this study, default parameters of debris weight and structural and non-structural damage state information were utilized with the actual building inventory.

The two main sources of debris are structural and non-structural. A major source of structural debris is created by partially or completely collapsed buildings. Non-structural damage is typically damage to ceilings, mechanical and electrical equipment, broken glass panes, damage to partitions and exterior walls, etc. There are two main types of debris: Type 1, consisting of wood / masonry / other, and Type 2 consisting of concrete / steel. Examples of Type 1 debris are mounds of brick generated from failing unreinforced masonry (URM) buildings and other accumulated non-structural materials such as glass, furniture, etc. Examples of Type 2 debris are failed exterior cladding, failed

Figure 3.11. Histogram of building damage by damage state for each dissemination area for an AB06 M6.5 (R_{epi} 15km) scenario.

Figure 3.12. Graphical representation of building damage by damage state for an M6.5 (R_{epi} 15km) scenario (GIS data sources: Statistics Canada).

steel members, and stacked concrete slabs. 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.

Table 3.6. and Table 3.7. presents the amount of debris (Type 1, Type 2 and total) generated by each scenario. Scenarios M7.0 (R_{epi} 23km) and M6.5 (R_{epi} 15km) for both AB95 and AB06 create the most debris. The M7.0 (R_{epi} 23km) scenario creates approximately 305,000 and 247,000 tonnes of debris, while the M6.5 (R_{epi} 15km) scenario creates 213,000 and 102,000 tonnes of debris for the AB95 and AB06 scenarios, respectively. Scenarios M5.0 (R_{epi} 1km) and M5.0 (R_{epi} 5km) produce the least amount of debris, creating approximately 3,000 and 0 tonnes for each scenario.

Debris generation – dissemination areas

Debris generation is influenced by not only building type and square footage, but also NEHRP classes and the concentration of buildings within the 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, outlined on Table 3.8. Area 005 has the largest square footage (Figure 3.13) and is located on the most sensitive NEHRP class in the entire study area (Figure 2.14). A strong relationship also exists between debris generation and total amount of

Table 3.6. Amount of debris (Type 1, Type 2 and total) generated by each AB95 scenario.

Scenarios	Epi. Dist. (km)	Debris (in thous.tonnes)		
		Type 1	Type 2	Total
M5.0d0	1.0	2	1	3
M5.0d1	5.0	2	1	3
M5.5d0	1.0	11	12	23
M5.5d1	7.0	11	12	23
M6.0d0	1.0	40	73	113
M6.0d1	10.0	40	73	113
M6.0d2	27.5	6	6	13
M6.0d3	53.0	1	1	2
M6.5d1	15.0	63	150	213
M6.5d2	31.0	8	9	17
M6.5d3	56.5	7	6	13
M7.0d1	23.0	85	220	305
M7.0d2	38.5	32	61	93
M7.0d3	64.0	17	19	36

Table 3.7. Amount of debris (Type 1, Type 2 and total) generated by each AB06 scenario.

Scenarios	Epi. Dist. (km)	Debris (in thous. tonnes)		
		Type 1	Type 2	Total
M5.0d0	1.0	0	0	0
M5.0d1	5.0	0	0	0
M5.5d0	1.0	3	1	4
M5.5d1	7.0	2	1	3
M6.0d0	1.0	21	26	47
M6.0d1	10.0	13	11	24
M6.0d2	27.5	1	0	1
M6.0d3	53.0	0	0	0
M6.5d1	15.0	39	63	102
M6.5d2	31.0	6	3	9
M6.5d3	56.5	1	0	1
M7.0d1	23.0	78	169	247
M7.0d2	38.5	18	20	38
M7.0d3	64.0	4	2	6

Table 3.8. Debris generation by dissemination area, all values are per thousand tonnes for an AB06 M6.5 (R_{epi} 15km) scenario.

Area	Type 1	Type 2	Debris Total
001	0.93	0.49	1.41
002	10.03	8.56	18.58
003	1.39	2.12	3.52
004	15.60	13.31	28.91
005	10.32	29.21	39.52
006	0.24	5.53	5.77
007	0.07	1.08	1.15
008	0.15	1.21	1.36
009	0.21	0.85	1.06
010	0.02	1.01	1.03
Total	38.96	63.37	102.31

Figure 3.13. Distribution of square footage per dissemination area.

building damage in each area, as the areas with the most building damage are also the areas with the most debris. For example, areas 002, 004, and 005 are the areas that generate the greatest number of damaged buildings (Table 3.5) and the most debris (Table 3.8). The dissemination area with the least amount of debris is area 010, which contains only four buildings. Figure 3.14 outlines Type 1 and Type 2 debris generated from an AB06 M6.5 (R_{epi} 15km) scenario.

3.1.1.2 Social losses

HAZUS uses population statistics to calculate casualties at four severity levels at three times during the day. The three times of the day are night time (2:00am), daytime (2:00pm) and commuting time (5:00pm). The severity levels are level 1 (minor injuries), level 2 (serious but non-life threatening injuries), level 3 (serious and life threatening injuries) and level 4 (fatalities). Table 3.9 and Table 3.10 present projected casualties at 2:00am, 2:00pm, and 5:00pm for AB95 and AB06 scenarios. Appendix H presents a breakdown of casualties into the four severity levels by occupancy class at the three times for AB06 scenarios.

Casualties – night time (2:00am)

In all scenarios, the least amount of casualties occurs during the night time (2:00am), when the overall population within the study area is lowest. AB95 scenarios generate a

Figure 3.14. Average Type 1 and Type 2 debris for each dissemination area generated by an AB06 M6.5 (R_{epi} 15km) scenario (GIS data sources: Statistics Canada).

Table 3.9. Casualties for AB95 scenarios at 2:00am, 2:00pm and 5:00pm.

Scenario	Epi. Dist. (km)	Casualties - 2:00am				
		SEV 1	SEV 2	SEV 3	SEV 4	Total
M5.0d0	1.0	0	0	0	0	0
M5.0d1	5.5	0	0	0	0	0
M5.5d0	1.0	1	0	0	0	1
M5.5d1	7.0	1	0	0	0	1
M6.0d0	1.0	7	1	0	0	8
M6.0d1	10.0	7	1	0	0	8
M6.0d2	27.5	0	0	0	0	0
M6.0d3	53.0	0	0	0	0	0
M6.5d1	15.0	15	3	0	0	18
M6.5d2	31.0	2	0	0	0	2
M6.5d3	56.5	0	0	0	0	0
M7.0d1	23.0	21	5	0	1	27
M7.0d2	38.5	6	1	0	0	7
M7.0d3	64.0	2	0	0	0	2

Scenario	Epi. Dist. (km)	Casualties - 2:00pm				
		SEV 1	SEV 2	SEV 3	SEV 4	Total
M5.0d0	1.0	2	0	0	0	2
M5.0d1	5.5	2	0	0	0	2
M5.5d0	1.0	24	3	0	1	28
M5.5d1	7.0	24	3	0	1	28
M6.0d0	1.0	126	23	3	5	157
M6.0d1	10.0	126	23	3	5	157
M6.0d2	27.5	13	2	0	0	15
M6.0d3	53.0	2	0	0	0	2
M6.5d1	15.0	241	49	6	11	307
M6.5d2	31.0	48	8	1	1	58
M6.5d3	56.5	13	2	0	0	15
M7.0d1	23.0	377	83	11	21	492
M7.0d2	38.5	122	22	3	5	152
M7.0d3	64.0	37	6	1	1	45

Table 3.9. Continued.

Scenario	Epi. Dist. (km)	Casualties - 5:00pm				Total
		SEV 1	SEV 2	SEV 3	SEV 4	
M5.0d0	1	1	0	0	0	1
M5.0d1	5.5	1	0	0	0	1
M5.5d0	1	12	2	0	0	14
M5.5d1	7	12	2	0	0	14
M6.0d0	1	68	12	1	3	84
M6.0d1	10	68	12	1	3	84
M6.0d2	27.5	7	1	0	0	8
M6.0d3	53	1	0	0	0	1
M6.5d1	15	129	27	4	6	166
M6.5d2	31	26	4	0	1	31
M6.5d3	56.5	7	1	0	0	8
M7.0d1	23	203	45	8	11	267
M7.0d2	38.5	65	12	1	3	81
M7.0d3	64	19	3	0	1	23

Table 3.10. Casualties for AB06 scenarios at 2:00am, 2:00pm, and 5:00pm.

Scenario	Epi. Dist. (km)	Casualties - 2:00am				
		SEV 1	SEV 2	SEV 3	SEV 4	Total
M5.0d0	1.0	0	0	0	0	0
M5.0d1	5.5	0	0	0	0	0
M5.5d0	1.0	0	0	0	0	0
M5.5d1	7.0	0	0	0	0	0
M6.0d0	1.0	3	0	0	0	3
M6.0d1	10.0	2	0	0	0	2
M6.0d2	27.5	0	0	0	0	0
M6.0d3	53.0	0	0	0	0	0
M6.5d1	15.0	8	1	0	0	9
M6.5d2	31.0	0	0	0	0	0
M6.5d3	56.5	0	0	0	0	0
M7.0d1	23.0	22	4	0	1	27
M7.0d2	38.5	3	0	0	0	3
M7.0d3	64.0	0	0	0	0	0

Scenario	Epi. Dist. (km)	Casualties - 2:00pm				
		SEV 1	SEV 2	SEV 3	SEV 4	Total
M5.0d0	1.0	0	0	0	0	0
M5.0d1	5.5	0	0	0	0	0
M5.5d0	1.0	4	0	0	0	4
M5.5d1	7.0	2	0	0	0	2
M6.0d0	1.0	50	8	1	1	60
M6.0d1	10.0	28	4	0	1	33
M6.0d2	27.5	1	0	0	0	1
M6.0d3	53.0	0	0	0	0	0
M6.5d1	15.0	110	19	2	4	135
M6.5d2	31.0	9	1	0	0	10
M6.5d3	56.5	1	0	0	0	1
M7.0d1	23.0	299	63	8	15	385
M7.0d2	38.5	40	6	1	1	48
M7.0d3	64.0	6	1	0	0	7

Table 3.10. Continued.

Scenario	Epi. Dist. (km)	Casualties - 5:00pm				
		SEV 1	SEV 2	SEV 3	SEV 4	Total
M5.0d0	1.0	0	0	0	0	0
M5.0d1	5.5	0	0	0	0	0
M5.5d0	1.0	2	0	0	0	2
M5.5d1	7.0	1	0	0	0	1
M6.0d0	1.0	27	4	0	1	32
M6.0d1	10.0	13	2	0	0	15
M6.0d2	27.5	1	0	0	0	1
M6.0d3	53.0	0	0	0	0	0
M6.5d1	15.0	60	11	1	2	74
M6.5d2	31.0	5	1	0	0	6
M6.5d3	56.5	1	0	0	0	1
M7.0d1	23.0	164	36	7	8	215
M7.0d2	38.5	22	3	0	1	26
M7.0d3	64.0	3	0	0	0	3

greater amount of level 1 and 2 casualties. However, AB95 level 3 and 4 casualties are the same as those generated by the AB06 scenarios. At 2:00am, the greatest amount of casualties occurs in URM building types and in the residential occupancy class. The scenario which produces the most casualties is M7.0 (R_{epi} 23km), where a total of 27 casualties are recorded for both the AB95 and AB06 scenarios. In this study, night time casualties only occur in commercial and residential occupancy classes, and are lowest in wood and steel building types.

During the night, the majority of the population (90%) is located within their residences (Table 2.15). Residential buildings are dominated by masonry (URM) building types (Table 2.13a) which tend to be low-rise and pre-code buildings. The lack of structural integrity and vulnerability to short period ground-motions of residential URM buildings provide an explanation to the distribution of casualties during the night.

Casualties – daytime (2:00pm)

In all scenarios, the greatest amount of casualties occurs during the daytime (2:00pm). Similar to the night time events, AB95 scenarios generate the greatest number of casualties, but in this case, do so in all four severity levels. At 2:00pm, the greatest number of casualties occurs in URM buildings types and in commercial occupancy classes. Concrete building types also generate a significant portion of total casualties. The scenario creating the most casualties is M7.0 (R_{epi} 23km), where a total of 492 and

385 are recorded for AB95 and AB06 scenarios, respectively. Daytime casualties only occur in commercial and residential occupancy classes. The lowest number of casualties occurs in wood building types.

During the day, the majority of the population (99%) is located at their workplace. Commercial buildings are dominated by both masonry (URM) and concrete building types. As mentioned previously, URM buildings are extremely vulnerable to earthquake ground shaking. The majority of concrete buildings, however, not only have low-code seismic design levels (Table 2.13c) and but also contain a large percentage of square footage (Table 2.14). 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. Wood buildings are primarily residential building types where the population is lowest during the day, hence the lowest number of casualties. A detailed discussion on the behaviour of building types during ground shaking is described in Section 3.2.2.

Casualties – commuting (5:00pm)

A moderate number of casualties occur during the peak commuting hour (5:00pm). Similar to the daytime events, AB95 scenarios generate the greatest amount of casualties for all four severity levels. At 5:00pm, the greatest number of casualties occurs in URM buildings types and in commercial occupancy classes. A total of 4 to 5 casualties are

recorded as commuting casualties. The scenario generating the greatest number of casualties is M7.0 (R_{epi} 23km), where casualties are 267 and 215 for the AB95 and AB06 scenarios, respectively. The lowest number of casualties occurs in wood building types.

During the commuting hours, the majority of the population is still located at or near their workplace; therefore casualty results are similar to those recorded during the day. Additionally, there are 4 to 5 casualties recorded as “commuting casualties.” These casualties are likely due to the increased foot and vehicle traffic and falling debris.

Casualties – dissemination areas

At 2:00pm and 5:00pm, area 004 records the greatest number of casualties, followed closely by area 005. At 2:00am, however, area 004 and 002 record the most casualties. The least number of casualties occurs in areas 008 to 010. Table 3.11 is a tabular summary of casualties at each severity at 2:00pm. Figure 3.15 and Figure 3.16 are graphical depictions of casualties at each severity level and per building type. A relation exists between the population of the dissemination areas (Table 2.16) and the number of casualties (Table 3.11), and is further discussed in Section 3.2.2.

Table 3.11. Casualties at the dissemination area level for an AB06 M6.5 (R_{epi} 15km) scenario at 2:00pm.

Area	Severity 1	Severity 2	Severity 3	Severity 4	Total
001	3	1	0	0	4
002	15	3	0	1	19
003	3	1	0	0	4
004	44	7	1	1	53
005	42	7	1	2	52
006	2	0	0	0	2
007	1	0	0	0	1
008	0	0	0	0	0
009	0	0	0	0	0
010	0	0	0	0	0
Total	110	19	2	4	135

Figure 3.15. Casualties for each severity level for an AB06 M6.5 (R_{epi} 15km) scenario at 2:00pm (GIS data sources: Statistics Canada).

Figure 3.16. Histogram of casualties by building type for an AB06 M6.5 (R_{epi} 15km) scenario at 2:00pm.

3.1.1.3 Direct economical losses

Two groups of economical losses exist. The first group consists of losses ensued directly from building damage which includes cost of repair and replacement of a damaged building, and cost of damage and losses to building contents. The second group consists of consequential and non-operational losses which include relocation expenses, and income, wage and rental losses. In this study, only the cost of repair and replacement of a damaged building from group 1 was computed. These values were calculated using the square footage of each building and applying the default cost table available in HAZUS methodology (FEMA and NIBS, 2006b). These figures do not include intrinsic or downtown real estate market values. Note that HAZUS' PGA-based loss estimates are calibrated based on experience in California, where PGA has a somewhat different character and is richer in lower frequencies - and has lower values. Thus some of the PGA-based aspects of loss estimation in HAZUS may not be applicable in eastern North America.

Table 3.12 and Table 3.13 present the direct economical losses for estimated building repair and replacement costs (due to structural and non-structural damage). The direct economical losses for both ground-motion relations tend to fluctuate. The greatest direct economic losses are recorded in concrete building types and in commercial occupancy classes. The scenario with the greatest direct economic loss is M7.0 (R_{epi} 23km), with a total of over \$215 and \$365 million, for AB95 and AB06 scenarios, respectively. The

Table 3.12. Summarizes a direct economical losses breakdown between structural damage and non-structural damage (in brackets) for the AB95 scenarios (measured in millions of dollars).

Scenario	Epi. Dist. (km)	Direct economical losses (in \$M)			
		Residential	Commercial	Others	Total
M5.0d0	1.0	0.05 (3.03)	0.45 (11.67)	0.02 (0.60)	15.82
M5.0d1	5.5	0.05 (3.03)	0.45 (11.67)	0.02 (0.60)	15.82
M5.5d0	1.0	0.43 (7.60)	4.62 (30.99)	0.18 (1.50)	45.32
M5.5d1	7.0	0.43 (7.60)	4.62 (30.99)	0.18 (1.50)	45.32
M6.0d0	1.0	2.80 (19.03)	21.01 (76.23)	0.82 (3.63)	123.52
M6.0d1	10.0	2.75 (18.55)	21.04 (75.67)	0.79 (3.53)	122.33
M6.0d2	27.5	0.21 (2.74)	2.59 (11.39)	0.10 (0.59)	17.62
M6.0d3	53.0	0.04 (0.61)	0.38 (2.38)	0.02 (0.12)	3.55
M6.5d1	15.0	6.30 (25.31)	37.01 (95.40)	1.48 (4.62)	170.12
M6.5d2	31.0	1.04 (5.28)	8.54 (22.58)	0.35 (1.13)	38.92
M6.5d3	56.5	0.23 (1.63)	2.70 (7.22)	0.10 (0.38)	12.26
M7.0d1	23.0	7.98 (28.50)	53.81 (117.79)	2.06 (5.51)	215.65
M7.0d2	38.5	2.71 (9.60)	19.97 (40.49)	0.80 (2.02)	75.59
M7.0d3	64.0	0.86 (3.08)	6.64 (12.97)	0.29 (0.69)	24.53

Table 3.13. Summarizes a direct economical losses breakdown between structural damage and non-structural damage (in brackets) for the AB06 scenarios (measured in millions of dollars).

Scenario	Epi. Dist. (km)	Direct economical losses (in \$M)			
		Residential	Commercial	Others	Total
M5.0d0	1.0	0.00 (4.89)	0.03 (22.42)	0.00 (1.08)	28.42
M5.0d1	5.5	0.00 (3.84)	0.02 (17.64)	0.00 (0.86)	22.36
M5.5d0	1.0	0.10 (13.75)	0.68 (53.10)	0.04 (2.78)	70.45
M5.5d1	7.0	0.07 (10.49)	0.40 (42.99)	0.02 (2.19)	56.16
M6.0d0	1.0	1.52 (33.68)	8.56 (120.60)	0.41 (6.26)	171.03
M6.0d1	10.0	0.74 (22.10)	4.34 (82.05)	0.23 (4.31)	113.77
M6.0d2	27.5	0.05 (1.55)	0.24 (7.92)	0.01 (0.37)	10.14
M6.0d3	53.0	0.00 (0.06)	0.03 (0.38)	0.00 (0.02)	0.49
M6.5d1	15.0	3.71 (43.33)	17.56 (147.68)	0.87 (7.83)	220.98
M6.5d2	31.0	0.28 (4.22)	1.61 (20.76)	0.09 (1.01)	27.97
M6.5d3	56.5	0.05 (0.40)	0.25 (1.92)	0.02 (0.10)	2.72
M7.0d1	23.0	8.81 (71.31)	41.30 (229.84)	2.01 (12.37)	365.64
M7.0d2	38.5	1.21 (9.05)	6.97 (37.56)	0.34 (1.95)	57.08
M7.0d3	64.0	0.16 (1.23)	1.03 (5.89)	0.06 (0.31)	8.68

lowest amount of direct economic losses occurs in scenario M6.0 (R_{epi} 53km), at \$3.5 million and \$0.5 million for AB95 and AB06 scenarios, respectively.

The fluctuations between AB95 and AB06 direct economical losses as well as the breakdown in structural and non-structural losses are related to PGA. These fluctuations are associated with the two different procedures used in the classification of soils and the calculation of soil amplification. The more site-specific procedure used to calculate soil amplifications for implementation with the AB06 scenarios may lead to overly conservative estimates of PGA in some NEHRP B soil polygons (discussed in Chapter 2); thus there is likely to be an overestimation of direct economical losses in the AB06 scenarios as implemented here.

Differences in economical losses exist between residential and commercial buildings. The distribution of occupancy classes is residential (33.5%), commercial (60%) and other (6.5%), while the distribution of economical losses is residential (15%), commercial (82%) and other (3%). Economical losses are related to total square footage. According to Section 2.3, (1) the majority of commercial buildings are masonry and concrete building types, and (2) square footage is dominated by concrete buildings. The dominance of square footage in commercial buildings increases the likelihood of building damage, resulting in greater economical losses.

The non-structural economical losses are greater than structural economical losses. Non-structural damage includes damage to ceilings, essential equipment (electrical and

mechanical), piping, elevators, partitions, exterior walls, windows, etc. To some extent, this can be explained by the lack adequate anchorage and restraints in building design (McKevitt et al., 1995). For example, the 1994 Northridge earthquake resulted in the failure of several non-structural components which led to fatalities, numerous casualties, and billions of dollars in economical damages (McKevitt et al., 1995). Significant non-structural losses were even recorded in buildings when little or no structural damage was observed (McKevitt et al., 1995).

