Proceedings of the Tenth Pacific Conference on Earthquake Engineering
Building an Earthquake-Resilient Pacific
6-8 November 2015, Sydney, Australia

Use of knowledge to reduce vulnerability to seismic hazards

M. Nastev, M-J Nollet, A. Abo-El-Ezz, A. Smirnoff, S. K. Ploeger, H. McGrath, M. Sawada, E. Stefanakis & M. Parent

Natural Resources Canada, École de tecnologie supérieure, University of Ottawa, University of New Brunswick, Canada.

ABSTRACT: While Canada is exposed to a variety of natural hazards, most risk and emergency managers currently lack the necessary tools and guidance to adequately undertake rigorous risk assessments. Unlike the complex computer models for natural hazard risk assessment intended for use by a small number of technical experts, user-friendly rapid risk assessment tools are being developed to allow non-expert users from the public safety community to run otherwise complex risk scenarios at a 'press of a button'. This paper reports on the ongoing activities carried out jointly by the federal government and academia on the development of inventory and seismic and flood risk analysis tools. Application examples at urban scales for Ottawa and Quebec City are given.

1 INTRODUCTION

In Canada, disastrous severe weather and geological hazards take place every single year. They continuously shape the landscape and have profound effects on the economic wellbeing, safety, and security of millions of people. An exhaustive list of the most significant natural disasters in Canada that have resulted in considerable damage, displaced households, injuries (≥100), fatalities (≥10), and/or where federal assistance was called upon is given by Public Safety Canada (2015). Since the beginning of the 20th century, the extreme flood event is the single most frequent natural hazard responsible for highest economic and social losses. Flooding has resulted directly or indirectly in the deaths of about 200 people and several billion dollars of damage (ICLR 2003). Severe natural hazards, however, are typically irregular events and those which lead to catastrophic consequences are relatively rare. The observation time-interval of about hundred years is too short to cover the frequency and intensity ranges of some hypothetical disastrous events, e.g., large earthquakes. As this threat seems remote to many people living in hazard prone areas and to the public safety community, the limited emergency resources are often planned to match more frequent events which take place in our lifetime.

Still, rare disastrous events happen and if not adequately addressed, the loss of life and property can be enormous. The conventional knowledge of the hazard information alone such as type, intensity and frequency is not sufficient for informed decision-making. Mitigation, preparedness and emergency response measures need to be tailored with respect to people and infrastructure at risk, respective vulnerabilities, and the capacity of adaptation of the community. The risk assessment process is thus central to achieving the overall safety. Numerous computer models are available for natural hazard risk analyses, e.g., OpenQuake (GEM 2015), SELENA (NORSAR 2015), HAZUS-MH (FEMA 2012), CAPRA (ERN-AL 2015), etc. Although technologically sophisticated, these programs are intended, first of all, for use by a small number of technical and scientific experts. In addition, they usually involve intensive data preparation and processing of the results and are therefore ill-suited for application by the broader non-expert public safety community. As such, communicating natural hazard risk to local stakeholders, so that they can indeed understand their exposure and vulnerability, represents an outstanding challenge.

Knowledge of exposure and vulnerability is the first prerequisite to any mitigation initiative. Recently, Natural Resources Canada (NRCan) has partnered with federal and provincial/territorial departments, municipalities and academia with the objective to develop standardized methods and tools for risk assessment and promote their understanding, acceptance and widespread usage. To attain these objectives and to meet the pressing need of Canadian municipalities and other levels of governments to perform multi-hazard risk assessment, few existing risk assessment tools were considered for adaptation (Nastev 2014). However, it was rapidly concluded that regardless of how comprehensive these tools are, they cannot be fully adapted for the Canadian hazard and exposure settings. The focus has thus turned on the development of tools with national out-of-the-box capacity which can run by a simple ‘push of the button’ in an acceptable amount of time. This paper describes part of the ongoing activities in Eastern Canada intended to address the need for user friendly tools with examples of seismic risk assessment in the Ottawa-Gatineau region and Quebec City.