Direct economical damage – dissemination areas

The area with the greatest amount of economical losses is area 005 with a loss estimation of approximately \$91 million (41% of total economical losses). The areas incurring the least amount of economic loss are areas 007 to 010 which total \$8.7 million (4.0%). Table 3.14 and Figure 3.17 outline direct economical losses (for structural and non-structural damages only) for an AB06 M6.5 (R_{epi} 15km) scenario.

As previously mentioned, direct economical losses are related to square footage. The results are in good agreement with Table 2.14. These total losses are somewhat expected due to (1) a dense number of buildings, (2) the presence of extremely vulnerable building types and occupancy classes, and (3) the building height with respect to square footage. In perspective, the 1994 Northridge earthquake which occurred in a modern North

Table 3.14. Summary of direct economical losses (listed in millions of dollars) for each dissemination area for an AB06 M6.5 (15km) scenario.

Area	Total (\$M)
001	12.5
002	47.0
003	7.7
004	41.4
005	90.6
006	12.9
007	2.6
008	2.2
009	2.2
010	1.7
Total	221.0

Figure 3.17. Average direct economical losses for each dissemination area from an AB06 M6.5 (R_{epi} 15km) scenario (GIS data sources: Statistics Canada).

American city with a similar magnitude incurred an estimated \$13B to \$26.5B in economical losses (FEMA and NIBS, 2001; USGS, 2008).

3.1.2 Functionality losses

HAZUS can estimate the loss-of-function and the restoration times for critical facilities and utility lifelines. In this study, there are four critical facility types: medical care facilities, emergency centres, schools, and military installations. There are also two utility types: electrical power facilities, and communication facilities and transmitters. Functionality estimates are expressed in terms of percent functionality for a number of days after an earthquake, including days 1, 3, 7, 14, 30 and 90.

Appendix I depict loss-of-function times versus restoration times for medical care facilities, emergency centres, schools, military installations, electrical power facilities and communication facilities and transmitters for five AB06 earthquake scenarios. A summary of loss-of-function times for an AB06 M6.5 (R_{epi} 15km) scenario is presented in Figure 3.18.

Medical care facilities and emergency centres demonstrate similar functionality losses. Functionality percentages are below 50% on day 1 for scenarios M6.5 (R_{epi} 15km) (AB95 only) and M7.0 (R_{epi} 23km) for medical care facilities and below 50% on day 1 for

Figure 3.18 Summary of loss-of-function times for critical facilities and utilities, for an AB06 M6.5 (R_{epi} 15km) scenario.

scenario M7.0 (R_{epi} 23km) for emergency centres. Functionality percentages are below 75% on day 1 for scenarios M6.0 (R_{epi} 1km), M6.0 (R_{epi} 10km) (AB95 only), M6.5 (R_{epi} 15km), and M7.0 (R_{epi} 38km) for medical care facilities and only scenario M6.5 (R_{epi} 15km) for emergency centres. After day 30, functionality is above 85% for all scenarios.

The facilities which exhibit the lowest functionality percentages on day 1 are schools and military installations. Functionality is below 50% on day 1 for scenarios M6.5 (R_{epi} 15km) (AB95 only) and M7.0 (R_{epi} 23km) for both schools and military installations. Functionality is below 75% on day 1 for scenarios M6.0 (R_{epi} 1km), M6.0 (R_{epi} 10km) (AB95 only), M6.5 (R_{epi} 15km) (AB06 only) and M7.0 (R_{epi} 38km). The most severe scenario is M7.0 (R_{epi} 23km), where functionality is approximately 32% for both schools and military installations. Functionality increases gradually to above 50% at day 7 and approximately above 85% at day 30, with the exception of the AB06 M7.0 (R_{epi} 23km) scenario for military installations which is measured at 84%.

In this study, the utility lifelines have shorter restoration times, that is, it takes less time to fully restore the damaged facility. At day 1, the only scenario with functionality (for electrical facilities) below 50% is scenario M7.0 (R_{epi} 23km). Functionality is below 75% at day 1 for scenarios M6.0 (R_{epi} 1km) (AB95 only), M6.0 (R_{epi} 10km) (AB95 only), M6.5 (R_{epi} 15km) and M7.0 (R_{epi} 38km) (AB95 only). After day 7, functionality is above 85% for all scenarios. Communication facilities and transmitters have functionality above

85% at day 1 for all scenarios with the exception of scenario M7.0 (R_{epi} 23km) where functionality is at 82% and 79% for the AB95 and AB06 scenarios, respectively.

3.1.3 Extent of induced hazards

Induced hazards include liquefaction and landslides; hazard maps were developed in Chapter 2. In all scenarios, no additional losses were recorded due to either liquefaction or landslides. To verify that the program was correctly reading the hazard maps, worst case scenario liquefaction maps were input into the program using the same earthquake scenario information. The worst case scenario liquefaction hazard map exhibited a class 5 for the artificial fill area, and a class 2 for the remainder of the study area. There was a significant increase in losses, verifying that the HAZUS program was correctly reading the user-supplied hazard maps.

3.2 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). Before recommendations in disaster management can be proposed, it is necessary to understand hazard and vulnerability, and how they influence loss estimations. For earthquake loss estimations, the two influential aspects are the natural and urban environments. The natural

environment comprises all non-anthropogenic components and processes, including, for example, geological units and earthquakes. The urban environment comprises anthropogenic and social components including, for example, zoning practices, construction and use of buildings.

The subsequent sections present a discussion on the influences of the natural and urban environments on losses, and on the implications of losses in response and recovery strategies in the context of a moderate-to-large earthquake striking the City of Ottawa. A simple validation of the integrity of the results of HAZUS is also attempted.

3.2.1 Influences of the natural environment on losses

The most important variables which influence losses in the natural environment are ground-motion, which is a function of earthquake magnitude and distance, and site condition. The amount of physical damage depends strongly on ground-motion. This is reflected in the results; (1) the M7.0 (R_{epi} 23km) scenario had the greatest amount of losses and M5.0 (R_{epi} 5km) had the least amount of losses (Table 3.1. and 3.2.). (2) In general, AB95 losses exceed AB06 losses because AB95 ground-motion inputs are richer in short period motions (Appendix B), which are damaging in particular to low-rise unreinforced masonry buildings. Appendix B summarizes the AB95 and AB06 ground-motions used in, and computed from, HAZUS.

Local site conditions play a significant role on loss estimations. NEHRP C and D soils are found in a portion of area 005, as shown in Figure 3.19. Results show that this area had the third highest amount of building damage (Table 3.5), second highest in Type 1 debris generation (Table 3.8) and number of casualties (Table 3.11), and first in Type 2 and total debris generation (Table 3.8).

Furthermore, earthquake-induced hazards such as liquefaction and landslides are influenced by the natural environment. Neither were observed in this study; based on HAZUS methodology and local geology, the risk is negligible.

3.2.2 Influences of the urban environment on losses

In earthquake loss estimation studies, the main factor which influences losses in the urban environment is building types. Building types differentiate building behaviour during ground shaking; various building types have substantially different damage and loss characteristics (FEMA and NIBS, 2006a). Building types, seismic design levels, and building height affect building behaviour, as discussed below.

Figure 3.19. Building inventory location for area 005 (grey area) with respect to NEHRP classes (GIS data sources: City of Ottawa, NRCan).

Building type - URM buildings

The building type experiencing the greatest amount of losses was 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. Hairline cracks begin to emerge in walls and in parapets; as shaking intensifies, larger cracks and separation from the diaphragm becomes apparent, finally out-of-plane failures occur, joints and beams slip from their foundations and there is an imminent danger of building failure (Bruneau and Lamontagne, 1994; FEMA and NIBS, 2006b). This behaviour 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 Temiscaming 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).

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 casualties recorded 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.

Building type – concrete buildings

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 of 64% of calculated square footage in the study area and therefore have a greater exposure to losses in terms of total area (Table 2.14). 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). Exterior cladding of brick and terra cotta on older concrete buildings can spell off during ground shaking (FEMA and NIBS, 2006a). In modern concrete buildings, a popular architectural feature is exterior glass panes or “glass buildings,” that when exposed to intense ground shaking can shatter. The above aspects can account for the high number of casualties in commercial (and concrete) buildings recorded in the earthquake scenarios.

Building type – wood buildings

Wood buildings are one of 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.

Building type – steel buildings

Steel buildings also experience the least amount of damage and are the least vulnerable building type. 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 recorded in steel buildings is likely due to the reliability of the steel frame during ground shaking.

Building height

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

$$T_a = 0.1N \quad [3.1]$$

Where N is the number of storeys (Saatcioglu and Humar, 2003). High-rise buildings (> 8 storeys) are sensitive to long period shaking ($> 0.8s$), while low-rise buildings (< 3 storeys) are sensitive to short period shaking ($< 0.3s$). In general, moderate events (M5.0 to M6.5) radiate short-period waves, but they attenuate quickly with distance. Large events ($> M7.0$) radiate significant long-period waves, which travel efficiently over significant distances. In this study, low-rise buildings experience greater damage (Figure 3.9) than buildings that are medium- and high-rise, which is consistent with what is expected for the moderate events that dominate hazard.

Occupancy classes

Occupancy class does not affect building damage, as occupancy is the designation of building use, however it does affect the number of casualties. As illustrated in Figure 3.5, the greatest damage occurred to masonry and concrete buildings which dominate commercial occupancies. Considering that the greatest amount of damage occurs in these two building types, it can be deduced that the population in these buildings would incur the most casualties. The results support this deduction as at least 90% of casualties occur in URM and concrete buildings. The number of casualties is greatest during the daytime, when a working population of greater than 76,000 is expected to be in the study area.

Occupancy classes – governmental and residential buildings

The least vulnerable occupancy classes were residential and governmental buildings. Vulnerability in occupancy classes is influenced by the distribution of its building type. Compared to commercial buildings, residential buildings have 18.5% more wood and steel building types (Table 2.13a) which experience the least amount of physical damage due to their flexible and durable frames. This may offer an explanation as to why residential buildings are least vulnerable to damage. Governmental buildings are not only dominated by URM buildings (65%) and concrete buildings (30%), but 74% have a pre-code seismic design level, which suggest that these buildings should incur a greater amount of damage. A likely explanation for their good performance in the scenarios is that they are located on shallow bedrock and experience less soil amplification than in other dissemination areas.

Occupancy classes –religious and non-profit organizations buildings (churches) and educational buildings (schools)

Religious buildings are the most vulnerable to damage due to their building type (URM) and seismic design level (pre-code). The vulnerability of religious buildings has been observed in previous eastern Canadian earthquakes. For example, in the 1925 Charlevoix–Kamouraska earthquake, a URM church was moderately damaged by out-of-plane failure of its gable and cracks in the wall (Bruneau and LaMontagne, 1994).

Educational buildings are also vulnerable to damage because they are dominated by URM building types. For example, the 1944 Cornwall–Massena earthquake damaged the local URM high school when falling masonry destroyed the gymnasium (Bruneau and Lamontagne, 1994). In this study, the number of casualties is unknown because the number of students for each educational facility was not tallied.

Functionality

Functionality is determined by the use of restoration curves embedded in the program. The two main classifications of curves that exist are social function classifications and specialized utility function classifications. Figure 3.20 illustrates the average loss-of-function times of critical facilities and utilities for an AB06 M6.5 (R_{epi} 15km) scenario. In this study, functionality and restoration times for essential facilities and high potential loss facilities did not perform as well as, and were not restored as quickly as utilities. Several utility classes follow specialized curves because they are essential elements in post-earthquake response planning (FEMA and NIBS, 2006a). This offers a potential explanation as to the discrepancy between the two curves.

Figure 3.20. Average loss-of-function curves for critical facilities and utilities for an AB06 M6.5 (R_{epi} 15km) scenario.

3.2.2.1 NY1 default inventory analysis

To investigate whether or not the sidewalk survey (actual inventory) was justified, a series of AB06 scenarios were run using the NY1 default inventory provided with the HAZUS program. The NY1 inventory is representative of the general building distribution of New York State; further details on the NY1 inventory are presented in Section 2.3. Table 3.15 summarizes the NY1 scenario results of various damage states and severity levels. Table 3.16 compares HAZUS loss estimations from the actual inventory with that using the default inventory (both for AB06 motions).

FEMA and NIBS (2001) reports that user-supplied data in HAZUS better matches documented data, and are therefore more reliable than default data. In all scenarios, the NY1 inventory underestimates building damages and its relative damage states, with the exception of the M5.0 (R_{epi} 5km) scenario. The underestimation is likely due to the distribution of building types in the NY1 inventory, as depicted in Figure 2.17. In the NY1 inventory, 64% of the building types are steel and wood; in reality these building types constitute only 20%. Steel and wood tend to perform well during earthquake ground shaking. By contrast, the estimated casualties are higher for the NY1 inventory, perhaps due to the distribution vulnerable building types and their characteristics.

The NY1 inventory underestimates building damage in every dissemination area relative to the actual inventory, as shown in Table 3.17. However, casualty results fluctuate

Table 3.15. Number of damaged buildings and building vulnerability for the NY1 building inventory.

Scenario	Epi. Dist. (km)	Building Damage – NY1					Total Damaged Buildings
		None (%)	Slight (%)	Moderate (%)	Extensive (%)	Complete (%)	
M5.0d0	1.0	596	1	0	0	0	1
		(99.8)	(0.2)	(0.0)	(0.0)	(0.0)	(0.2)
M5.0d1	5.5	596	1	0	0	0	1
		(99.8)	(0.2)	(0.0)	(0.0)	(0.0)	(0.2)
M5.5d0	1.0	568	21	7	1	0	29
		(95.1)	(3.5)	(1.2)	(0.2)	(0.0)	(4.9)
M5.5d1	7.0	579	14	4	0	0	18
		(97.0)	(2.3)	(0.7)	(0.0)	(0.0)	(3.0)
M6.0d0	1.0	452	89	46	9	1	145
		(75.7)	(14.9)	(7.7)	(1.5)	(0.2)	(24.3)
M6.0d1	10.0	501	62	29	5	0	96
		(83.9)	(10.4)	(4.9)	(0.9)	(0.0)	(16.1)
M6.0d2	27.5	586	8	3	0	0	11
		(98.5)	(1.3)	(0.5)	(0.0)	(0.0)	(1.8)
M6.0d3	53.0	596	1	0	0	0	1
		(99.8)	(0.2)	(0.0)	(0.0)	(0.0)	(0.2)
M6.5d1	15.0	359	127	86	22	3	238
		(60.1)	(21.3)	(14.4)	(3.7)	(0.5)	(39.9)
M6.5d2	31.0	539	40	15	3	0	58
		(90.3)	(6.7)	(2.5)	(0.5)	(0.0)	(9.7)
M6.5d3	56.5	585	9	3	0	0	12
		(98.0)	(1.5)	(0.5)	(0.0)	(0.0)	(2.0)
M7.0d1	23.0	222	152	151	58	14	375
		(37.2)	(25.5)	(25.3)	(9.7)	(2.3)	(62.8)
M7.0d2	38.5	463	83	42	8	1	134
		(77.5)	(13.9)	(7.0)	(1.3)	(0.2)	(22.4)
M7.0d3	64.0	559	28	9	1	0	38
		(93.9)	(4.7)	(1.5)	(0.2)	(0.0)	(6.4)

Table 3.16 Comparison of physical and social losses for the actual (AB06) versus the default (NY1) inventories for all scenarios at 2:00pm.

Scenario	Epi. Dist. (km)	Building Damage		Casualties	
		AB06	NY1	AB06	NY1
M5.0d0	1.0	2	1	0	0
M5.0d1	5.0	1	1	0	0
M5.5d0	1.0	30	29	4	8
M5.5d1	7.0	20	18	2	5
M6.0d0	1.0	168	145	60	81
M6.0d1	10.0	112	96	33	44
M6.0d2	27.5	14	11	1	3
M6.0d3	53.0	2	1	0	0
M6.5d1	15.0	265	238	135	184
M6.5d2	31.0	60	58	10	19
M6.5d3	56.5	14	12	1	3
M7.0d1	23.0	395	375	385	531
M7.0d2	38.5	149	134	48	72
M7.0d3	64.0	41	38	7	13

Table 3.17. Comparison of physical and social losses for the actual (AB06) versus the default (NY1) inventories at the dissemination area level for an M6.5 (R_{epi} 15km) scenario.

Area	Building Damages		Casualties	
	AB06	NY1	AB06	NY1
001	22	16	4	3
002	83	77	19	15
003	30	23	4	4
004	49	42	53	66
005	40	37	52	85
006	4	3	2	9
007	1	1	1	1
008	1	1	0	0
009	1	1	0	1
010	0	0	0	1

between under- and overestimations, shown in Table 3.17. A possible explanation for these fluctuations is the distribution of building types in the NY1 inventory within each area.

In summary, it is beneficial to perform a sidewalk survey and input a user-supplied inventory, though the default inventory provides a good initial estimate. In disaster management, an underestimation of potential losses will lead to a lack of preparedness amongst emergency coordinators and first responders.

3.2.3 Managing losses

The City of Ottawa has created a comprehensive Emergency Program / plan, the highest level of emergency management programs in Ontario. The City of Ottawa Emergency Plan (City of Ottawa, 2004) involves substantial inter-agency cooperation. For example, under the health care services category, it is the joint responsibility of the paramedic service, hospitals, fire service and public health to participate, maintain and provide health care to victims.

Since the adoption of the comprehensive Emergency Program, the City approved a 5 year, \$7.1M emergency management program, which includes the development of a Vulnerability Analysis Report (Multi Risk Strategies, 2003). This poorly substantiated report outlines the top 10 threats to the City of Ottawa, where earthquakes are ranked

second in terms of public safety risk. In this report, the earthquake scenario is defined as “an earthquake with a magnitude 5 on the Richter scale with the epicentre within a 50 km radius of the City of Ottawa.” The report also describes the consequences of this scenario; human casualties, including fatalities, collapsed buildings and bridges, disruption to utilities, and millions of dollars of repairs. Multi Risk Strategies (2003) failed to explain the methodology that was used to derive their results, therefore their results can not be reproduced or challenged by other scientists. However, the consequences projected for an event of M5.0 at an epicentral distance of 50 km are clearly unrealistic based on general experience.

This project uses a credible, tested and comprehensive quantitative methodology to determine earthquake loss estimations. The results of this research project show that for scenario M5.0 (R_{epi} 1km), the closest M5.0 scenario to the study area, only two URM buildings are slightly damaged, no casualties are reported and the functionality of critical facilities and utilities is no less than 99%. The scenario that would better fit consequences described in Multi Risk Strategies (2003) would be M6.0 (R_{epi} 1km) or M6.5 (R_{epi} 15km).

Moderate historical earthquakes in eastern North America have caused relatively little damage, largely due to their occurrence away from major population centres. For example the 2002 M5.0 Au Sable Forks earthquake occurred 10km from the small community of Au Sable in upper state New York, but hundreds of kilometres from major cities. It caused slight damage (cracked walls, toppled chimneys, etc.) locally to

buildings and utilities were restored within 10 hours (Pierre and Lamontagne, 2004).

A second example was the 1988 $M_s 5.7$ Saguenay, Québec. No major structural damage or fatalities occurred as a result of this earthquake, however, significant damage to URM buildings (collapsed chimneys, etc.) and non-structural damage (fallen ceiling tiles, etc.) to several building types was reported in Chicoutimi (epicentral distance of approximately 35km) (Mitchell et al., 1990). Quebec City (epicentral distance of approximately 150km) also reported damage from this earthquake which was localized to soft soil deposits and included a partial failure of a masonry wall, cracked walls and the derailment of an elevator from its vertical guide rails (Mitchell et al., 1990).

Managing losses in the City of Ottawa – scenario $M6.5$ (R_{epi} 15km) (2:00pm)

Managing losses generated by a moderate-to-large earthquake in Ottawa is a significant and daunting task. The following discussion is focussed on managing losses for a daytime $M6.5$ (R_{epi} 15km) scenario, by interpreting and extrapolating techniques and results from the study area across the City of Ottawa.

A dominant factor in the calculation of losses is ground-motion, which can be amplified or de-amplified by near surface sediments. The majority of the study area is located on NEHRP B, a particularly firm soil where little amplification is generated, depicted in Figure 2.14. The loss estimations generated for the study area provide a false impression of optimism, in that soils present in other regions of Ottawa are poorly-consolidated, as

illustrated in Figure 3.21, and are classed as NEHRP C, D and E. Table 3.18 and Figure 3.22 show the increase in losses from the NEHRP B, the dominant site classes of the study area, to NEHRP E for an M6.5 (R_{epi} 15km) scenario. Note that heavy losses (extensive and complete damage levels) increase dramatically when NEHRP classes shift from firm to soft soils. Although no specific earthquake loss estimation studies have been performed in other areas of Ottawa, Table 3.18 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.). Note that the study area comprises of 10 dissemination areas, while the National Capital Region comprises of over 1,700 dissemination areas; thus this study considers damage potential for a very limited sample of the city.

Emergency response - deployment

The performance of emergency crews is a crucial aspect in emergency response efforts. The first obstacle encountered is whether they are physically able to be deployed. For example, a relevant question would be, “did the building, equipment or personnel experience losses?” There are no police, fire or paramedic facilities in the study area; the following interpretations are based on NEHRP classes and likely building design and layout. NEHRP classes were determined using similar methods to those explained in Section 2.2.3.2.

Figure 3.21. Soil conditions in City of Ottawa. The colours reflect the soil type and shades represent soil depth. Dark green and yellow shades are likely to be poorly-consolidated soil (GIS data sources: Natural Resources Canada, Statistics Canada).

Table 3.18. Projected damages to study area when NEHRP soil class is changed from B to E for an M6.5 (R_{epi} 15km) scenario. For simplicity the AB95 default option was used, where a uniform NEHRP class could be selected for the entire study area.

	Physical Losses			Social Losses		Economical Losses
	Light	Heavy	Debris	Non-serious	Serious	Direct
NEHRP B	283	48	213	290	17	\$170
NEHRP C	339	102	339	538	39	\$255
NEHRP D	339	173	589	1065	92	\$399
NEHRP E	276	287	1071	2285	229	\$724

Figure 3.22. Histogram comparing of building damage for varying NEHRP classes for a M6.5 (R_{epi} 15km) scenario.

Emergency response – deployment of fire services

There are over 40 fire service facilities, including station houses, administrative and training facilities in the City of Ottawa. In this discussion, NEHRP classifications were determined for the location of 13 fire service facilities across the City of Ottawa (GIS data source: Regional Municipality of Ottawa-Carleton). Approximately 31% are located each on NEHRP B and C, 23% on NEHRP A, and 15% on NEHRP D. The behaviour of the building is dependent on the building type and layout. Considering that 85% of these fire stations are located on rock (NEHRP A and B), probable damage would likely be non-structural such as fallen light fixtures and pieces of equipment, as well as possible misalignment of the vehicle bay doors. There is a strong possibility that the majority of fire crews would be available to participate in emergency response efforts.

Emergency response – deployment of police services

There are over 40 policing facilities, including both police and community police stations in the City of Ottawa. In this discussion, NEHRP classifications were determined for the location of 19 policing facilities across the City of Ottawa (GIS data source: Regional Municipality of Ottawa-Carleton). Approximately 32% are located each on NEHRP A and B, 26% on NEHRP D, and 5% each on NEHRP C and E. The three main police headquarters are located on NEHRP D. If vehicle parking lots are located outdoors, there is a good possibility that police vehicles and equipment would be relatively undamaged and available for emergency response efforts. The number of casualties to members of

the police department is unknown. If members are outside the police stations (for example on patrol), then there is a good possibility that several police crews would be available to participate in emergency response efforts.

Emergency response – deployment of ambulance services

There are over 15 ambulance bases in the City of Ottawa. NEHRP classifications were determined for the location of 6 ambulance bases (GIS data source: Regional Municipality of Ottawa-Carleton). Approximately 50% are located on NEHRP B, 33% are located on NEHRP A and 17% on NEHRP E. Damage to vehicles and equipment would be similar to those experienced in the fire stations. There is a good possibility that the majority of ambulance crews would be able to respond immediately; delays in response are possible for bases located on NEHRP E.

Emergency response – en route

A second obstacle experienced by the emergency responders would be en route to the scene(s) as roadways and bridges may be impassable. Depending on the intensity of ground shaking and building type, enormous amounts of debris may be produced. In the study area, it is estimated that approximately 102,000 tonnes of debris could be produced, 38% of which will be Type 1 (brick, wood and other). The average size dump truck can carry a maximum of 17.5 tonnes. This amounts to over 2,200 of truckloads of Type 1

debris from the study area alone. Larger equipment is needed to remove Type 2 debris, which comprises 62% of the total. If Type 2 debris can be removed using the average sized dump truck then it would require at least 3,600 truckloads, totalling at least 5,800 truckloads of debris from the study area alone. The City of Ottawa Emergency Plan identifies Public Works and Fire Services as those responsible in clearing roadways.

The accessibility to the emergency scene(s) can also be affected by bridge damage. There are five bridges within the study area. Bruneau (1990) observed that bridge damage reported in the 1989 Loma Prieta, California, earthquake was directly pertinent to Canada, as older Canadian bridges were built with pre-code seismic design levels. In the study area, three bridges were built pre-1950 and only one has been recently remodelled. Ottawa comprises of several small neighbourhoods including Old Ottawa South and Lower Town that are only accessible by bridges. Emergency responders may encounter difficulty accessing these neighbourhoods if the structural integrity any of the bridges leading into the neighbourhood is compromised.

Emergency response – hindrances to rescue operations

During a large scale disaster, additional obstacles may hinder rescue operations which include earthquake-induced fire ignitions, water main damage, and unexpected inundation.

HAZUS has the capability to model the number of fires ignited following an earthquake, but this was not modelled in this research project. After the 1994 Northridge earthquake, which measured M6.7, approximately 110 fires were initiated. Therefore, it is reasonable to assume that fires may be initiated in the M6.5 (R_{epi} 15km) scenario and hinder rescue operations, but it is not known how many fires would be in the study area. The availability of water will play a major role in fire suppression activities. HAZUS can also calculate potable water facility and pipeline damage, which is another factor that was not modelled in this research project. Damages to water mains will impair fire suppression, but Ottawa has several waterways which could be drafted from. Note that the historic lock systems are not modelled, as only dams and levees can be modelled in HAZUS. In Ottawa, lock failure may result in the outpouring of water from Mooney's Bay into the Rideau Canal or River, or the outpouring the Rideau River or Canal into the Ottawa River, which may result in localized inundation, further hampering rescue efforts.

Emergency response – high priority rescue operations

One of the most important response operations will be to schools. Worldwide, including North America, schools experience a disproportionate amount of damage during earthquakes (Monk, 2007). For example, the 1933 Long Beach, California, earthquake severely damaged 120 schools, including 70 collapses, the 1952 Kern County, California, earthquake damaged 20 including 1 complete collapse, and the 1944 Cornwall–Massena earthquake which damaged the local high school when falling masonry destroyed the

gymnasium (Bruneau and Lamontagne, 1994; Monk, 2007). In several cases, schools experience the greatest amount of damage within the affected area. 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. Numerous examples of school collapses exist for both occupied and unoccupied schools during an earthquake. North America, however, has never experienced a damaging earthquake during school hours. This has led to a sense of complacency among North American engineers and other key officials (Monk, 2007).

The functionality of schools in the study area is 51.5% after day 1; if these schools were located on NEHRP E, the functionality would be only 2%. There are a substantial number of schools in the City of Ottawa. In this discussion, NEHRP classifications were determined for 22 schools (12 elementary schools and 11 high schools) (GIS data source: Regional Municipality of Ottawa-Carleton). Approximately 32% are located on NEHRP C, 23% on NEHRP D, 18% each on NEHRP A and B, and 9% on NEHRP E. Schools located on NEHRP D and E will have functionalities of less than 10% on day 1 and will incur significant physical and social losses in the event of a significant earthquake.

Another important site for rescue operations will be the Parliament Buildings. Results of this project show that governmental buildings are the least vulnerable occupancy class; however, current structural conditions of the Parliament Buildings were not considered. It has been reported that the Parliament Buildings are in poor condition and could collapse

due to a small earthquake (Cook, 2007). If significant damage were to occur to the Parliament Buildings during an earthquake, it would be imperative for the political stability of Canada that one of the primary targets for emergency operations is held at this location.

Emergency response – casualties

The main goal in emergency response is to aid the public. Social losses are measured in terms of the number of casualties. In the study area, approximately 135 casualties were recorded, 4 of which were fatalities. This casualty estimate only includes working and residential populations; visitors (tourists) were not accounted for. It is plausible to assume that the number of casualties will increase significantly once the number of visitors is taken into account, as the study area is the main tourist district of the city.

There are ten hospitals in the City of Ottawa. In this discussion, NEHRP classifications were determined for all ten hospitals (GIS data source: Regional Municipality of Ottawa-Carleton). Approximately 80% are located on NEHRP B, and 10% each on NEHRP A and C. Three medical care facilities were located in the study area, with an average functionality of at least 50% on day 1. Therefore, it is plausible to assume that the functionality of the Ottawa hospitals will also be at least 50% on day 1, if not better due to superior design levels that are used for hospitals built to modern codes

Recovery of the city will be a major task, most likely involving all three levels of government. The cost of repair and restoration to the general building stock in the study area is estimated to be at least \$221 million for an AB06 M6.5 (R_{epi} 15km) scenario. This estimation does not include intrinsic, downtown real estate market values, content costs or indirect losses and should be considered a minimum. A preliminary estimate from the 1994 Northridge earthquake, an event with a similar earthquake magnitude and in a modern North American city, was \$13B to \$26.5B (FEMA and NIBS, 2001; USGS, 2008). However, note that the Northridge earthquake occurred in the much larger and more populous Los Angeles region.

Areas most physically and socially vulnerable

Identifying areas most physically and socially vulnerable to earthquake ground shaking is one of many benefits of the HAZUS program. After interpreting results generated in this project, the most vulnerable areas are 005, 004, and 002, as illustrated in Figure 3.23. Most vulnerable areas were determined by a simple ranking system presented in Table 3.19; where 1 is the most vulnerable and 10 is the least vulnerable. Area vulnerability was not related directly to the total building count; as area 005 had the greatest amount of total losses but the least number of buildings out of the top three areas, while area 002 had the least amount of total losses but nearly twice the number of buildings out of the top three areas.

Figure 3.23. Three most socially and physically vulnerable areas in the study area. Area 002 is the most physically vulnerable to building damage, area 005 is the most physical vulnerable to debris generation and most socially vulnerable (to fatalities) (GIS data sources: City of Ottawa, NRCan).

Table 3.19. Ranking system used to determine areas most physically and socially vulnerable, where 1 is the most vulnerable and 10 is the least vulnerable.

Area	Physical		Social		Economical	Rank
	Buildings	Debris	Casualties	Fatalities	Direct	
001	5	6	4	3	5	5
002	1	3	3	2	2	3
003	4	5	4	3	6	4
004	2	2	1	2	3	2
005	3	1	2	1	1	1
006	6	4	5	3	4	4
007	7	8	6	3	7	6
008	7	7	7	3	8	7
009	7	9	7	3	9	8
010	8	10	7	3	10	9

The area with the most vulnerability is 005 which contains a local high school, City Hall, military installations, a provincial court and several commercial buildings. The second most vulnerable area to losses is 004, encompassing Parliament Hill, the Supreme Court of Canada and several key Government of Canada buildings. The third most vulnerable area is 002, encompassing Byward Market, Rideau Centre, and six hotels.

Additional factors must be considered when ranking these vulnerable areas, those factors are: (1) casualties are likely to increase when factoring in the number of visitors, especially area 002 where there are numerous retail stores and restaurants (commercial) that are URM buildings in close confinement, likely leading to more casualties; (2) economical losses will increase substantially when considering the real estate value of buildings and content costs, especially in area 004, which includes Parliament Hill; and (3) building damage to the Parliament Buildings will likely increase as Parliament is reported to be in poor condition (Cook, 2007) .

3.2.4 Losses in historical context

Empirical validation of the results could not be performed because Ottawa has not experienced a significant earthquake in historical times. Instead, two additional and simple scenarios based on historical eastern Canadian earthquakes were performed using AB06 ground-motions and site-specific amplifications to validate losses in a historical context. Comparative scenarios of the 1925 Charlevoix–Kamouraska and 1944

Cornwall–Massena earthquakes were superimposed on the Ottawa study area and building inventory, as illustrated in Figure 3.24. Relative to Ottawa, the historical scenarios were placed at its distance from (1) Quebec City (for the 1925 event), and (2) Cornwall (for the 1944 event). For these additional scenarios, all variables of this research project remained the same (building inventory, population) except for earthquake characteristics (epicentral distance, magnitude, depth), which were altered to match those of the aforementioned 1925 and 1944 earthquakes. NEHRP classes were also altered to reflect the soil classes present in Quebec City and Cornwall, respectively, which range from NEHRP B to D. The purpose of these additional scenarios was to compare predicted HAZUS losses to reported historical losses from these earthquakes, at the closest cities to which they occurred.

1925 Charlevoix–Kamouraska earthquake

Damage in Quebec City was not expected during the 1925 Charlevoix–Kamouraska earthquake, as the epicentre was approximately 182 km away (Table 3.20). However, URM buildings, specifically grain elevators and the train terminal, were damaged because they are built on marine clays which amplified the incoming seismic waves (Bruneau and Lamontagne, 1994). Six fatalities (heart attacks) were attributed to the earthquake.

Figure 3.24. Map of actual earthquake epicentres and epicentral distances to the city centres, Quebec City and Cornwall (solid line), with these historical references superimposed on Ottawa (dashed line). The centre of each circle (solid line) represents the epicentre and depicts its epicentral distance to the city in the historical context validation exercise.

Table 3.20. Earthquake characteristics of the two eastern Canadian earthquakes used in the simple historical validation exercise.

Historical earthquake	Magnitude (M)	Depth (km)	R_{epi} (km)
1925 Charlevoix-Kamouraska			
Québec	6.2	10	182
1944 Cornwall-Massena	5.8	20	26.5

Table 3.21 outlines the losses recorded from the comparative HAZUS scenario of the 1925 Charlevoix-Kamouraska earthquake, if it occurred 182 km from Ottawa. Results from the comparative scenario show that damage would be initiated only on soft soil deposits, similar to the damage incurred during the historical earthquake. Additionally, the majority of damaged buildings were URM buildings. One severity 1 casualty was also recorded during the scenario.

1944 Cornwall–Massena earthquake

Significant damage was reported during the 1944 Cornwall–Massena earthquake in Cornwall, where the greatest amount of damage occurred on marine clays. Reported damages included (1) approximately 2,000 damaged chimneys, (2) considerable damage to the local high school, and (3) several damaged URM buildings (including one partial collapse) (Bruneau and Lamontagne, 1994).

Table 3.22 outlines the losses recorded from the comparative HAZUS scenario of the 1944 Cornwall–Massena earthquake (M5.8 at 27 km). Results from the comparative scenario show that buildings would be damaged on both NEHRP B and D soil classes; in some cases buildings would be heavily damaged. In all cases, the majority of damaged buildings are URM buildings. No casualties are recorded. Note that the AB06 ground-motion inputs are based the on results of both SITEAMP and MATLAB outputs

Table 3.21. HAZUS results of building damage with number of damaged URM buildings, and casualties for the 1925 Charlevoix – Kamouraska Québec earthquake.

1925 Charlevoix - Kamouraska Québec				
Soil Class	Damaged Buildings		Casualties	
	AB95 (<i>URM</i>)	AB06 (<i>URM</i>)	AB95	AB06
NEHRP B	0	0	0	0
NEHRP D	9 (6)	0	1	0

Table 3.22. HAZUS results of building damage with number of damaged URM buildings, and casualties for the 1944 Cornwall - Massena earthquake.

1944 Cornwall - Massena				
Soil Class	Damaged Buildings		Casualties	
	AB95 (<i>URM</i>)	AB06 (<i>URM</i>)	AB95	AB06
NEHRP B	26 (18)	4 (4)	0	0
NEHRP D	147 (86)	2 (2)	0	0

(Section 2.1.4) of the 44 soil polygons. As previously discussed, some NEHRP B polygons have unrealistically high amplification factors, which is an explanation as to why NEHRP B losses are slightly greater than NEHRP D losses.

The results of the comparative scenarios are expected for the following reasons: (1) The AB95 damages, both physical and social, exceed those of the AB06, as seen in the project results and the validation study, (2) damages are greater on softer soils, i.e. NEHRP D, with the exception of the AB06 1944 Cornwall-Massena scenario, and (3) the majority of damage was to URM buildings. Note that the comparative scenarios represented only a small geographic area (approximately 2.5 km²); all reported losses in Quebec City (454.26km²) and Cornwall (61.83 km²) from the actual earthquakes were representative of the entire city.

Chapter 4: Conclusions and recommendations

The aim of this study was to identify areas most physically and socially vulnerable to earthquake ground shaking and to present earthquake loss estimations for downtown Ottawa, Canada, using the HAZUS-MH software tool. The study area consists of two census tracts, which can be further divided into 10 dissemination areas, and contains 597 buildings, including the Federal Parliament. 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, including (a) specifying ground motion, (b) developing hazard maps, (c) compiling inventories and (d) tallying demographic data. (3) Preparing and inputting data, and manipulating HAZUS. (4) Interpreting loss estimations for downtown Ottawa. 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.

4.0 Conclusions

The main conclusions of this study are:

1. The City of Ottawa is an area of significant seismic risk. Previous earthquakes in eastern Ontario include the 1935 M6.2 Temiscaming and the 1944 M5.8 Cornwall-Massena earthquakes; additional evidence suggests pre-historic M7.0 earthquakes

have also occurred in this area. The seismic risk in Ottawa heightened by its large and unprepared population. Microzonation studies play an integral role in estimating the intensity of ground shaking at the surface within the study area. The acquisition and interpretation of data reveals the presence of NEHRP D sediments, with amplification factors in the near-surface sediments as high as 4.8 (for PSA 0.3s). This generally occurs in pockets containing at least 7m of clay and/or fill deposits. However, most of the study area was on firm soil (NEHRP B).

2. The building inventory within the study area is dominated by the following: (1) unreinforced masonry building types, (2) commercial occupancy classes, (3) pre-code seismic design levels, and (4) low-rise buildings.
3. Earthquake loss estimations are heavily influenced by the ground shaking amplitudes, which are controlled by earthquake magnitude, distance and site condition.
4. Earthquake loss estimations are heavily influenced by the urban environment. The most vulnerable building types are unreinforced masonry and concrete buildings, primarily because of their lack of structural integrity and frame design. The majority of these building types are also pre- or low-code. The damage to these building types is also associated with the total amount of debris generation and direct economical losses for each dissemination area.
5. The most vulnerable occupancy class is the commercial class, which includes retail stores, restaurants and office buildings. Although occupancy class does not influence building damage, it does play a leading role in casualties. At least 90% of casualties occur in unreinforced masonry and concrete buildings. The most casualties occur

during the daytime (2:00pm) when a working population of greater than 76,000 is expected to be in the study area.

6. The most vulnerable downtown areas are 005 (which includes City Hall, an URM high school, a Provincial court, and several financial institutions), 004 (which includes Parliament Hill, the Supreme Court of Canada, and several Federal Government complexes), and 002 (Byward Market, a major shopping centre, and several large hotels). Area 002 was most physically vulnerable to building damage. Area 004 was most socially vulnerable (total casualties). Area 005 was the most vulnerable area as it was the most physically vulnerable to indirect damage (debris generation), socially vulnerable (total fatalities) and incurred the greatest amount of economical losses.
7. HAZUS-MH can be utilized for level 2 earthquake loss estimation analysis in a Canadian setting, at a local scale, provided that the procedure outlined in Appendix E is followed.
8. A refined building inventory completed via a sidewalk survey is beneficial and influences the accuracy of loss estimations. However, the default NY1 inventory did identify the general areas most physically and socially vulnerable.
9. The study area is located on firm soil. Extrapolations of the results to other areas of Ottawa with poorly-consolidated soil show a significant increase in losses.
10. 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 Ottawa.

4.1 Recommendations

Recommendations following from this study are:

HAZUS

1. Given the importance of soil conditions, the manipulated HAZUS-MH program should be run in regions of Ottawa underlain by poorly-consolidated soils. In this research project, scenarios were run on firm soils with an aged building inventory; while other regions of Ottawa are on poorly-consolidated soils with a modern building inventory (for example, Orleans).
2. The manipulated HAZUS-MH program should be run with its full capabilities for an entire Canadian municipality. This will ensure that HAZUS-MH can be used to its fullest potential in Canada and that specialized neighbourhood plans (as some neighbourhoods are more vulnerable to losses than others) can be integrated into a municipal emergency plan.
3. Historical scenarios should be performed on previous eastern Canadian earthquakes. This will enable Canadian users of HAZUS-MH to measure the

accuracy of the manipulated 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 United States (i.e. Canada). Also needed, is to test whether the PGA-based economical calibrations are pertinent to eastern North American scenarios.

4. The Provincial and Federal governments should begin to compile default databases, similar to those available on the HAZUS-MH data DVDs, for Canada. Having a national database of soil conditions, infrastructure, building inventory, etc., is not only useful for multi-hazard loss estimations programs, but also provides readily accessible databases for emergency planners in the event of a provincial or national scale emergency.
5. This study has not addressed modification of the engineering functions to reflect Canadian practice, which would improve applicability of HAZUS to Canada.

Mitigation

6. An earthquake-specific emergency plan should be created for the City of Ottawa for two reasons: (1) Earthquakes are the only large-scale hazard with crippling physical, social and economical damages presented in the Multi Risk Strategies (2003) report, and (2) loss estimations can reveal areas (or neighbourhoods) most physically and socially vulnerable to earthquake ground shaking. With the results

and the extrapolations to other regions of Ottawa presented in this project, vulnerable areas can be identified and targeted for emergency response efforts. Additionally, specialized plans for the most vulnerable neighbourhoods can be created, which would ease in the coordination and organization of localized response efforts during and after a seismic event as well as increasing the efficiency of resource allocation. High priority rescue operations can also be integrated in the emergency plan, as some neighbourhoods include schools, the Federal Parliament, international embassies, hospitals, and important military installations.

7. There is a need for development and implementation of public awareness campaigns. It has been reported by (Bruneau and Lamontagne, 1994) that eastern Canadians are unaware of the seismic risk that they are exposed to. On the most basic level of emergency management, the individual level, eastern Canadians are already at a disadvantage. A comprehensive educational campaign would help alleviate this disadvantage, creating an aware population, and lower the risk of injury and death during a seismic event.
8. Incentives and regulations should be introduced for the assessment and reinforcement of vulnerable buildings (URM buildings etc.). Incentives to home and business owners, as well as regulations to publicly owned facilities will reduce inherent risk to the city and its residents. For example, Italy provides tax incentives to owners to upgrade their buildings (Spence, 2004), and British Columbia has committed to ensuring that schools will meet acceptable seismic

life safety standards (Monk, 2007). Reinforcing vulnerable buildings will also preserve functionality, limit damages and protects its occupants.

The City of Ottawa has the opportunity to set an example in earthquake mitigation and emergency management strategies in eastern Canada. Developing mitigation strategies can reduce the inherent risks of an earthquake and translate into direct human and monetary savings for the City of Ottawa and Government of Canada (Bruneau and Lamontagne, 1994). The results of this study provide an indication of some of the most vulnerable areas (URM and commercial buildings; site with NEHRP D and E classes, etc.) in the City of Ottawa.

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Appendix A

A1: Summary of HAZUS inputs as summarized in FEMA (2004).

Inventory category	General fields	Earthquake specific fields
Essential facilities		
Emergency response	ID Number, Building Class, Tract, Name, Address, City, Zip Code, State, Contact, Phone Number, Year Built, Number of Stories, Replacement Cost, Backup Power, Shelter Capacity, Building Area, Kitchen, Latitude, Longitude, Comment	Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Fire stations	D Number, Building Class, Tract, Name, Address, City, Zip Code, State, Contact, Phone Number, Year Built, Number of Stories, Backup Power, Shelter Capacity, Building Area, Kitchen, Number of Trucks, Latitude, Longitude, Comment	N/A
Medical care	ID Number, Building Class, Tract, Name, Address, City, Zip Code, State, Contact, Phone Number, Use, Year Built, Number of Stories, Replacement Cost, Backup Power, Number of Beds, AHA ID, Latitude, Longitude, Comment	Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Police stations	ID Number, Building Class, Tract, Name, Address, City, Zip Code, State, Contact, Phone Number, Year Built, Number of Stories, Cost, Backup Power, Shelter Capacity, Building Area, Kitchen, Latitude, Longitude, Comment	N/A
Schools	ID Number, Building Class, Tract, Name, Address, City, Zip Code, State, Contact, Phone Number, Year Built, Number of Stories, Replacement Cost,	Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth

	Number of Students, Backup Power, Shelter Capacity, Building Area, District, Kitchen, Latitude, Longitude, Comment	
High potential loss facilities		
Dams	ID Number, Dam Class, Tract, Name, County Name, Owner, Cost, River, Near City, Distance City, Purpose, Year Completed, Dam Length, Dam Height, Structural Height, Max discharge, Hydro Height, Max Storage, Normal Storage, Surface Area, Drain Area, Hazard, EAP, Spill Type, Spill Width, Volume, NAT ID, Primary Agency, Latitude, Longitude, Comment	Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Levees	ID Number, County FIP, County Name, Levee Name, Levee width, Levee Height, Levee Crest, normal Height, Owner, River, Near City, Distance City, Year Completed, Hazard, Comment	Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Military installations	ID Number, Building Class, Tract, Name, Address, City, Zip Code, State, Contact, Phone Number, Year Built, Number of Stories, Owner, Shelter Capacity, Use, Building Cost, Content Cost, Latitude, longitude, Comment	Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Nuclear power facilities	ID Number, Building Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Year Built, Number of Stories, Replacement Cost, Latitude, Longitude, Capacity, Comment	Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Hazardous materials facilities	ID Number, Building Class, Tract, Name, Address, City, State, Zip Code, Contact, Cas #, Chemical Name, Chemical Quantity, SIC Code, Year Built, EPA ID, Permit Amount, Latitude, Longitude, Comment	Building Type, Building Quality, Design Level, Foundation Type, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth

Transportation systems		
Highway segments	Number, Segment Class, County FIP, Name, Owner, Length, Traffic, Cost, Number of Lanes, Pavement, Width, Capacity, Comment	None
Highway bridges	ID Number, Bridge Class, Tract, Name, Owner, Bridge Type, Width, Number of Spans, Length, Maximum Span Length, Skew Angle, Seat Length, Seat Width, Year Built, Year Remodelled, Pier Type, Foundation Type, Scour Index, Traffic, Traffic Index, Condition, Cost, Latitude, Longitude, Comment	Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Highway tunnels	ID Number, Tunnel Class, Tract, Name, Owner, Type, Width, Length, Year Built, Traffic, Cost, Latitude, Longitude, Comment	Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Rail segments	ID Number, Segment Class, County FIP, Name, Owner, Length, Traffic, Cost, Number of Tracks, Comment	None
Rail bridges	ID Number, Bridge Class, Tract, Name, Owner, Bridge Type, Width, Number of Spans, Length, Maximum Span Length, Skew Angle, Seat Length, Seat Width, Year Built, Year Remodelled, Pier Type, Foundation Type, Scour Index, Traffic, Traffic Index, Condition, Cost, Latitude, Longitude, Comment	Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Rail tunnels	ID Number, Tunnel Class, Tract, Name, Owner, Type, Width, Length, Year Built, Traffic, Cost, Latitude, Longitude, Comment	Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Rail facilities	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Cost, Backup Power, Traffic, Latitude, Longitude, Comment	Anchor, Foundation Type, Building Type, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Light rail	ID Number, Segment Class,	None

segments	County FIPS, Name, Owner, Length, Traffic, Cost, Number of Tracks, Comment	
Light rail bridges	ID Number, Bridge Class, Tract, Name, Owner, Bridge Type, Width, Number of Spans, Length, Maximum Span Length, Skew Angle, Seat Length, Seat Width, Year Built, Year Remodelled, Pier Type, Foundation Type, Scour Index, Traffic, Traffic Index, Condition, Cost, Latitude, Longitude, Comment	Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Light rail tunnels	ID Number, Tunnel Class, Tract, Name, Owner, Type, Width, Length, Year Built, Traffic, Cost, Latitude, Longitude, Comment	Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Light rail facilities	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Number of Stories, Cost, Backup Power, Traffic, Latitude, Longitude, Comment	Anchor, Foundation Type, Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Bus	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Cost, Backup Power, Traffic, Latitude, Longitude, Comment	Anchor, Foundation Type, Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Port	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Backup Power, Cost, Capacity, Number of Berths, Number of Cranes, Latitude, Longitude, Comment	Anchor, Foundation Type, Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Ferry	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, number of Stories, Cost, Backup Power, Traffic, Latitude, Longitude, Comment	Anchor, Foundation Type, Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Airport facilities	ID Number, Facility Class, Tract,	Anchor, Foundation Type,

	Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Cost, Cargo, Number of Flights, Number of Passengers, Backup Power, Latitude, Longitude, Comment	Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Airport runways	ID Number, Facility Class, Tract, Name, Airport ID, Runway Length, Cost, Capacity, pavement, Latitude, Longitude, Comment	Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Utility systems		
Potable water pipelines	ID Number, Pipeline Class, County FIPS, Name, Owner, Material, Diameter, Pipe Length, Joint, Year Built, Cost, Source ID, Comment	None
Potable water distribution pipes	Tract, Ductile Pipe, Brittle Pipe, Total Pipe, Presented by Census tract	None
Potable water facilities	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Number of Stories, Cost, System ID, G Class, Backup Power, Year Upgraded, Capacity, Demand, Latitude, Longitude, Comment	Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Wastewater pipelines	ID Number, Pipeline Class, County FIPS, Name, Owner, Material, Diameter, Pipe Length, Joint, Year Built, Cost, Source ID, Comment	None
Wastewater distribution sewers	Tract, Ductile Pipe, Brittle Pipe, Total Pipe	None
Waste water facilities	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Number of Stories, Cost, System ID, G Class, Backup Power, Year Upgraded, Capacity, Demand, Latitude, Longitude, Comment	Anchor, Foundation Type, Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth

Crude and refined oil pipelines	ID Number, Pipeline Class, County FIPS, Name, Owner, Material, Diameter, Pipe Length, Joint, Year Built, Cost, Source ID, Comment	None
Crude and refined oil pipeline facilities	ID Number, Facility Class, Tract, Name, Address, City, Zip code, State, Owner, Contact, Phone Number, Use, Year Built, Cost, Backup Power, Capacity, Latitude, Longitude, Comment	Anchor, Foundation Type, Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Natural gas pipelines	ID Number, Pipeline Class, County FIPS, Name, Owner, Material, Diameter, Pipe Length, Joint, Year Built, Cost, Source ID, Comment	None
Natural gas distribution pipes	Tract, Ductile Pipe, Brittle Pipe, Total Pipe	None
Natural gas facilities	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Cost, Number of Stories, Backup Power, Capacity, Latitude, Longitude, Comment	Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
Electric power plants	ID Number, Facility Class, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Description, Use, Year Built, Number of Stories, Cost, Capacity, Latitude, Longitude, Comment	N/A
Electric power substations	ID Number, Facility Class, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Description, Use, Year Built, Number of Stories, Cost, Capacity, Latitude, Longitude, Comment	N/A
Electric power	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Number of Stories, Capacity,	Anchor, Foundation Type, Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide

	Cost, Latitude, Longitude, Comment	Susceptibility, Water Depth
Communication control offices and switching stations	ID Number, Facility Class, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Description, Use, Cost, installation Year, Backup Power, Latitude, Longitude, Comment	N/A
Communication vaults and central stations	ID Number, Facility Class, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Description, Use, Cost, Installation Year, Backup Power, Latitude, Longitude, Comment	N/A
Communication broadcast facility	Number, Facility Class, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Description, Use, Cost, Installation Year, Backup Power, Latitude, Longitude, Comment	N/A
Communications	ID Number, Facility Class, Tract, Name, Address, City, Zip Code, State, Owner, Contact, Phone Number, Use, Year Built, Cost, Backup Power, Latitude, Longitude, Comment	Anchor, Foundation Type, Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth
General		
Demographics	Block, Population, Households, Group Quarters, Population Age Distribution, Male Population, Female Population, Race Distribution, Income, Daytime Residency, Night Residency, Hotel, Visitor, Working Com, Working Ind, Commuting 5pm, Number of Home Owners, Number of Renters, Number of Vacant Homes, Building Age, Median Age, Average Rent, Average Value, School Enrolment	None
General building stock	Exposure, Count, and Square Footage by General Occupancy,	None

	Specific Occupancy, and Building Type	
User supplied	ID Number, Occupancy, Tract, Name, Address, City, Zip code, State, Contact, Phone Number, Year Built, Cost, Backup Power, Number of Stories, Area, Content Cost, Shelter Capacity, Latitude, Longitude, Comment	Building Type, Building Quality, Design Level, Soil Type, Liquefaction Susceptibility, Landslide Susceptibility, Water Depth

A2: Summary of HAZUS outputs as summarized in FEMA and NIBS (2006a). Items marked with an (*) require a Level 2 or 3 analysis.

HAZUS output	Description
Map of seismic hazards	<ul style="list-style-type: none"> - Intensities of ground shaking for each census unit - Contour maps of intensities of ground shaking - Permanent ground displacements for each census unit* - Contour map of permanent ground displacements* - Liquefaction probability* - Landsliding probability*
Damage to general building stock	- Structural and non-structural damage probabilities by census units, building type and occupancy class (probabilities and building counts)
Transportation and utility lifelines	<ul style="list-style-type: none"> - For components of the 13 lifeline systems: damage probabilities, cost of repair or replacement and expected functionality for various times following earthquake - For all pipeline systems: the estimated number of leaks and breaks - For potable water and electric power systems: estimate of service outages
Essential facilities	<ul style="list-style-type: none"> - Damage probabilities - Probability of functionality - Loss of beds in hospitals
High potential loss facilities	<ul style="list-style-type: none"> - Locations of dams - Locations of nuclear plants - Damage probabilities and cost of repair for of military facilities* - Locations of other identified high potential loss facilities
Fire following earthquake	<ul style="list-style-type: none"> - Number of ignitions by census unit - Percentage of burned area by census unit
Inundated areas	- Exposed population and exposed dollar value of general building stock*
Hazardous material sites	- Location of facilities which contain hazardous materials
Debris	- Total debris generated by weight and type of material
Social losses	<ul style="list-style-type: none"> - Number of displaced households - Number of people requiring temporary shelter - Casualties in four levels of severity based on three different times of day
Dollar losses associated with general building stock	<ul style="list-style-type: none"> - Structural and non-structural cost of repair or replacement - Loss of contents - Business inventory loss - Relocation costs - Business income loss - Employee wage loss - Loss of rental income

Indirect economic impact	<ul style="list-style-type: none">- Long-term economical effects on the region based on a synthetic economy- Long-term economical effects on the region based on a specialized model*
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Appendix B

B1: Input ground motions on NEHRP A determined from Atkinson and Boore (2006) relations, values in brackets include site-specific amplification factors. Note that HAZUS uses only PSA 0.3s, 1.0s, PGA and PGV. PGV is measured in cm/s.

Magnitude 5.0 and 5.5

PSA (g)	Magnitudes			
	M5.0		M5.5	
	d0	d1	d0	d1
2.0	0.003	0.002	0.089	0.007
1.0	0.012 (0.013)	0.010 (0.011)	0.033 (0.036)	0.027 (0.030)
0.5	0.043	0.038	0.102	0.085
0.315	0.080 (0.117)	0.071 (0.104)	0.167 (0.240)	0.141 (0.204)
0.1	0.289	0.257	0.527	0.445
PGA	0.208 (0.410)	0.185 (0.364)	0.370 (0.681)	0.311 (0.589)
PGV	3.019 (3.613)	2.664 (3.187)	6.319 (7.287)	5.287 (6.187)

Magnitude 6.0 and 6.5

PSA (g)	Magnitudes						
	M6.0				M6.5		
	d0	d1	d2	d3	d1	d2	d3
2.0	0.025	0.019	0.007	0.003	0.042	0.015	0.007
1.0	0.080 (0.088)	0.062 (0.068)	0.021 (0.023)	0.009 (0.010)	0.118 (0.130)	0.043 (0.047)	0.019 (0.022)
0.5	0.216	0.166	0.053	0.022	0.284	0.097	0.042
0.315	0.322 (0.455)	0.249 (0.0.354)	0.077 (0.116)	0.030 (0.046)	0.395 (0.556)	0.129 (0.195)	0.054 (0.081)
0.1	0.918	0.711	0.185	0.064	1.062	0.292	0.106
PGA	0.627 (1.116)	0.481 (0.870)	0.096 (0.205)	0.028 (0.059)	0.694 (1.222)	0.149 (0.316)	0.046 (0.097)
PGV	12.715 (14.377)	9.743 (12.068)	2.675 (3.335)	0.989 (1.232)	16.877 (18.945)	5.097 (6.354)	2.038 (2.540)

Magnitude 7.0

PSA (g)	Magnitude		
	M7.0		
	d1	d2	d3
2.0	0.077	0.031	0.015
1.0	0.190	0.074	0.035
	(0.209)	(0.081)	(0.039)
0.5	0.423	0.153	0.069
0.315	0.560	0.195	0.085
	(0.782)	(0.287)	(0.129)
0.1	1.472	0.429	0.163
PGA	0.927	0.214	0.070
	(1.600)	(0.422)	(0.148)
PGV	27.293	9.110	3.919
	(30.294)	(10.900)	(4.887)

B2: Ground motions which include NEHRP-based amplification factors determined from the HAZUS Atkinson and Boore (1995) relations option. PGV is measured in cm/s.

Magnitude 5.0 and 5.5

PSA (g)	Magnitudes			
	M5.0		M5.5	
	d0	d1	d0	d1
2.0				
1.0	0.026	0.026	0.058	0.058
0.5				
0.3	0.189	0.189	0.368	0.368
0.1				
PGA	0.259	0.259	0.400	0.400
PGV	0.981	0.981	2.151	2.151

Magnitude 6.0 and 6.5

PSA (g)	Magnitudes						
	M6.0				M6.5		
	d0	d1	d2	d3	d1	d2	d3
2.0							
1.0	0.120	0.118	0.044	0.023	0.163	0.077	0.044
0.5							
0.315	0.664	0.654	0.242	0.122	0.751	0.353	0.203
0.1							
PGA	0.581	0.568	0.149	0.095	0.535	0.240	0.129
PGV	4.492	4.430	1.650	0.838	6.094	2.893	1.672

Magnitude 7.0

PSA (g)	Magnitude		
	M7.0		
	d1	d2	d3
2.0			
1.0	0.204	0.119	0.071
0.5			
0.315	0.757	0.436	0.261
0.1			
PGA	0.444	0.244	0.136
PGV	7.643	4.454	2.678

Appendix C:

SITEAMP input for the 44 soil polygons shown in Figure 2.5.

Polygon identifier	Layer 1			Layer2		
	Depth (m)	Density (g/cm ³)	Velocity (m/s)	Depth (m)	Density (g/cm ³)	Velocity (m/s)
0	2.7	1.9	675	1.8	2.1	278
1	1.4	1.5	200	0.1	1.5	238
2	0.7	1.5	200	0.1	1.5	238
3	3.5	1.8	295			
4	0.4	1.5	200	0.1	1.5	238
5	1.8	1.5	200	5.3	1.3	150
6	1.2	1.5	200	1.2	1.5	238
7	0.8	1.5	200	1.2	1.7	456
8	0.4	1.5	200	1.2	1.9	675
9	0.8	1.5	200	2.4	1.9	675
10	5.3	1.9	675	3.7	2.1	278
11	0.9	1.5	200	3.3	2.1	548
12	1.1	1.5	200	0.8	1.9	675
13	0.5	1.5	200			
14	1.8	1.9	675			
15	0.3	1.5	200	1	1.3	150
16	1.3	1.5	200	0.2	1.5	238
17	1.2	1.5	238	2	1.3	150
18	3.7	1.5	238	6.1	1.3	150
19	1.8	1.5	238	3	1.3	150
20	1.5	1.4	175			
21	2.9	1.5	200	0.2	1.5	238
22	6.3	1.5	355			
23	1.2	1.9	675			
24	1.8	1.9	675			
25	0.6	1.9	675			
26	1.2	1.9	675			
27	12.7	1.5	355			
28	4.6	1.5	200	2	1.5	259
29	2.3	1.5	200	1	1.5	259
30	4.9	1.9	675			
31	1.5	1.7	456			
32	17.1	1.3	150	2.6	1.9	675
33	2.4	1.9	675			
34	0.8	1.7	456			
35	1.2	1.5	200			
36	8.5	1.3	150	1.3	1.9	675
37	2.9	1.5	200	0.2	1.5	238
38	3.2	1.5	355			
39	12.5	1.5	200			
40	7.5	1.5	200			
41	2.4	1.8	496			
42	2.3	1.5	200	0.5	2.1	548
43	0.3	1.5	238	2.1	2.1	200

Polygon identifier	Layer 3			Layer 4		
	Depth (m)	Density (g/cm ³)	Velocity (m/s)	Depth (m)	Density (g/cm ³)	Velocity (m/s)
0						
1	2.5	1.3	150	0.3	1.5	238
2	5	1.5	200	1	1.5	238
3						
4	3.3	1.5	200	0.7	1.5	238
5	1.4	1.5	238	3.8	1.9	675
6						
7	1.7	2.1	548			
8	1.4	1.5	238	9.7	1.9	675
9	0.3	1.5	238	19.5	1.9	675
10						
11						
12	2.3	1.3	150	1.8	1.9	675
13						
14						
15	0.6	1.9	675			
16	9.9	1.5	200	2.1	1.5	238
17	0.3	1.5	238	8.6	1.9	675
18	0.9	1.5	238	25.9	1.9	675
19	0.5	1.5	238	12.9	1.9	675
20						
21	5	1.3	150	0.5	1.5	238
22						
23						
24						
25						
26						
27						
28	3.2	1.9	675			
29	1.6	2.1	548			
30						
31						
32						
33						
34						
35						
36						
37	5	1.3	150	0.5	1.5	238
38						
39						
40						
41						
42						
43						

Polygon identifier	Layer 5			Layer 6		
	Depth (m)	Density (g/cm ³)	Velocity (m/s)	Depth (m)	Density (g/cm ³)	Velocity (m/s)
0						
1	0.9	1.9	548	1.6	2.1	548
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						
14						
15						
16						
17						
18						
19						
20						
21	1.8	1.9	675	3.3	2.1	548
22						
23						
24						
25						
26						
27						
28						
29						
30						
31						
32						
33						
34						
35						
36						
37	1.8	1.9	675	3.3	2.1	548
38						
39						
40						
41						
42						
43						

Polygon identifier	Bedrock (< 70 m)			Bedrock (70 – 900 m)		
	Depth (m)	Density (g/cm ³)	Velocity (m/s)	Depth (m)	Density (g/cm ³)	Velocity (m/s)
0	< 70	2.5	2209	70 - 900	2.5	2500
1	< 70	2.5	2209	70 - 900	2.5	2500
2	< 70	2.5	2209	70 - 900	2.5	2500
3	< 70	2.5	2209	70 - 900	2.5	2500
4	< 70	2.5	2209	70 - 900	2.5	2500
5	< 70	2.5	2209	70 - 900	2.5	2500
6	< 70	2.5	2209	70 - 900	2.5	2500
7	< 70	2.5	2209	70 - 900	2.5	2500
8	< 70	2.5	2209	70 - 900	2.5	2500
9	< 70	2.5	2209	70 - 900	2.5	2500
10	< 70	2.5	2209	70 - 900	2.5	2500
11	< 70	2.5	2209	70 - 900	2.5	2500
12	< 70	2.5	2209	70 - 900	2.5	2500
13	< 70	2.5	2209	70 - 900	2.5	2500
14	< 70	2.5	2209	70 - 900	2.5	2500
15	< 70	2.5	2209	70 - 900	2.5	2500
16	< 70	2.5	2209	70 - 900	2.5	2500
17	< 70	2.5	2209	70 - 900	2.5	2500
18	< 70	2.5	2209	70 - 900	2.5	2500
19	< 70	2.5	2209	70 - 900	2.5	2500
20	< 70	2.5	2209	70 - 900	2.5	2500
21	< 70	2.5	2209	70 - 900	2.5	2500
22	< 70	2.5	2209	70 - 900	2.5	2500
23	< 70	2.5	2209	70 - 900	2.5	2500
24	< 70	2.5	2209	70 - 900	2.5	2500
25	< 70	2.5	2209	70 - 900	2.5	2500
26	< 70	2.5	2209	70 - 900	2.5	2500
27	< 70	2.5	2209	70 - 900	2.5	2500
28	< 70	2.5	2209	70 - 900	2.5	2500
29	< 70	2.5	2209	70 - 900	2.5	2500
30	< 70	2.5	2209	70 - 900	2.5	2500
31	< 70	2.5	2209	70 - 900	2.5	2500
32	< 70	2.5	2209	70 - 900	2.5	2500
33	< 70	2.5	2209	70 - 900	2.5	2500
34	< 70	2.5	2209	70 - 900	2.5	2500
35	< 70	2.5	2209	70 - 900	2.5	2500
36	< 70	2.5	2209	70 - 900	2.5	2500
37	< 70	2.5	2209	70 - 900	2.5	2500
38	< 70	2.5	2209	70 - 900	2.5	2500
39	< 70	2.5	2209	70 - 900	2.5	2500
40	< 70	2.5	2209	70 - 900	2.5	2500
41	< 70	2.5	2209	70 - 900	2.5	2500
42	< 70	2.5	2209	70 - 900	2.5	2500
43	< 70	2.5	2209	70 - 900	2.5	2500

Polygon identifier	Bedrock (0.9 – 13 km)			Bedrock (13 km)		
	Depth (km)	Density (g/cm ³)	Velocity (m/s)	Depth (km)	Density (g/cm ³)	Velocity (m/s)
0	0.9 - 13	2.7	3400	13	2.8	3700
1	0.9 - 13	2.7	3400	13	2.8	3700
2	0.9 - 13	2.7	3400	13	2.8	3700
3	0.9 - 13	2.7	3400	13	2.8	3700
4	0.9 - 13	2.7	3400	13	2.8	3700
5	0.9 - 13	2.7	3400	13	2.8	3700
6	0.9 - 13	2.7	3400	13	2.8	3700
7	0.9 - 13	2.7	3400	13	2.8	3700
8	0.9 - 13	2.7	3400	13	2.8	3700
9	0.9 - 13	2.7	3400	13	2.8	3700
10	0.9 - 13	2.7	3400	13	2.8	3700
11	0.9 - 13	2.7	3400	13	2.8	3700
12	0.9 - 13	2.7	3400	13	2.8	3700
13	0.9 - 13	2.7	3400	13	2.8	3700
14	0.9 - 13	2.7	3400	13	2.8	3700
15	0.9 - 13	2.7	3400	13	2.8	3700
16	0.9 - 13	2.7	3400	13	2.8	3700
17	0.9 - 13	2.7	3400	13	2.8	3700
18	0.9 - 13	2.7	3400	13	2.8	3700
19	0.9 - 13	2.7	3400	13	2.8	3700
20	0.9 - 13	2.7	3400	13	2.8	3700
21	0.9 - 13	2.7	3400	13	2.8	3700
22	0.9 - 13	2.7	3400	13	2.8	3700
23	0.9 - 13	2.7	3400	13	2.8	3700
24	0.9 - 13	2.7	3400	13	2.8	3700
25	0.9 - 13	2.7	3400	13	2.8	3700
26	0.9 - 13	2.7	3400	13	2.8	3700
27	0.9 - 13	2.7	3400	13	2.8	3700
28	0.9 - 13	2.7	3400	13	2.8	3700
29	0.9 - 13	2.7	3400	13	2.8	3700
30	0.9 - 13	2.7	3400	13	2.8	3700
31	0.9 - 13	2.7	3400	13	2.8	3700
32	0.9 - 13	2.7	3400	13	2.8	3700
33	0.9 - 13	2.7	3400	13	2.8	3700
34	0.9 - 13	2.7	3400	13	2.8	3700
35	0.9 - 13	2.7	3400	13	2.8	3700
36	0.9 - 13	2.7	3400	13	2.8	3700
37	0.9 - 13	2.7	3400	13	2.8	3700
38	0.9 - 13	2.7	3400	13	2.8	3700
39	0.9 - 13	2.7	3400	13	2.8	3700
40	0.9 - 13	2.7	3400	13	2.8	3700
41	0.9 - 13	2.7	3400	13	2.8	3700
42	0.9 - 13	2.7	3400	13	2.8	3700
43	0.9 - 13	2.7	3400	13	2.8	3700

Appendix D

D1: Building type descriptions as written in FEMA and NIBS (2006a).

Building Type	Code	Description
Wood, Light Frame	W1	<p>“These are typically single- or multiple-family dwellings. The essential structural feature of these buildings is repetitive framing by wood rafters or joists on wood stud walls. Loads are light and spans are small. These buildings may have relatively heavy masonry chimneys and may be partially or fully covered with masonry veneer. Most of these buildings, especially the single family residences, are not engineered but constructed in accordance with “conventional construction” provisions of building codes. Hence, they usually have the components of a lateral-force-resisting system even though it may be incomplete. Lateral loads are transferred by diaphragms to shear walls. The diaphragms are roof panels and floors which may be sheathed with wood, plywood or fiberboard sheathing. Shear walls are exterior walls sheathed with boards, stucco, plaster, plywood, gypsum board, particle board, or fiberboard, or interior partition walls sheathed with plaster or gypsum board.”</p>
Wood, Commercial and Industrial	W2	<p>“These buildings are usually commercial or industrial buildings with a floor area of 5,000 ft² or more and with few, if any, interior walls. The essential structural character of these buildings is framing by beams or major horizontally spanning members over columns. These horizontal members may be glued-laminated wood, solid-sawn wood beams, or wood trusses, or steel beams, or trusses. Lateral loads are usually resisted by wood diaphragms and exterior walls sheathed with plywood, stucco, plaster, or other paneling. The walls may have diagonal rod bracing. Large openings for storefronts and garages often require post-and-beam framing. Lateral load resistance on those lines may be achieved with steel rigid frames (moment frames) or diagonal bracing.”</p>
Steel Moment Frame	S1	<p>“These buildings have a frame of steel columns and beams. In some cases, the beam-column connections have very small moment resisting capacity but, in other cases, some of the beams and columns are fully developed as moment frames to resist lateral forces. Usually the structure is concealed on the outside by exterior walls, which can be of almost any material (curtain walls, brick masonry, or</p>

		<p>precast concrete panels), and on the inside by ceilings and column furring. Lateral loads are transferred by diaphragms to moment resisting frames. The diaphragms can be almost any material. The frames develop their stiffness by full or partial moment connections. The frames can be located almost anywhere in the building. Usually the columns have their strong directions oriented so that some columns act primarily in one direction while the others act in the other direction. Steel moment frame buildings are typically more flexible than shear wall buildings. This low stiffness can result in large inter-story drifts that may lead to relatively greater non-structural damage.”</p>
Steel Braced Frame	S2	<p>“These buildings are similar to steel moment frame buildings except that the vertical components of the lateral-force-resisting system are braced frames rather than moment frames.”</p>
Steel Light Frame	S3	<p>“These buildings are pre-engineered and pre-fabricated with transverse rigid frames. The roof and walls consist of lightweight panels, usually corrugated metal. The frames are designed for maximum efficiency, often with tapered beam and column sections built up of light steel plates. The frames are built in segments and assembled in the field with bolted joints. Lateral loads in the transverse direction are resisted by the rigid frames with loads distributed to them by diaphragm elements, typically rod-braced steel roof framing bays. Loads in the longitudinal direction are resisted entirely by shear elements which can be either the roof and wall sheathing panels, an independent system of tension-only rod bracing, or a combination of panels and bracing.”</p>
Frame with Cast-In-Place Concrete Shear Walls	S4	<p>“The shear walls in these buildings are cast-in-place concrete and may be bearing walls. The steel frame is designed for vertical loads only. Lateral loads are transferred by diaphragms of almost any material to the shear walls. The steel frame may provide a secondary lateral-force resisting system depending on the stiffness of the frame and the moment capacity of the beam column connections. In modern “dual” systems, the steel moment frames are designed to work together with the concrete shear walls in proportion to their relative rigidities.”</p>
Steel Frame with Unreinforced Masonry Infill Walls	S5	<p>“This is one of the older types of buildings. The infill walls usually are offset from the exterior frame members, wrap around them, and present a smooth masonry exterior with no indication of the frame. Solidly in-filled masonry panels, when they fully engage the surrounding frame members</p>

		(i.e. lie in the same plane), provide stiffness and lateral load resistance to the structure.”
Reinforced Concrete Moment Resisting Frames	C1	“These buildings are similar to steel moment frame buildings except that the frames are reinforced concrete. There is a large variety of frame systems. Some older concrete frames may be proportioned and detailed such that brittle failure of the frame members can occur in earthquakes, leading to partial or full collapse of the buildings. Modern frames in zones of high seismicity are proportioned and detailed for ductile behaviour and are likely to undergo large deformations during an earthquake without brittle failure of frame members and collapse.”
Concrete Shear Walls	C2	“The vertical components of the lateral-force-resisting system in these buildings are concrete shear walls that are usually bearing walls. In older buildings, the walls often are quite extensive and the wall stresses are low but reinforcing is light. In newer buildings, the shear walls often are limited in extent, thus generation concerns about boundary members and overturning forces.”
Concrete Frame Buildings with Unreinforced Masonry Infill Walls	C3	“These buildings are similar to steel frame buildings with unreinforced masonry infill walls except that the frame is of reinforced concrete. In these buildings, the shear strength of the columns, after cracking of the infill, may limit the semi-ductile behaviour of the system.”
Precast Concrete Tilt-Up	PC1	“These buildings have a wood or metal deck roof diaphragm, which often is very large, that distributes lateral forces to precast concrete shear walls. The walls are thin but relatively heavy while the roofs are relatively light. Older buildings often have inadequate connections for anchorage of the walls to the roof for out-of-plane forces, and the panel connections often are brittle. Tilt-up buildings usually are one or two stories in height. Walls can have numerous openings for doors and windows of such size that the wall looks more like a frame than a shear wall.”
Precast Concrete Frames with Concrete Shear Walls	PC2	“These buildings contain floor and roof diaphragms typically composed of precast concrete elements with or without cast-in-place concrete topping slabs. The diaphragms are supported by precast concrete girders and columns. The girders often bear on column corbels. Closure strips between precast floor elements and beam-column joints usually are cast-in-place concrete. Welded steel inserts often are used to interconnect precast elements. Lateral loads are resisted by precast or cast-in-place

		concrete shear walls. For buildings with precast frames and concrete shear walls to perform well, the details used to connect the structural elements must have sufficient strength and displacement capacity; however, in some cases, the connection details between the precast elements have negligible ductility.”
Reinforced Masonry Bearing Walls with Wood or Metal Deck Diaphragms	RM1	“These buildings have perimeter bearing walls of reinforced brick or concrete-block masonry. These walls are the vertical elements in the lateral-force-resisting system. The floors and roofs are framed either with wood joists and beams with plywood or straight or diagonal sheathing, or with steel beams with metal deck with or without a concrete fill. Wood floor framing is supported by interior wood posts or steel columns; steel beams are supported by steel columns.”
Reinforced Masonry Bearing Walls with Precast Concrete Diaphragms	RM2	“These buildings have bearing walls similar to those of reinforced masonry bearing wall structures with wood or metal deck diaphragms, but the roof and floors are composed of precast concrete elements such as planks or tee-beams and the precast roof and floor elements are supported on interior beams and columns of steel or concrete (cast-in-place or precast). The precast horizontal elements often have a cast-in-place topping.”
Unreinforced Masonry Bearing Walls	URM	“These buildings include structural elements that vary depending on the building’s age and, to a lesser extent, its geographic location. In buildings built before 1900, the majority of floor and roof construction consists of wood sheathing supported by wood sub-framing. In large multi-story buildings, the floors are cast-in-place concrete supported by the unreinforced masonry walls and/or steel or concrete interior framing. In unreinforced masonry constructed after 1950 wood floors usually have plywood rather than board sheathing. In regions of lower seismicity, buildings of this type constructed more recently can include floor and roof framing that consists of metal deck and concrete fill supported by steel framing elements. The perimeter walls, and possibly some interior walls, are unreinforced masonry. The walls may or may not be anchored to the diaphragms. Ties between the walls and diaphragms are more common for the bearing walls than for walls that are parallel to the floor framing. Roof ties usually are less common and more erratically spaced than those at the floor levels. Interior partitions that interconnect the floors and roof can have the effect of reducing diaphragm displacements.”

Mobile Homes	MH	“These are prefabricated housing units that are trucked to the site and then placed on isolated piers, jack-stands, or masonry block foundations (usually without any positive anchorage). Floors and roofs of mobile homes usually are constructed with plywood and outside surfaces are covered with sheet metal.”
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D2: Occupancy class descriptions as described in FEMA and NIBS (2006b).

Occupancy Class	Code	Description
Residential		
Single Family Dwelling	RES1	House
Mobile Home	RES2	Mobile Home
Multi Family Dwelling	RES3	Apartments and condominiums
Temporary Lodging	RES4	Hotel, motel, bed and breakfast
Institutional Dormitory	RES5	Group housing (military, college)
Nursing Home	RES6	
Commercial		
Retail Trade	COM1	Store
Wholesale Trade	COM2	Warehouse
Personal / Repair Services	COM3	Service station, funeral home, Laundromat, etc
Professional / Technical Services	COM4	Offices
Banks	COM5	
Hospital	COM6	
Medical Office / clinic	COM7	
Entertainment and Recreation	COM8	Restaurants and Bars
Theatres	COM9	
Parking	COM10	Parking garages
Industrial		
Heavy	IND1	Factory
Light	IND2	Factory
Food / Drugs / Chemicals	IND3	Factory, college laboratory, etc.
Metals / Mineral Processing	IND4	Factory, college laboratory, etc.
High Technology	IND5	Factory, college laboratory, etc.
Construction	IND6	Warehouse
Agricultural		
Agriculture	AGR1	Warehouse
Religious / Non-profit		
Church / Non - profit	REL1	Church
Government		
General Services	GOV1	Town hall, courthouse, post office, etc.
Emergency Response	GOV2	Police and fire station
Education		
Grade Schools	EDU1	Elementary and high school
College and Universities	EDU2	College and university

Appendix E: Data Preparation

E.0 Introduction

HAZUS is a comprehensive and flexible software program which allows user-supplied input, but it was originally designed only 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. Given that the program is developed to retrieve information from databases to determine loss estimations, the possibility to manipulate these databases with non-American information exists and is the basis for applying HAZUS to an international setting.

There are drawbacks to manipulating 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. HAZUS provides only basic American databases which are the foundation of a level 1 analysis. A second drawback is that the program uses a fixed, and specific nomenclature to designate variables. A third drawback 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.

E.1 HAZUS methodology for an international setting at a local scale

To use HAZUS for an international setting at a local scale, a lengthy procedure needs to take place. 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: (1) Collecting, preparing and managing the required inventories and other loss estimation data. Data collection is covered in detail in the previous chapter while data preparation and management is explained in Section E.1.1. (2) Defining the study region using HAZUS specifications and identifications. (3) Creating the study region in a GIS, where the construction of geodatabases takes place outside the HAZUS program but uses exact HAZUS specifications. (4) Populating the geodatabases outside and within HAZUS. (5) Organizing geodatabases to their respective folders and modifying the configuration file needed to retrieve the new international data. Procedures for basic, user-supplied inputs, including susceptibility and ground-motion hazard maps, remain the same in both in American and international settings.

In this chapter, study region is a generic term to describe the international region being created for loss estimations at a local scale. Study area is the exact geographic area used in this research project, as defined in Section 1.3.

The following methodology requires a firm knowledge of GIS; only steps pertaining to the modification of HAZUS and geodatabase management, will be explained in detail.

E.1.1 Preparing and managing HAZUS inventories in ArcGIS

In order to use the newly acquired inventories (actual downtown Ottawa data) and information in HAZUS, the data needs to be prepared and managed using a GIS, in this case ArcGIS. ArcGIS is a widely used software program available commercially, and is built using the latest industry standards.

There are two major components of ArcGIS: ArcMap and ArcCatalogue. ArcMap creates layers and edits data, while ArcCatalogue searches for, previews and manages the geographic data.

For simplicity, loss estimation inventories are organized outside ArcGIS using a spreadsheet program, in this case Microsoft Excel. In this study, a master copy of all inventories was created using Microsoft Excel and further organized into a set of 10 worksheets representing information on each dissemination area within the study area. Individual worksheets contained information on sidewalk survey references and comments, geographic coordinates, specific building information such as building types and occupancy classes, square footage calculations in units of 1,000 ft², and a series of summary tables of square footage and building counts for general and specific

occupancies. The cost of each building (not including content cost) was calculated in a separate spreadsheet in units of \$1,000.

Once data are organized in Microsoft Excel, they must be projected and managed in ArcGIS. In this study, a new spreadsheet containing only the geographic coordinates (eastings and northings), and building identification numbers were entered and saved as a .dbf file. ArcMap will recognize the .dbf extension as a table containing xy data or geographical coordinates that can be added as a layer. At this stage, a complete building inventory has been created as a point file in ArcMap. To match HAZUS specifications, the projection of the building inventory point file must be changed to GCS NAD 1983 (Geographic Coordinate System – North American Datum).

All categories of critical facilities must be isolated and exported as new point files. In this study, the following individual point files were created: medical care facilities, emergency centres, schools, military installations, electric power facilities and communication facilities. These newly created point files will be revisited when the essential facilities, high potential loss facilities, and utilities geodatabases are ready to be populated.

E.1.2 HAZUS specifications and identifications

HAZUS will not function properly or at all if the correct specifications and identifications are not used and it is therefore imperative that the user understands the required data architecture. HAZUS defines its geographic boundaries using census data. There are three geographic levels that can be selected: State, county, and census tract. Considering that this study is based at a local level, the ‘census tract’ option was selected. However, for a finer resolution of loss estimations, dissemination areas were used in place of census tracts. The study area is divided into two census tracts, which can be further subdivided into 10 dissemination areas, refer to Figure 1.3a. It should be noted that HAZUS will list the 10 dissemination areas as census tracts, therefore, for consistency and clarity, dissemination areas are herein referred to as census tracts in Appendix E. The user must also apply the same geographic coordinate system as HAZUS, which is GCS NAD 1983.

The user must choose which United States state best represents their study region. In this research project, New York State was chosen for two reasons. First, it is the closest geographically to the study area. HAZUS contains an American database of past earthquakes; some events may apply to study regions that are close to the Canada – United States border. Second, both the study area and New York are located in eastern North America. HAZUS ground-motion prediction equations are selected for either the western United States (WUS) or central and eastern United States (CEUS), and it is imperative that the user chooses a State that is in the correct tectonic region. It is further assumed that construction practices in New York and Ontario may be broadly similar.

HAZUS utilizes Federal Information Processing Standards (FIPS) codes as a unique identifier for each census tract. FIPS are represented as an 11 digit code; the first 2 digits identify the State, the next 3 digits represent the County, and the remaining 6 digits represent the census tracts. The FIPS identifiers used for this study area are: State – New York (36), County – St. Lawrence County, renamed as ‘Ottawa’ (089) and the census tracts are (000001) to (000010), refer to Figures 1.3a, E.1 and E.2. Using the HAZUS identification (FIPS) ensures that the loss estimation can be run but the international study regions are listed as if they existed within the United States. In this research project, HAZUS lists Ottawa as being located in New York State.

E.1.3 Creating a study region

Creation of a study region requires several steps. Numerous steps outlined in this project are also presented in Hansen and Bausch (2007). Steps marked with an (*) have been modified or added by the author for a study region at a local scale. These steps reference the procedure used for this research project (the Canadian setting of Ottawa, Canada). Since HAZUS was developed for explicit use in the United States, geodatabases in the New York folder must be replaced with the new local data.

1. In order for the data to remain organized, it is beneficial to create temporary folders and datasets. In the working directory of your choice, create the following folders to set the working environment:
 - a) FinalData, a folder to contain the final geodatabases that will replace your New York folder.

Create New Region

Census Tract Selection

The census tract selection defines the census tract(s) within previously selected counties, to include in the study region.

Please select the census tract(s) for the study region you want to create.

Counties:

Ottawa, NY

Sort by state

Tracts (10 selected):

36089000001
36089000002
36089000003
36089000004
36089000005
36089000006
36089000007
36089000008
36089000009
36089000010

Total: 10

☐ Auto select all

Select all tracts

Deselect all tracts

Show map

< Back Next > Cancel

Figure E.1. The 'Create New Region' wizard window in HAZUS indicating the FIPS of the study area; Ottawa is listed as being in New York State.

Figure E.2. Map of the study area showing the FIPS identifiers for each dissemination area (Data Sources: Statistics Canada).

- b) OrigData, a folder to contain the original New York geodatabases.
 - c) IntData, a folder to contain intermediate geodatabases that will be loaded into the FinalData folder.
 - d) syBoundary, a folder to contain the syBoundary.mbd geodatabase that will be edited.
 - e) Working, a folder to contain the working directory to store intermediate datasets and any GIS layers or feature classes (a geodatabase that stores text or graphics about the feature/layer) that you may wish to work with.
2. Copy the syBoundary.mdb geodatabase from HAZUS data DVD #6 into the syBoundary folder.
 3. Copy the geodatabases presented in Figure E.3 from the original NY1 (New York) folder into the FinalData and OrigData folders.
 4. In ArcCatalogue, delete the existing feature classes and tables in each geodatabase in the FinalData folder.
 5. Replace the deleted feature classes and tables in the FinalData folder with new empty datasets using the following sub-steps:
 - a) In ArcCatalogue, add a new feature class to the bndrygbs.mdb named **hztract**.

Figure E.3. A list of geodatabases to be copied from the OrigData folder to the FinalData folder.

- b) In the 'Field Definition' window, import the **hztract** feature class from the OrigData folder. The Field properties are the following: Geometry Type – Polygon, and Spatial Reference – GCS_North_American_1983.
 - c) Repeat sub-steps (a) and (b) for the feature classes and tables located in the FinalData folder and listed in Figure E.4.
6. Copy the new set of geodatabases from the FinalData folder into the IntData folder.
 7. Add a new field, a population ratio field, to specific tables in geodatabase bndrygbs.mdb in the IntData folder. The population ratio field is used to distribute the general building inventory over the study region as a default setting, unless the building inventory is upgraded.
 - a) In ArcCatalogue, select the properties of the **hzBldgCountOccupT** table.
 - b) In the 'Table Properties' window add a new field named *POP_RATIO* as type 'Double'.
 - c) Repeat the sub-steps (a) and (b) for the **hzExposureContentOccupT**, **hzExposureOccupT**, and **hzSqFootageOccupT** tables.
 8. (*) For contingency, make a copy of all the empty geodatabases, in the event that the methodology needs to be revisited unexpectedly in the future (optional).

bndrygbs.mdb <ul style="list-style-type: none"> eqTractAttribs hzBldgCountOccupT hzCounty hzDemographicsT hzExposureContentOccupT hzExposureOccupT hzMeansCountyLocationFactor hzSqFootageOccupT hzTract 	EF.mdb <ul style="list-style-type: none"> eqCareFlty eqEmergencyCtr eqFireStation eqPoliceStation eqSchool hzCareFlty hzEmergencyCtr hzFireStation hzPoliceStation hzSchool 	HPLF.mdb <ul style="list-style-type: none"> eqDams eqHazmat eqLevees eqMilitary eqNuclearFlty hzDams hzHazmat hzLevees hzMilitary hzNuclearFlty 	TRN.mdb <ul style="list-style-type: none"> eqAirportFlty eqBusFlty eqFerryFlty eqHighwayBridge eqHighwaySegment eqHighwayTunnel eqLightRailBridge eqLightRailFlty eqLightRailSegment eqLightRailTunnel eqPortFlty eqRailFlty eqRailwayBridge eqRailwaySegment eqRailwayTunnel eqRunway hzAirportFlty hzBusFlty hzFerryFlty hzHighwayBridge hzHighwaySegment hzHighwayTunnel hzLightRailBridge hzLightRailFlty hzLightRailSegment hzLightRailTunnel hzPortFlty hzRailFlty hzRailwayBridge hzRailwaySegment hzRailwayTunnel hzRunway 	UTIL.mdb <ul style="list-style-type: none"> eqCommunicationFlty eqElectricPowerFlty eqNaturalGasDL eqNaturalGasFlty eqNaturalGasPl eqOilFlty eqOilPl eqPotableWaterDL eqPotableWaterFlty eqPotableWaterPl eqWasteWaterDL eqWasteWaterFlty eqWasteWaterPl hzCommunicationFlty hzElectricPowerFlty hzNaturalGasFlty hzNaturalGasPl hzOilFlty hzOilPl hzPotableWaterFlty hzPotableWaterPl hzWasteWaterFlty hzWasteWaterPl
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Figure E.4. A list of feature classes (38) and tables (46) (denoted by point, line, polygon, and table symbols) within the geodatabases with new empty datasets that need to be loaded.

The next set of steps is to prepare and upload a GIS layer that defines the geographic boundaries of the study region into the geodatabases.

9. In ArcMap, open the polygon layer that defines your (1) study region unit boundaries and (2) study region boundaries. In this research project, the unit boundaries were defined by 10 polygons representing the 10 dissemination areas in the study area (listed as census tracts) as illustrated in Figure 1.3. The study region boundary consists of only 1 polygon which is the perimeter of the entire study region. Name the study region unit boundary as *Region_Unt* and the study region boundary as *Region_Bnd*.

10. Add new fields to the *Region_Unt* Attributes Table. This series of sub-steps are required by HAZUS and the field names must be exactly the same as those used in HAZUS.

ai) Add a new field named *OBJECTID* as type 'ShortInt'. This field will be used to calculate the FIPS for the census tracts.

aii) Begin an edit session. Edit the *OBJECTID* field and number sequentially the census tracts from 1 to 10. Save and end the edit session.

bi) Add a new field named *GRID_CODE* as type 'Double'. This field will be used to calculate the population ratio.

bii) Begin an edit session. Edit the *GRID_CODE* field and add the populations for each census tract. Save and end the edit session.

- c) In the Attribute Table of Region_Unt, choose the 'Statistics' option of the *GRID_CODE* field. Record the Sum (the population of the study area is 5,956 according to Statistics Canada; the sum of the residential population at 2:00am), which represents the total population in the study area.
- di) Add a new field named *POP_RATIO* as type 'Double'.
- dii) Begin an edit session. Edit the *POP_RATIO* field by using the 'Calculate Values' option. Enter the expression illustrated in Figure E.5 in the Field Calculator. Save and end the edit session.

11. Calculate identification codes using FIPS.

- ai) In the Region_Unt Attribute Table, add a new field named *Tract* as type 'Text', with a length of 11.
- aii) Begin an edit session. Edit the *Tract* field by using the 'Calculate Fields' option. Check the advanced box and enter the VBA (Visual Basic Applications) Script Code presented in Figure E.6. Save and end the edit session. In the 11 digit FIPS identifier, the first 2 digits (36) identify the State as New York, the next 3 digits (089) identify the County as St. Lawrence County, and the last 6 digits (000001) to (000010) identify the census tract.
- bi) Add a new field named *Tract6* as type 'Text', with a length of 6.
- bii) Begin an edit session. Edit the *Tract6* field by using the 'Calculate Fields' option. Enter the expression shown in Figure E.7 in the Field Calculator. Save and end the edit session. This will compute the last 6 digits of the FIPS.

Figure E.5. Field calculator expression for *POP_RATIO* field.

Figure E.6. Field calculator expression (VBA script) for the *Tract* field (Hansen and Bausch, 2007).

Figure E.7. Field calculator expression for *Tract6* field.

- ci) Add a new field named *CountyFips* as type 'Text', with a length of 5.
- cii) Begin an edit session. Edit the *CountyFips* field by using the 'Calculate Values' option. Enter the expression "36089." Save and end the edit session. This 5 digit code is the State and County identifier for St. Lawrence County in New York.
- di) Add a new field named *TractArea*, as type 'Float'.
- dii) (*) Begin an edit session. Edit the *TractArea* field by using the 'Calculate Values' option. Enter the expression presented in Figure E.8. Save and end the edit session. This expression can only be used if the geographic coordinate system is already (GCS) in NAD 1983. If the GCS is not NAD 1983, refer to the expression used in Hansen and Bausch (2007).
- ei) Add a new field named *CenLat*, as type 'Double'.
- eii) Begin an edit session. Edit the *CenLat* field by using the 'Calculate Values' option. Enter the expression shown in Figure E.9. Save and end edit session.
- fi) Add a new field named *CenLongit*, as type 'Double'.
- fii) Begin an edit session. Edit the *CenLongit* field using the 'Calculate Values' option. Enter the expression illustrated in Figure E.10. Save and end the edit session.
- gi) (*) Add a new field named *NumAggrBoc*, as type 'Long Integer'.
- gii) Begin an edit session. Edit the *NumAggrBoc* field by using the 'Calculate Values' option. Enter the following expression: "1". Save and end the edit session. The *NumAggrBocs* field is designated to show the number of census blocks within a study region. However, the earthquake module in HAZUS can operate only as

Figure E.8. Field calculator expression (modified VBA script) for *TractArea* field. This script can only be used if the GCS is NAD 1983 (Hansen and Bausch, 2007).

Figure E.9. Field calculator expression (VBA script) for *CenLat* field (Hansen and Bausch, 2007).

Figure E.10. Field calculator expression (VBA script) for *CenLongit* field (Hansen and Bausch, 2007).

low as the census tract level, and the program will not accept a null value, and therefore, a factor of 1 is inserted.

hi) (*) Add a new field named *BldgScheme*, as type 'Text', with length of 5.

hii) Begin an edit session. Edit the *BldgScheme* field by using the 'Calculate Values' option. Enter the following expression: "NY1". Save and end the edit session. The *BldgScheme* field identifies which default building inventory is used, in this case NY1 represents New York State. This value will be utilized in the scenarios only as a default; the user has the ability to upgrade the default settings to better reflect local inventories.

i) (*) In the 'Display' Window, choose the 'Properties' option from the Region_Unt layer. Under the tab name 'Fields' add the aliases of *NumAggrBocks* and *BldgSchemesId* to *NumAggrBoc* and *BldgSchemes*, respectively.

E.1.4 Populating the geodatabases

At this stage in the methodology, most of the loss estimation data has been organized and prepared to meet HAZUS specifications. The following is the procedure to populate the intermediate geodatabases into the IntData folder that will eventually be uploaded into the final geodatabases in the FinalData folder.

12. Load data into the intermediate databases in the IntData folder by using the 'Simple Data Loader' option. The Region_Unt file created in steps 9 to 11 will be

uploaded to the following databases: **hztract**, **hzBldgCountOccupT**, **hzExposureContentOccupT**, **hzExposureOccupT**, **hzSqFootageOccupT**, and **DemographicsT**. In the ‘Simple Data Loader’ window, all fields should automatically find their counterparts. The exceptions are: (1) **hztract** and the matching source field of *length*. (2) **hzBldgCountOccupT**, **hzExposureContentOccupT**, **hzExposureOccupT**, and **hzSqFootageOccupT** where the only matching source fields are *Tract* and *POP_RATIO*. (3) **DemographicsT** where the only matching source field is *Tract*.

13. Similar to the previous step, load the Region_Bnd dataset into the **hzCounty** feature class. In this step, none of the fields will match. In order to calculate the missing fields, the following steps are needed:
 - a) In ArcMap, open **hzCounty** feature class from the FinalData folder.
 - b) Begin an edit session. Manually edit the following fields: *CountyFips* = “36089”, *CountyFips3* = “001”, *CountyName* = “Ottawa”, *State* = “NY”, *StateFips* = “36” and *NumAggrTract* = “10”. Save and end the edit session.
14. Load the data into the final geodatabases in the FinalData folder using the ‘Simple Data Loader’ option. Load the following data from the IntData folder to the FinalData folder: **hzTract**, **hzCounty**, **hzBldgCountOccupT**, **hzExposureContentOccupT**, **hzExposureOccupT**, **hzSqFootageOccupT** and **DemographicsT**.

At this stage, the databases have defined geographic boundaries based on the new Canadian data. Specific data including number of buildings, demographics, etc., however, has not yet been loaded into the geodatabases. The steps needed to complete this task are as follows:

15. (*) In ArcMap, input the tabulated data into the geodatabase tables and feature classes.
 - a) Open the **hzBldgCountOccupT** table.
 - b) Begin an edit session. Manually input the building count for each building type based on the summary table found in the building inventory spreadsheet. Save and end the edit session.
 - c) Repeat sub-steps (a) and (b) for **hzDemographics** (add population relevant data for casualty calculations), **hzExposureContentOccupT** (this study did not include content cost), **hzExposureOccupT** (add building costs in units of \$1,000, as tabulated previously in Microsoft Excel), and **hzSqFootageOccupT** (add building square footage in units 1,000 ft², as tabulated previously in Microsoft Excel).
16. (*) In ArcMap, open the critical facility point files, in GCS NAD 1983, as created in section E.1.1.
 - a) Open the medical care facilities point file.

- b) Add a new field named *Tract* as type 'Text', with length of 11. Add another new field named *CareFltyId* as type 'Text', with length of 8.
- c) Start an edit session. Edit the *Tract* field. Manually input the census tract to which each medical care facility is located. Use HAZUS identifications as computed in step 11a. For example, if the medical facility is located in the first census tract, the identification would be 36089000001, where 36 represents the State, 089 represents the County and 000001 represents the census tract. Edit the *CareFltyId* field. Manually input the code NY000001. For example, in this research project only three medical care facilities are located in the study area and therefore, the *CareFltyId* was listed from NY000001 to NY000003. Save and end the edit session.
- d) Repeat sub-steps (a), (b) and (c) for every category of critical facilities located within the study region. In this research project, the following is a list of critical facilities and their respective identifiers located within the study area: medical care facilities (*CareFltyId*), emergency centers (*EocId*), schools (*SchoolId*), military installations (*MilitaryFltyId*), electric power facilities (*ElectricPowerFltyId*), and communication facilities (*CommunicationId*).

17. (*) In ArcCatalogue, load the critical facility point files created in the previous step and in Section E.1.1. to their respective feature classes and tables in the FinalData folder using the 'Simple Data Loader' option. In all cases, the *Tract*

and the critical facility *Id* fields should automatically find their counterparts for the feature class files, and only the *Id* field for the tables.

18. (*) In ArcMap, open the *hzCareFlty* feature class from the FinalData folder.
 - a) Begin an edit session and manually input the required information, as listed in Appendix A1. Save and end the edit session.
 - b) Repeat step (a) for all critical facility feature classes and tables.
19. (*) In ArcCatalogue, verify that the new inventory information has been loaded properly, and preview the graphical and tabular data.
20. (*) User-supplied hazard maps of ground-motion, using relations presented in Atkinson and Boore (2006) will be input into the HAZUS program for analysis. This option requires that the fragility curve database (the probability of reaching or exceeding various damage states for a given building response) be modified to match with the default fragility curves for the New York building inventory. This will ensure that when default ground-motions of the study region are run against their user-supplied hazard map equivalent, the losses should be identical. For example, both the Atkinson and Boore (1995) HAZUS option and the Atkinson and Boore (1995) calculated values in a user-supplied hazard map should lead similar losses.

- a) Navigate to the Fragility Curve database via Program Files > HAZUS-MH > DATA > EQ > EqAnalParams.
- b) Open the Fragility Curve database in Microsoft Access and choose the eqFragilityCurve database.
- c) Copy and paste the entire dataset into Microsoft Excel.
- d) Modify the following values: ReturnPeriod, SlightMedian, SlightBeta, SlightOffset, ModerateMedian, ModerateBeta, ModerateOffset, ExtensiveMedian, ExtensiveBeta, ExtensiveOffset, CompleteMedian, CompleteBeta and CompleteOffset, for the CategoryId of GBS_SFC, GBS_NSD and GBS_NSA, according to Figure E.11 (E. Escalona, personal communication, 2008). This example is for the Structural Fragility Curves for C1H with the default data and the modified data; all user-defined fragility values are replaced by the standard NY default values.

At this stage, all geodatabases have been modified and loaded with Canadian data, with the exception of the building type database. The final step is to load the new Canadian files into the NY1 aggregation folder which will replace the original NY1 aggregation data. HAZUS will retrieve all the data from this 'run' folder.

21. Copy the geodatabases in the FinalData folder to the NY1 aggregation folder.

DesignLevel	ReturnPeriod	SlightMedian	SlightBeta	SlightOffset	ModerateMedian	ModerateBeta	ModerateOffset	ExtensiveMedian	ExtensiveBeta	ExtensiveOffset	CompleteMedian	CompleteBeta	CompleteOffset	CategoryId
HC	0	2.16	0.66	0	4.32	0.64	0	12.96	0.67	0	34.56	0.78	0	GBS_SFC_HCODE0 High-Code
HC	-1	2.16	0.66	0	4.32	0.64	0	12.96	0.67	0	34.56	0.78	0	GBS_SFC_HCODE100 High-Code / User Defined
LC	0	2.16	0.7	0	3.46	0.81	0	8.64	0.89	0	21.6	0.97	0	GBS_SFC_LCODE0 Low Code
LC	-1	2.16	0.7	0	3.46	0.81	0	8.64	0.89	0	21.6	0.97	0	GBS_SFC_LCODE100 Low - Code / User Defined
MC	0	2.16	0.66	0	3.74	0.67	0	10.08	0.76	0	25.92	0.91	0	GBS_SFC_MCODE0 Moderate Code
MC	-1	2.16	0.66	0	3.74	0.67	0	10.08	0.76	0	25.92	0.91	0	GBS_SFC_MCODE100 Moderate - Code / User Defined
PC	0	1.73	0.71	0	2.76	0.8	0	6.91	0.94	0	17.28	1.01	0	GBS_SFC_PCODE0 Pre - Code
PC	-1	1.73	0.71	0	2.76	0.8	0	6.91	0.94	0	17.28	1.01	0	GBS_SFC_PCODE100 Pre - Code / User Defined
HS	0	2.16	0.66	0	4.32	0.64	0	12.96	0.67	0	34.56	0.78	0	GBS_SFC_HSUP0 Special High - Code
HS	-1	2.16	0.66	0	4.32	0.64	0	12.96	0.67	0	34.56	0.78	0	GBS_SFC_HSUP100 Special High - Code / User Defined
LS	0	2.16	0.7	0	3.46	0.81	0	8.64	0.89	0	21.6	0.97	0	GBS_SFC_LSUP0 Special Low - Code
LS	-1	2.16	0.7	0	3.46	0.81	0	8.64	0.89	0	21.6	0.97	0	GBS_SFC_LSUP100 Special Low - Code / User Defined
MS	0	2.16	0.66	0	3.74	0.67	0	10.08	0.76	0	25.92	0.91	0	GBS_SFC_MSUP0 Special Moderate - Code
MS	-1	2.16	0.66	0	3.74	0.67	0	10.08	0.76	0	25.92	0.91	0	GBS_SFC_MSUP100 Special Moderate - Code / user Defined

DesignLevel	ReturnPeriod	SlightMedian	SlightBeta	SlightOffset	ModerateMedian	ModerateBeta	ModerateOffset	ExtensiveMedian	ExtensiveBeta	ExtensiveOffset	CompleteMedian	CompleteBeta	CompleteOffset	CategoryId
HC	0	2.16	0.66	0	4.32	0.64	0	12.96	0.67	0	34.56	0.78	0	GBS_SFC_HCODE0 High-Code
HC	-1	2.16	0.5	0	4.32	0.5	0	12.96	0.5	0	34.56	0.5216321	0	GBS_SFC_HCODE100 High-Code / User Defined
LC	0	2.16	0.7	0	3.46	0.81	0	8.64	0.89	0	21.6	0.97	0	GBS_SFC_LCODE0 Low Code
LC	-1	2.16	0.5	0	3.46	0.53294	0	8.64	0.5639371	0	21.6	0.5960075	0	GBS_SFC_LCODE100 Low - Code / User Defined
MC	0	2.16	0.66	0	3.74	0.67	0	10.08	0.76	0	25.92	0.91	0	GBS_SFC_MCODE0 Moderate Code
MC	-1	2.16	0.5	0	3.74	0.5	0	10.08	0.5141984	0	25.92	0.571861	0	GBS_SFC_MCODE100 Moderate - Code / User Defined
PC	0	1.73	0.71	0	2.76	0.8	0	6.91	0.94	0	17.28	1.01	0	GBS_SFC_PCODE0 Pre - Code
PC	-1	1.73	0.5	0	2.76	0.5291502	0	6.91	0.5838664	0	17.28	0.6123928	0	GBS_SFC_PCODE100 Pre - Code / User Defined
HS	0	2.7	0.63	0	5.4	0.63	0	16.2	0.63	0	43.2	0.69	0	GBS_SFC_HSUP0 Special High - Code
HS	-1	2.7	0.5	0	5.4	0.5	0	16.2	0.5	0	43.2	0.5	0	GBS_SFC_HSUP100 Special High - Code / User Defined
LS	0	2.7	0.66	0	4.32	0.71	0	10.8	0.79	0	27	0.94	0	GBS_SFC_LSUP0 Special Low - Code
LS	-1	2.7	0.5	0	4.32	0.5	0	10.8	0.5253808	0	27	0.5838664	0	GBS_SFC_LSUP100 Special Low - Code / User Defined
MS	0	2.7	0.64	0	4.68	0.64	0	12.6	0.68	0	32.4	0.82	0	GBS_SFC_MSUP0 Special Moderate - Code
MS	-1	2.7	0.5	0	4.68	0.5	0	12.6	0.5	0	32.4	0.5367495	0	GBS_SFC_MSUP100 Special Moderate - Code / user Defined

Figure E.11. Example (provided by Eduardo Escalona) showing the modifications to the fragility curve dataset. The modified database is the top table, while the original database is the bottom table. This specific example is for the Structural Fragility Curves for C1H with the default data and the modified data (Eduardo Escalona, personal communication, 2008).

22. Edit the syBoundary.mbd database with the geographic boundary files.

- a) In ArcMap, add **syState**, **syCounty** and **syTract** feature classes from the syBoundary folder.
- b) Begin an edit session. Delete all features referencing New York in each feature class. Use the following queries, using the 'Selection by Attribute' option, for each dataset to select the appropriate NY features. Save and end the edit session.

syState – *StateFips* = "36"

syCounty – *CountyFips* LIKE '36*'

syTract – *Tract* LIKE "36*"

23. Load data into the syBoundary.mdb database.

- a) Load **hzTract**, using the 'Simple Data Loader', from the FinalData folder into the **hzTract** of the syBoundary file. All fields should automatically find their counterparts.
- b) Load **hzCounty** from the FinalData folder into the **syCounty** of the syBoundary file. All the fields should automatically find their counterparts except for the *NumTracts* field, which will have to be selected manually to match *NumAggrTracts*.
- c) Load **hzCounty** from the FinalData folder into the **syState** of the syBoundary file. There will be no Matching Source Fields for State, Name, Region, NumCounties, HUState. Calculate these fields, use the following procedure:
 - ci) In ArcMap, open the **syState** feature class from the syBoundary folder.
 - cii) Begin an edit session. Manually edit the **syState** feature class with the data listed below: Save and end the edit session.

StateName = "Canada"

Region = "0"

NumCounties = "1"

HUState = "0"

24. Copy the syBoundary to the run folder. This folder will already contain the NY1 folder. The final folder should contain the following information illustrated in Figure E.12.

25. (*) Any changes made to a geodatabase, in the event Canadian data are updated, must be performed in the FinalData folder. The entire geodatabase must be copied and pasted into the NY1 file. Errors in the HAZUS program will occur if only a single feature class or table is transferred.

At this stage of the methodology, HAZUS is able to run loss estimations using the default building types and ground-motion relations available in the program. Upgrades and enhancements to the general building inventory will be performed with an 'Occupancy Mapping' option embedded within the HAZUS program. This is step 28, and will be explained once the HAZUS program is functioning properly and retrieving the new Canadian data.

Figure E.12. Folders and geodatabases in the final 'run' folder. It is imperative that all required files are updated and located within this folder.

E.1.5 HAZUS configuration and program set up

HAZUS is designed to retrieve data from an accompanying DVD data set. In order for HAZUS to retrieve the new Canadian data, the configuration file must be modified. The following steps outline the procedure to modify this file (D. Bausch, personal communication, 2007).

26. (*) In the Windows start menu, select the 'Run' option. Enter the following:

'regedit' and the 'Registry Editor' window will appear. Follow these steps exactly to prevent any damage to your Window's registry.

- a) Navigate to HKey Local Machine > Software > FEMA > HAZUS > GENERAL and select DataPath1.
- b) Change the folder path to the run folder, as illustrated in Figure E.13. It should be noted that the folder path must end with a backslash ('\').

All the required information has now been supplied for HAZUS to function properly. The following is the procedure to set up the international study region in HAZUS.

The screenshot shows the FEMA HAZUS-MH configuration window. On the left, a tree view shows the folder structure: FEMA > HAZUS-MH > EQ > EqDataBrowser > General. The 'General' folder is selected. On the right, a table displays configuration data for two data paths.

Name	Type	Data
DataPath1	REG_SZ	C:\Documents and Settings\sploeger\My Documents\HAZUS_GA2\run_GA2\
DataPath2	REG_SZ	NONE_

Figure E.13. Folder path for HAZUS configuration.

27. Open HAZUS. Create a new project using the Create New Region Wizard.

- a) Select 'Create a New Region'.
- b) Enter the study region name and description, refer to Figure E.14.
- c) Select the earthquake hazard type, illustrated in Figure E.15, which should be the only available option.
- d) Select census tract as the Aggregation Level, refer to Figure E.16.
- e) Select Canada, NY, as the State Selection, refer to Figure E.17.
- f) Select Ottawa, as the County Selection, refer to Figure E.18.
- g) Select the 'Select all tracts' option, as the census tract selection, refer to Figure E.1.
- h) A processing bar will appear as the program retrieves the new Canadian data.

Once completed, the study region will appear in the HAZUS program window.

The screenshot shows a software window titled "Create New Region" with a standard Windows-style title bar (blue with a close button). The window is divided into sections. The top section, titled "Study Region Name", contains the instruction "Each study region needs to identified with a unique name." and a small map of the United States. The middle section prompts the user to "Enter below a name which uniquely identifies your region. The name can be up to 50 characters long." and features a text input field containing "Ottawa, Ontario, Canada". Below this, a section labeled "Region description (optional):" has a text input field containing "2 census tracts / 10 dissemination areas in downtown Ottawa". The bottom of the window contains three buttons: "< Back", "Next >" (which is highlighted with a black border), and "Cancel".

Create New Region

Study Region Name
Each study region needs to identified with a unique name.

Enter below a name which uniquely identifies your region. The name can be up to 50 characters long.

Ottawa, Ontario, Canada

Region description (optional):

2 census tracts / 10 dissemination areas in downtown Ottawa

< Back Next > Cancel

Figure E.14. 'Create New Region' wizard window for Study Region Name.

Figure E.15. 'Create New Region' wizard window for Hazard Type selection.

The screenshot shows a software window titled "Create New Region". Inside, the section "Aggregation Level" is highlighted. Below the title, a text box explains that the aggregation level defines the study procedure. To the right is a small map of the United States. The main area contains instructions to choose from four geographic levels: State, County, Census tract, and Census block. The "Census tract" option is selected with a radio button. At the bottom, there are three buttons: "< Back", "Next >", and "Cancel".

Create New Region

Aggregation Level
The aggregation level defines the procedure by which the study is defined.

You can define your study region at one of four geographic levels. We call this the aggregation level. Please select below the aggregation level you want to use.

☐ State

☐ County

☒ Census tract

☐ Census block

< Back Next > Cancel

Figure E.16 'Create New Region' wizard window for Aggregation Level selection.

Figure E.17. 'Create New Region' wizard window for State selection.

The screenshot shows a software window titled "Create New Region" with a close button in the top right corner. Below the title bar, the section is titled "County Selection" in bold. A descriptive text states: "The county selection defines the county or counties within previously selected state(s), to include in the study region." To the right of this text is a small map of the United States with one state highlighted in yellow. Below the text, a prompt reads: "Please select the county or counties for the study region you want to create." There are two list boxes: "States:" containing "Canada (NY)" and "Counties (1 selected):" containing "Ottawa". To the right of these list boxes are three buttons: "Select all counties", "Deselect all counties", and "Show map". Below the "Counties" list box, it says "Total: 1". At the bottom right, there is a checkbox labeled "Auto select all" which is currently unchecked. At the very bottom of the window are three buttons: "< Back", "Next >", and "Cancel".

Create New Region

County Selection

The county selection defines the county or counties within previously selected state(s), to include in the study region.

Please select the county or counties for the study region you want to create.

States: Canada (NY)

Counties (1 selected): Ottawa

Select all counties

Deselect all counties

Show map

Total: 1

☐ Auto select all

< Back Next > Cancel

Figure E.18. 'Create New Region' wizard window for County selection.

E.1.6 Incorporating user-supplied data

At this stage, the manipulated HAZUS program can run loss estimations using the ground-motion prediction equations provided in the program, including Atkinson and Boore (1995). The program has relevant information on the critical facilities, demographics, number of buildings and their assigned occupancy classes in the study region, but not on the building types. Without modifications to the building type inventory, the program will use the NY1 default distribution as assigned in step 11h in the *BldgScheme* field. To modify building type, the following steps are required:

28. (*) In the HAZUS program, navigate to Occupancy Mapping via Inventory > General Building Stock.
 - a) Create a new mapping scheme based on the NY1 data. Name the new scheme after a census tract within the study region. This will ensure that the schemes are organized in a logical order.
 - b) Occupancy mapping is based off of percentages, therefore tallying must be done in Microsoft Excel. For example, if in census tract 36089000001, there are 6 wood and 4 masonry RES1 buildings, the percentage would be 60% and 40%, respectively. Once tallied, input the percentage into each cell, as illustrated in Figure E.19. It should be noted that if no buildings of that building type exist, insert 100 under 'Manu. Housing %'. There are no mobile homes within the study area, and therefore the program will not retrieve any information listed under manufactured housing.

Parameters for 690. Right-click cell for context menu.

Occupancy	Wood %	Concrete %	Steel %	Masonry %	Manu. Housing %	Total
RES1	60	0	0	40	0	100
RES2	0	0	0	0	100	100
RES3A	54	0	0	46	0	100
RES3B	67	0	0	33	0	100
RES3C	100	0	0	0	0	100
RES3D	0	0	0	0	100	100
RES3E	0	0	0	0	100	100
RES3F	0	100	0	0	0	100
RES4	0	100	0	0	0	100
RES5	0	0	0	0	100	100
RES6	0	100	0	0	0	100
COM1	0	22	0	78	0	100
COM2	0	0	0	0	100	100
COM3	0	0	0	100	0	100
COM4	50	0	50	0	0	100
COM5	0	0	0	0	100	100
COM6	0	0	0	0	100	100
COM7	0	100	0	0	0	100
COM8	0	25	0	75	0	100
COM9	0	0	0	0	100	100
COM10	0	100	0	0	0	100
IND1	0	0	0	0	100	100
IND2	0	0	0	0	100	100
IND3	0	0	0	0	100	100
IND4	0	0	0	0	100	100
IND5	0	0	0	0	100	100
IND6	0	0	0	0	100	100
AGR1	0	0	0	0	100	100
REL1	0	0	0	100	0	100
GOV1	0	0	0	0	100	100
GOV2	0	0	0	0	100	100
EDU1	0	0	0	100	0	100
EDU2	0	0	0	0	100	100

Figure E.19. 'New Mapping Scheme' window for occupancy mapping. All values are based on percentages. Census tract 690 is the Statistics Canada identification for census tract 36089000001.

- c) To provide specific data on each building type, assign a new building type distribution. A new table will appear. Manually input the percentage of each building type in association to its seismic design level, as presented in Figure E.20.
- d) Repeat sub-steps (a) to (c) for all 10 census tracts and all occupancy classes within each scheme.

It is strongly suggested that a template is created of this project file; it has all the relevant data needed for loss estimations, with the exception of the user-supplied hazard maps. In some cases, once user-supplied maps are input into the project, they cannot be removed and therefore no new scenarios can be performed unless step 28 is repeated in the new project file. In the 'Create New Region Wizard' of HAZUS, choose to duplicate this region and name it TEMPLATE. When new projects are started, make a duplicate of this template providing a new name for each project.

All hazard maps should be stored in a geodatabase, which requires a specific procedure to take place. Before creating a geodatabase, the user-supplied maps must have correct HAZUS identifications.

29. (*) In ArcMap, open all PESH files created in Chapter 2.

- a) Open the Attribute Table for the map of NEHRP classes.
- b) Add a new field named Type as type 'Text' with a length of 1.

Type Distribution for RES1 -Masonry

Tallied building type:

Seismic design level:

DesignLevel	RM1LP	RM1MP	RM2LP	RM2MP	RM2HP	URMLP	URMMP
LC	0	0	0	0	0	25	0
LS	0	0	0	0	0	0	0
PC	0	0	0	0	0	50	25
MC	0	0	0	0	0	0	0
MS	0	0	0	0	0	0	0
HC	0	0	0	0	0	0	0
HS	0	0	0	0	0	0	0

Figure E.20. 'Type Distribution for RES1 – Masonry' window for occupancy mapping. Tallied building type and seismic design level values are input as percentages.

- c) Begin an edit session, and manually input the associated NEHRP class in each cell. Save and end the edit session.
- d) Repeat sub-steps (a) to (c) for the liquefaction and landslide susceptibility maps. These new fields, however, will be named Type as type 'Short Integer'. Liquefaction susceptibility ranges from 0 to 5, and landslide susceptibility ranges from 0 to 10.

30. (*) In ArcMap, open all ground-motion files created in Chapter 2. There are 4 ground-motion maps: PGA, PGV, Sa(0.3s) and Sa(1.0s).

- a) Open the Attribute Table for the PGA map.
- b) Add a new field named ParamValue as type 'Double'.
- c) Begin an edit session, and manually input the associated ground-motion values, including any soil amplifications. In this research project, this step was completed using Boore's SITEAMP program and nonlinearity calculations described in Chapter 2. Save and end the edit session.
- d) Repeat sub-steps (a) to (c) for the PGV, Sa(0.3s), Sa(1.0s) ground-motion layers.

31. (*) In ArcCatalogue, create a new geodatabase in the working directory of your choice.

- a) Create a new feature class for each hazard map. In the 'New Feature Class' window, the SHAPE is listed as polygon and the geographic coordinates should

be set to GCS NAD 1983. The fields and their types that are outlined in steps 29 and 30 should also be created.

- b) Load the PESH and ground-motion data, using the 'Simple Data Loader' into the newly created feature classes.

32. (*) In HAZUS, user-supplied hazard maps can be added with the 'Data Maps' option under 'Hazard'.

- a) Select the 'Add map to list' option, and navigate to the working directory from step 31.
- b) Provide a name for the hazard map, select the type of hazard map, and use the dropdown list to navigate to the map name within the geodatabase.

33. (*) Once all necessary maps are uploaded, they must be defined. This step is done by using the 'Scenario Definition Wizard' via Hazard > Scenario.

- a) Select the 'Define hazard map' option. Navigate to the hazard map, using the dropdown list option. For water depth, input the average water depth in metres. For this research project, the average depth to water was determined to be 15 m.
- b) To input ground-motion hazard maps, reopen the 'Scenario Definition wizard'. Define a new scenario and choose the 'User-supplied hazard' option. Navigate to the correct ground-motion map, using the dropdown list. Provide the magnitude and name of the scenario.

After completing the steps outlined above, HAZUS has all the relevant information to run a user-defined earthquake scenario. The steps listed here qualify the investigation to be a level 2 analysis. Although the procedure for a level 2 analysis, international setting at a local scale is lengthy, the benefits are substantial. Loss estimations calculated by HAZUS using that approach can be used in all levels of government and in seismically vulnerable regions throughout the world.

Appendix F:

M6.5 (R_{epi} 15km) at 2:00pm loss estimations for an AB06 scenario for the dissemination area level with site-specific amplification factors.

Physical Losses

Damage Levels by building type.

Area	Total number of damaged buildings				
	Slight	Moderate	Extensive	Complete	Total
001	14	7	1	0	22
002	42	33	7	1	83
003	16	11	2	1	30
004	27	17	4	1	49
005	21	16	3	0	40
006	3	1	0	0	4
007	1	0	0	0	1
008	1	0	0	0	1
009	1	0	0	0	1
010	0	0	0	0	0

Area	Wood building type				
	Slight	Moderate	Extensive	Complete	Total
001	6	2	0	0	8
002	12	5	1	0	18
003	5	2	0	0	7
004	1	0	0	0	1
005	0	0	0	0	0
006	0	0	0	0	0
007	0	0	0	0	0
008	0	0	0	0	0
009	0	0	0	0	0
010	0	0	0	0	0

Area	Steel building type				
	Slight	Moderate	Extensive	Complete	Total
001	0	0	0	0	0
002	0	0	0	0	0
003	0	0	0	0	0
004	1	0	0	0	1
005	2	1	0	0	3
006	1	0	0	0	1
007	0	0	0	0	0
008	0	0	0	0	0
009	0	0	0	0	0
010	0	0	0	0	0

Area	Concrete building type				
	Slight	Moderate	Extensive	Complete	Total
001	0	0	0	0	0
002	8	9	1	0	18
003	2	1	0	0	3
004	6	3	0	0	9
005	11	8	1	0	20
006	2	1	0	0	3
007	1	0	0	0	1
008	1	0	0	0	1
009	1	0	0	0	1
010	0	0	0	0	0

Area	Masonry building type				
	Slight	Moderate	Extensive	Complete	Total
001	8	5	1	0	14
002	22	19	5	1	47
003	9	8	2	1	20
004	19	14	4	1	38
005	8	7	2	0	17
006	0	0	0	0	0
007	0	0	0	0	0
008	0	0	0	0	0
009	0	0	0	0	0
010	0	0	0	0	0

Area	Pre-code seismic design level				Total
	Slight	Moderate	Extensive	Complete	
001	11	6	1	0	18
002	36	28	7	1	72
003	14	11	2	1	28
004	21	16	4	1	42
005	7	6	2	0	15
006	0	0	0	0	0
007	0	0	0	0	0
008	0	0	0	0	0
009	0	0	0	0	0
010	0	0	0	0	0

Area	Low-code seismic design level				Total
	Slight	Moderate	Extensive	Complete	
001	3	1	0	0	4
002	5	5	0	0	10
003	2	0	0	0	2
004	4	1	0	0	5
005	13	10	1	0	24
006	2	1	0	0	3
007	1	0	0	0	1
008	1	0	0	0	1
009	1	0	0	0	1
010	0	0	0	0	0

Area	Moderate-code seismic design level				Total
	Slight	Moderate	Extensive	Complete	
001	0	0	0	0	0
002	0	0	0	0	0
003	0	0	0	0	0
004	2	0	0	0	2
005	1	0	0	0	1
006	1	0	0	0	1
007	0	0	0	0	0
008	0	0	0	0	0
009	0	0	0	0	0
010	0	0	0	0	0

Area	High-code seismic design level				
	Slight	Moderate	Extensive	Complete	Total
001	0	0	0	0	0
002	1	0	0	0	1
003	0	0	0	0	0
004	0	0	0	0	0
005	0	0	0	0	0
006	0	0	0	0	0
007	0	0	0	0	0
008	0	0	0	0	0
009	0	0	0	0	0
010	0	0	0	0	0

Damage levels by building height

Area	Low-rise building height				
	Slight	Moderate	Extensive	Complete	Total
001	14	7	1	0	22
002	41	32	7	1	81
003	15	11	2	1	29
004	21	15	4	1	41
005	9	8	2	0	19
006	0	0	0	0	0
007	0	0	0	0	0
008	0	0	0	0	0
009	0	0	0	0	0
010	0	0	0	0	0

Area	Medium-rise building height				
	Slight	Moderate	Extensive	Complete	Total
001	0	0	0	0	0
002	1	1	0	0	2
003	0	0	0	0	0
004	1	1	0	0	2
005	1	1	0	0	2
006	0	0	0	0	0
007	0	0	0	0	0
008	0	0	0	0	0
009	0	0	0	0	0
010	0	0	0	0	0

Area	High-code building height				
	Slight	Moderate	Extensive	Complete	Total
001	0	0	0	0	0
002	0	0	0	0	0
003	1	0	0	0	1
004	5	1	0	0	6
005	11	7	1	0	19
006	3	1	0	0	4
007	1	0	0	0	1
008	1	0	0	0	1
009	1	0	0	0	1
010	0	0	0	0	0

Damage levels by square footage for each building type (in thousands of square feet).

Area	Total building type damage by square foot				
	Slight	Moderate	Extensive	Complete	Total
001	105.42	66.95	15.21	3.02	463.96
002	1371.86	906.49	209.49	31.66	6108.02
003	342.58	168.28	33.85	6.62	1477.02
004	2178.90	1499.83	284.71	39.09	9828.99
005	3148.91	2050.12	423.87	66.72	14419.99
006	915.89	347.86	31.94	5.55	4326.00
007	138.18	60.23	9.72	1.33	613.99
008	159.61	71.07	11.93	1.68	731.02
009	114.91	49.24	8.34	1.68	502.01
010	141.86	57.83	6.98	1.06	649.99

Area	Wood building type damage by square foot				
	Slight	Moderate	Extensive	Complete	Total
001	20.75	9.07	1.21	0.10	31.76
002	170.86	77.15	10.32	0.93	264.51
003	20.99	9.82	1.35	0.12	31.66
004	68.83	31.64	4.24	0.37	107.14
005	11.22	3.81	0.44	0.02	16.62
006	0.00	0.00	0.00	0.00	0.00
007	0.00	0.00	0.00	0.00	0.00
008	0.00	0.00	0.00	0.00	0.00
009	0.00	0.00	0.00	0.00	0.00
010	0.00	0.00	0.00	0.00	0.00

Area	Steel building type damage by square foot				
	Slight	Moderate	Extensive	Complete	Total
001	0.99	0.81	0.12	0.03	2.00
002	23.46	12.42	2.07	0.33	39.45
003	19.84	9.06	0.89	0.10	28.82
004	73.34	31.10	3.14	0.40	112.57
005	296.00	165.49	32.10	3.88	554.18
006	372.15	136.80	3.89	1.02	537.15
007	27.21	17.13	3.92	0.44	50.64
008	35.55	22.01	5.00	0.54	65.56
009	0.00	0.00	0.00	0.00	0.00
010	0.00	0.00	0.00	0.00	0.00

Area	Concrete building type damage by square foot				
	Slight	Moderate	Extensive	Complete	Total
001	38.72	19.23	2.35	0.23	62.69
002	627.12	368.62	82.39	8.78	1118.30
003	234.19	90.28	12.21	1.58	326.17
004	833.78	446.85	60.12	10.01	1392.31
005	2268.71	1376.26	241.30	33.61	4257.94
006	537.33	205.24	25.65	3.83	804.08
007	107.95	40.88	5.14	0.77	161.19
008	114.84	42.56	5.31	0.74	170.10
009	106.55	41.69	5.33	0.81	160.69
010	141.86	57.83	6.98	1.06	215.76

Area	Masonry building type damage by square foot				
	Slight	Moderate	Extensive	Complete	Total
001	44.96	37.84	11.53	2.66	98.16
002	550.42	448.30	114.71	21.62	1151.19
003	67.56	59.12	19.40	4.82	149.12
004	1202.95	990.24	217.21	28.31	2476.21
005	572.98	504.56	150.03	29.21	1308.99
006	6.41	5.82	2.40	0.70	15.52
007	3.02	2.22	0.66	0.12	6.01
008	9.22	6.50	1.62	0.40	18.16
009	8.36	7.55	3.01	0.87	20.02
010	0.00	0.00	0.00	0.00	0.00

Debris generation in thousands of tonnes.

Area	Debris generation		
	Type 1	Type 2	Total
001	0.93	0.49	1.41
002	10.03	8.56	18.58
003	1.39	2.12	3.52
004	15.60	13.31	28.91
005	10.32	29.21	39.52
006	0.24	5.53	5.77
007	0.07	1.08	1.15
008	0.15	1.21	1.36
009	0.21	0.85	1.06
010	0.02	1.01	1.03

Casualties by severity type for each building type.

Area	Total casualties by building type				
	Wood	Steel	Concrete	Masonry	Total
001	0.024	0.031	0.400	2.966	3.421
002	0.353	0.162	4.126	14.841	19.482
003	0.120	0.083	1.340	1.732	3.275
004	0.340	0.660	9.229	43.197	53.426
005	0.051	2.895	23.967	24.454	51.367
006	0.000	0.658	1.035	0.258	1.951
007	0.000	0.010	0.022	1.319	1.351
008	0.000	0.010	0.017	0.006	0.033
009	0.000	0.000	0.470	0.022	0.492
010	0.000	0.000	0.473	0.000	0.473

Area	Severity 1 casualties by building type				
	Wood	Steel	Concrete	Masonry	Total
001	0.022	0.024	0.329	2.278	2.653
002	0.316	0.134	3.359	11.619	15.428
003	0.108	0.07	1.135	1.325	2.638
004	0.305	0.589	7.625	35.281	43.800
005	0.047	2.528	20.281	19.009	41.865
006	0.000	0.595	0.901	0.195	1.691
007	0.000	0.009	0.019	1.039	1.067
008	0.000	0.009	0.015	0.005	0.029
009	0.000	0.000	0.384	0.016	0.400
010	0.000	0.000	0.388	0.000	0.388

Area	Severity 2 casualties by building type				
	Wood	Steel	Concrete	Masonry	Total
001	0.002	0.005	0.053	0.496	0.556
002	0.035	0.022	0.574	2.357	2.988
003	0.012	0.010	0.164	0.292	0.478
004	0.033	0.065	1.236	6.042	7.376
005	0.004	0.324	2.992	3.961	7.281
006	0.000	0.058	0.113	0.045	0.216
007	0.000	0.001	0.003	0.206	0.210
008	0.000	0.001	0.002	0.001	0.004
009	0.000	0.000	0.065	0.004	0.069
010	0.000	0.000	0.064	0.000	0.064

Area	Severity 3 casualties by building type				
	Wood	Steel	Concrete	Masonry	Total
001	0.000	0.001	0.006	0.065	0.072
002	0.001	0.002	0.065	0.294	0.362
003	0.000	0.001	0.014	0.039	0.054
004	0.001	0.002	0.124	0.642	0.769
005	0.000	0.015	0.236	0.504	0.755
006	0.000	0.002	0.007	0.006	0.015
007	0.000	0.000	0.000	0.025	0.025
008	0.000	0.000	0.000	0.000	0.000
009	0.000	0.000	0.007	0.001	0.008
010	0.000	0.000	0.007	0.000	0.007

Area	Severity 4 casualties by building type				
	Wood	Steel	Concrete	Masonry	Total
001	0.000	0.001	0.012	0.127	0.140
002	0.001	0.004	0.128	0.571	0.704
003	0.000	0.002	0.027	0.076	0.105
004	0.001	0.004	0.244	1.232	1.481
005	0.000	0.028	0.458	0.980	1.466
006	0.000	0.003	0.014	0.012	0.029
007	0.000	0.000	0.000	0.049	0.049
008	0.000	0.000	0.000	0.000	0.000
009	0.000	0.000	0.014	0.001	0.015
010	0.000	0.000	0.014	0.000	0.014

Economical losses by damage type for each occupancy class.

Area	Total economical losses	
	Structural Damage (thous. \$)	Non-Structural Damage (thous. \$)
001	\$361.84	\$12,170.52
002	\$5,065.39	\$41,983.15
003	\$762.88	\$6,964.46
004	\$4,815.64	\$36,577.46
005	\$9,016.41	\$81,610.82
006	\$1,168.96	\$11,751.41
007	\$238.20	\$2,355.58
008	\$285.64	\$1,944.09
009	\$207.64	\$2,001.51
010	\$221.12	\$1,496.09

Area	Residential class economical losses	
	Structural Damage (thous. \$)	Non-Structural Damage (thous. \$)
001	\$110.55	\$4,782.00
002	\$962.01	\$12,177.45
003	\$498.56	\$4,735.51
004	\$688.65	\$5,948.20
005	\$311.12	\$5,085.67
006	\$286.73	\$3,335.49
007	\$224.30	\$2,110.00
008	\$272.56	\$1,859.28
009	\$184.22	\$1,933.65
010	\$171.88	\$1,368.90

Area	Commercial class economical losses	
	Structural Damage (thous. \$)	Non-Structural Damage (thous. \$)
001	\$167.26	\$5,974.34
002	\$3,878.53	\$28,207.56
003	\$189.51	\$1,432.10
004	\$3,841.54	\$28,541.46
005	\$8,517.55	\$74,682.33
006	\$882.23	\$8,415.93
007	\$13.90	\$245.59
008	\$0.00	\$0.00
009	\$21.57	\$57.94
010	\$49.24	\$127.18

Area	Religious class economical losses	
	Structural Damage (thous. \$)	Non-Structural Damage (thous. \$)
001	\$48.19	\$862.38
002	\$10.22	\$66.33
003	\$6.70	\$195.47
004	\$109.51	\$686.92
005	\$81.01	\$658.73
006	\$0.00	\$0.00
007	\$0.00	\$0.00
008	\$0.00	\$0.00
009	\$0.00	\$0.00
010	\$0.00	\$0.00

Area	Governmental class economical losses	
	Structural Damage (thous. \$)	Non-Structural Damage (thous. \$)
001	\$0.00	\$0.00
002	\$214.62	\$1,531.81
003	\$68.11	\$601.38
004	\$56.33	\$413.23
005	\$27.15	\$356.35
006	\$0.00	\$0.00
007	\$0.00	\$0.00
008	\$0.00	\$0.00
009	\$0.00	\$0.00
010	\$0.00	\$0.00

Area	Educational class economical losses	
	Structural Damage (thous. \$)	Non-Structural Damage (thous. \$)
001	\$35.85	\$551.80
002	\$0.00	\$0.00
003	\$0.00	\$0.00
004	\$119.60	\$987.66
005	\$79.58	\$827.75
006	\$0.00	\$0.00
007	\$0.00	\$0.00
008	\$13.08	\$84.81
009	\$1.86	\$9.91
010	\$0.00	\$0.00

Economical losses by damage type for each building type.

Area	Wood type economical losses	
	Structural Damage (thous. \$)	Non-Structural Damage (thous. \$)
001	\$38.24	\$2,099.70
002	\$290.29	\$5,734.36
003	\$36.37	\$534.27
004	\$45.46	\$945.36
005	\$10.17	\$893.44
006	\$0.00	\$0.00
007	\$0.00	\$0.00
008	\$0.00	\$0.00
009	\$0.00	\$0.00
010	\$0.00	\$0.00

Area	Steel type economical losses	
	Structural Damage (thous. \$)	Non-Structural Damage (thous. \$)
001	\$3.66	\$183.25
002	\$57.59	\$1,578.72
003	\$18.38	\$215.08
004	\$118.29	\$715.28
005	\$714.82	\$5,222.23
006	\$393.66	\$3,906.33
007	\$72.82	\$512.92
008	\$93.21	\$471.62
009	\$0.00	\$0.00
010	\$0.00	\$0.00

Area	Concrete type economical losses	
	Structural Damage (thous. \$)	Non-Structural Damage (thous. \$)
001	\$71.91	\$5,065.31
002	\$1,866.69	\$17,498.25
003	\$339.58	\$3,554.85
004	\$1,549.92	\$14,457.33
005	\$5,576.24	\$50,122.23
006	\$742.76	\$7,297.77
007	\$151.48	\$1,597.07
008	\$156.67	\$1,205.87
009	\$159.84	\$1,515.77
010	\$221.12	\$1,496.09

Area	Masonry type economical losses	
	Structural Damage	Non-Structural Damage
	(thous. \$)	(thous. \$)
001	\$248.04	\$4,822.27
002	\$2,850.82	\$17,171.82
003	\$368.55	\$2,660.25
004	\$3,101.98	\$20,459.49
005	\$2,715.18	\$25,372.92
006	\$32.54	\$547.32
007	\$13.90	\$245.59
008	\$35.76	\$266.59
009	\$47.81	\$485.74
010	\$0.00	\$0.00

Appendix G

G1: Breakdown of the number of damaged buildings into damage states (none, slight, moderate, extensive and complete) by building type.

Scenario	No damage to building types				Total
	Wood	Steel	Concrete	Masonry	
M5.0d0	84	33	214	264	595
M5.0d1	84	33	214	265	596
M5.5d0	81	32	210	244	567
M5.5d1	82	33	210	251	577
M6.0d0	63	29	170	166	429
M6.0d1	71	30	189	195	485
M6.0d2	82	33	212	256	583
M6.0d3	84	33	214	264	595
M6.5d1	48	22	134	124	328
M6.5d2	76	32	204	225	537
M6.5d3	82	33	213	255	583
M7.0d1	31	15	84	72	202
M7.0d2	66	30	175	177	448
M7.0d3	79	33	208	236	556

Scenario	Slight damage to building types				Total
	Wood	Steel	Concrete	Masonry	
M5.0d0	0	0	0	2	2
M5.0d1	0	0	0	1	1
M5.5d0	3	0	3	16	22
M5.5d1	2	0	2	11	15
M6.0d0	15	3	27	55	100
M6.0d1	11	2	17	43	73
M6.0d2	2	0	1	8	11
M6.0d3	0	0	0	2	2
M6.5d1	23	6	44	66	140
M6.5d2	7	1	7	27	42
M6.5d3	2	0	1	8	11
M7.0d1	29	9	57	64	159
M7.0d2	14	2	24	51	91
M7.0d3	4	0	5	21	30

Scenario	Moderate damage to building types				
	Wood	Steel	Concrete	Masonry	Total
M5.0d0	0	0	0	0	0
M5.0d1	0	0	0	0	0
M5.5d0	0	1	1	5	7
M5.5d1	0	0	1	3	4
M6.0d0	5	1	14	34	55
M6.0d1	2	1	7	23	33
M6.0d2	0	0	1	2	3
M6.0d3	0	0	0	0	0
M6.5d1	10	3	29	55	97
M6.5d2	1	0	3	12	16
M6.5d3	0	0	0	3	3
M7.0d1	19	7	54	82	162
M7.0d2	4	1	12	31	48
M7.0d3	1	0	1	8	10

Scenario	Extensive damage to building types				
	Wood	Steel	Concrete	Masonry	Total
M5.0d0	0	0	0	0	0
M5.0d1	0	0	0	0	0
M5.5d0	0	0	0	1	1
M5.5d1	0	0	0	1	1
M6.0d0	1	0	3	7	11
M6.0d1	0	0	1	4	5
M6.0d2	0	0	0	0	0
M6.0d3	0	0	0	0	0
M6.5d1	1	1	5	17	24
M6.5d2	0	0	0	2	2
M6.5d3	0	0	0	0	0
M7.0d1	4	2	16	37	59
M7.0d2	0	0	3	6	9
M7.0d3	0	0	0	1	1

Scenario	Complete damage to building types				
	Wood	Steel	Concrete	Masonry	Total
M5.0d0	0	0	0	0	0
M5.0d1	0	0	0	0	0
M5.5d0	0	0	0	0	0
M5.5d1	0	0	0	0	0
M6.0d0	0	0	0	2	2
M6.0d1	0	0	0	1	1
M6.0d2	0	0	0	0	0
M6.0d3	0	0	0	0	0
M6.5d1	0	0	1	3	4
M6.5d2	0	0	0	0	0
M6.5d3	0	0	0	0	0
M7.0d1	1	0	3	11	15
M7.0d2	0	0	0	1	1
M7.0d3	0	0	0	0	0

G2: Breakdown of the number of damaged buildings into damage states (none, slight, moderate, extensive and complete) by occupancy class.

Scenario	No damage to occupancy classes					Total
	COM	EDU	GOV	REL	RES	
M5.0d0	356	6	23	11	199	595
M5.0d1	356	6	23	11	200	596
M5.5d0	339	6	22	10	190	567
M5.5d1	345	6	23	10	193	577
M6.0d0	256	4	17	8	144	429
M6.0d1	290	5	19	8	163	485
M6.0d2	349	6	23	10	195	583
M6.0d3	356	6	23	11	199	595
M6.5d1	201	3	13	5	111	333
M6.5d2	322	5	22	9	179	537
M6.5d3	348	6	23	11	195	583
M7.0d1	122	2	8	2	68	202
M7.0d2	268	4	18	8	150	448
M7.0d3	333	6	22	10	185	556

Scenario	Slight damage to occupancy Classes					Total
	COM	EDU	GOV	REL	RES	
M5.0d0	1	0	0	0	1	2
M5.0d1	1	0	0	0	0	1
M5.5d0	13	0	1	1	7	22
M5.5d1	9	0	0	1	6	16
M6.0d0	58	1	4	2	35	100
M6.0d1	42	1	3	2	25	73
M6.0d2	6	0	0	1	4	11
M6.0d3	1	0	0	0	1	2
M6.5d1	79	2	5	3	50	139
M6.5d2	24	1	1	1	15	42
M6.5d3	7	0	0	0	4	11
M7.0d1	91	1	6	3	58	159
M7.0d2	53	1	3	2	32	91
M7.0d3	17	0	1	1	11	30

Scenario	Moderate damage to occupancy classes					Total
	COM	EDU	GOV	REL	RES	
M5.0d0	0	0	0	0	0	0
M5.0d1	0	0	0	0	0	0
M5.5d0	4	0	0	0	3	7
M5.5d1	3	0	0	0	1	4
M6.0d0	34	1	2	1	17	55
M6.0d1	20	0	1	1	11	33
M6.0d2	2	0	0	0	1	3
M6.0d3	0	0	0	0	0	0
M6.5d1	59	1	4	2	31	97
M6.5d2	10	0	0	1	5	16
M6.5d3	2	0	0	0	1	3
M7.0d1	99	2	7	3	51	162
M7.0d2	29	1	2	1	15	48
M7.0d3	6	0	0	0	4	10

Scenario	Extensive damage to occupancy classes					Total
	COM	EDU	GOV	REL	RES	
M5.0d0	0	0	0	0	0	0
M5.0d1	0	0	0	0	0	0
M5.5d0	1	0	0	0	0	1
M5.5d1	0	0	0	0	0	0
M6.0d0	7	0	0	0	4	11
M6.0d1	4	0	0	0	1	5
M6.0d2	0	0	0	0	0	0
M6.0d3	0	0	0	0	0	0
M6.5d1	15	0	1	1	7	24
M6.5d2	1	0	0	0	1	2
M6.5d3	0	0	0	0	0	0
M7.0d1	36	1	2	2	18	59
M7.0d2	6	0	0	0	3	9
M7.0d3	1	0	0	0	0	1

Scenario	Complete damage to occupancy classes					Total
	COM	EDU	GOV	REL	RES	
M5.0d0	0	0	0	0	0	0
M5.0d1	0	0	0	0	0	0
M5.5d0	0	0	0	0	0	0
M5.5d1	0	0	0	0	0	0
M6.0d0	1	0	0	0	1	2
M6.0d1	1	0	0	0	0	1
M6.0d2	0	0	0	0	0	0
M6.0d3	0	0	0	0	0	0
M6.5d1	3	0	0	0	1	4
M6.5d2	0	0	0	0	0	0
M6.5d3	0	0	0	0	0	0
M7.0d1	9	0	0	1	5	15
M7.0d2	1	0	0	0	0	1
M7.0d3	0	0	0	0	0	0

Breakdown of casualties into the four severity levels at the three times for AB06 scenarios with site-specific amplification factors. No educational casualties are recorded as the student population was not input into HAZUS.

2:00am

Scenario	Severity 1 casualties - 2:00am				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	1	0		2	3
M6.0d1	1	0		1	2
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	2	0		6	8
M6.5d2	0	0		0	0
M6.5d3	0	0		0	0
M7.0d1	6	0		16	22
M7.0d2	1	0		2	3
M7.0d3	0	0		0	0

Scenario	Severity 2 casualties - 2:00am				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	0	0		0	0
M6.0d1	0	0		0	0
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	0	0		1	1
M6.5d2	0	0		0	0
M6.5d3	0	0		0	0
M7.0d1	1	0		3	4
M7.0d2	0	0		0	0
M7.0d3	0	0		0	0

Scenario	Severity 3 casualties - 2:00am				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	0	0		0	0
M6.0d1	0	0		0	0
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	0	0		0	0
M6.5d2	0	0		0	0
M6.5d3	0	0		0	0
M7.0d1	0	0		0	0
M7.0d2	0	0		0	0
M7.0d3	0	0		0	0

Scenario	Severity 4 casualties - 2:00am				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	0	0		0	0
M6.0d1	0	0		0	0
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	0	0		0	0
M6.5d2	0	0		0	0
M6.5d3	0	0		0	0
M7.0d1	0	0		1	1
M7.0d2	0	0		0	0
M7.0d3	0	0		0	0

2:00pm

Scenario	Severity 1 casualties - 2:00pm				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	4	0		0	4
M5.5d1	2	0		0	2
M6.0d0	50	0		0	50
M6.0d1	25	0		0	28
M6.0d2	1	0		0	1
M6.0d3	0	0		0	0
M6.5d1	110	0		0	110
M6.5d2	9	0		0	9
M6.5d3	1	0		0	1
M7.0d1	298	0		1	299
M7.0d2	40	0		0	40
M7.0d3	6	0		0	6

Scenario	Severity 2 casualties - 2:00pm				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	8	0		0	8
M6.0d1	4	0		0	4
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	19	0		0	19
M6.5d2	1	0		0	1
M6.5d3	0	0		0	0
M7.0d1	63	0		0	63
M7.0d2	6	0		0	6
M7.0d3	1	0		0	1

Scenario	Severity 3 casualties - 2:00pm				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	1	0		0	1
M6.0d1	0	0		0	0
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	2	0		0	2
M6.5d2	0	0		0	0
M6.5d3	0	0		0	0
M7.0d1	8	0		0	8
M7.0d2	1	0		0	1
M7.0d3	0	0		0	0

Scenario	Severity 4 casualties - 2:00pm				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	1	0		0	1
M6.0d1	1	0		0	1
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	4	0		0	4
M6.5d2	0	0		0	0
M6.5d3	0	0		0	0
M7.0d1	15	0		0	15
M7.0d2	1	0		0	1
M7.0d3	0	0		0	0

5:00pm

Scenario	Severity 1 casualties - 5:00pm				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	2	0		0	2
M5.5d1	1	0		0	1
M6.0d0	26	0		1	27
M6.0d1	13	0		0	13
M6.0d2	1	0		0	1
M6.0d3	0	0		0	0
M6.5d1	58	0		2	60
M6.5d2	5	0		0	5
M6.5d3	1	0		0	1
M7.0d1	157	1		6	164
M7.0d2	21	0		1	22
M7.0d3	3	0		0	3

Scenario	Severity 2 casualties - 5:00pm				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	4	0		0	4
M6.0d1	2	0		0	2
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	11	0		0	11
M6.5d2	1	0		0	1
M6.5d3	0	0		0	0
M7.0d1	34	1		1	36
M7.0d2	3	0		0	3
M7.0d3	0	0		0	0

Scenario	Severity 3 casualties - 5:00pm				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	0	0		0	0
M6.0d1	0	0		0	0
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	1	0		0	1
M6.5d2	0	0		0	0
M6.5d3	0	0		0	0
M7.0d1	5	2		0	7
M7.0d2	0	0		0	0
M7.0d3	0	0		0	0

Scenario	Severity 4 casualties - 5:00pm				
	Commercial	Commuting	Educational	Residential	Total
M5.0d0	0	0		0	0
M5.0d1	0	0		0	0
M5.5d0	0	0		0	0
M5.5d1	0	0		0	0
M6.0d0	1	0		0	1
M6.0d1	0	0		0	0
M6.0d2	0	0		0	0
M6.0d3	0	0		0	0
M6.5d1	2	0		0	2
M6.5d2	0	0		0	0
M6.5d3	0	0		0	0
M7.0d1	8	0		0	8
M7.0d2	1	0		0	1
M7.0d3	0	0		0	0

Appendix I:

Loss-of-function times / restoration times for medical care facilities, emergency centres, schools, military facilities, electrical power facilities and communication facilities and transmitters for an AB06 M6.5 (R_{epi} 15km) scenario.

Schools functionality for AB06 scenarios at R_{epi} 15 km

Military installations functionality for AB06 scenarios at R_{epi} 15 km

Electrical power facilities functionality for AB06 scenarios at R_{epi} 15 km