2 SEISMIC RISK ANALYSIS

NRCan is traditionally involved in monitoring and forecasting of geohazard events, such as earthquakes, landslides, volcanoes, etc. Every five years, NRCan updates the seismic hazard for the National Building Code of Canada (NBCC). Currently, it is part of a multi-institutional and multi-disciplinary team focusing on the development of seismic risk assessment methods and tools for: generation of ground motion scenarios considering local site effects (ShakeMap), simplified dynamic response of exposed structures, and seismic vulnerability evaluation.

2.1 Seismic scenario

Eastern Canada is characterized by relatively low intraplate seismicity and no historic records of large earthquakes exist to be used as reasonable scenarios for potential damage assessment. To generate representative ground motion scenarios considering local site effects, a simplified 3D geologic model was first generated for a study area extending from Ottawa to Quebec City (Howlett 2013). It consists of (from top): sand unit, clay unit, till unit, and two bedrock units with stratigraphic profiles defined over a regular 500 m grid. To assess the expected site amplification at each grid point, shear wave velocity (V_S) vs. depth function was assigned for sand (V_S=103.1+31.1depth$^{0.5}$ m/s) and for clay unit (V_S=114.5+1.35depth m/s), whereas unique interval V_S value was assigned for till (V_S=385 m/s).

An algorithm has been developed with a shakemap generation capacity for the study area for: (i) earthquake events with specified magnitude, distance and simple fault geometry (point source or finite fault) by applying Atkinson and Adams (2013) ground motion prediction equation (GMPE) for Eastern North America, AA13, which being proposed for the 2015 edition of the NBCC; and (ii) probabilistic scenarios from embedded seismic hazard database with eight specified return periods (1/100 through 1/2475 year). The ground motion for the reference site conditions is corrected for the local soil conditions with the amplitude and frequency dependent site amplification factors as defined by the NBCC 2010 (NRC 2010), or by amplification factors of Boore and Atkinson (2008) with respect to the computed average V_{S30} in the grid cell.

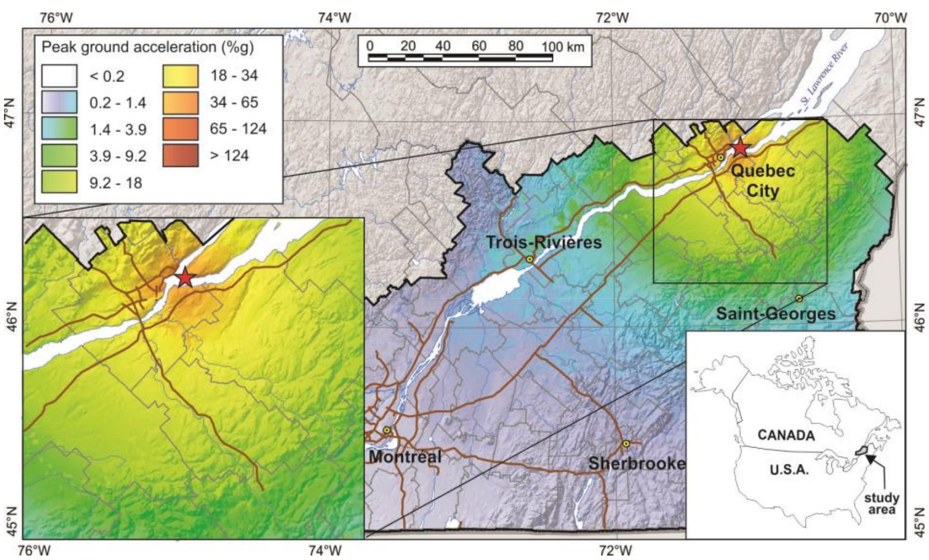

__Fig. 1.__ Example shakemap: Peak ground acceleration (M6.0 and depth=10km).

The example ShakeMap shown in Figure 1 applies the AA13 GMPE to obtain the spatial distribution of the peak ground acceleration for a point source scenario in the Quebec City region for a scenario comparable to the building code probability of 2% in 50 yr.

2.2 **Vulnerability to seismic shaking**

Seismic risk assessment at urban or regional scales involves seismic hazard, local inventory of assets at risk and respective vulnerability. Central to the vulnerability analysis is the concept of a fragility curve assumed representative for a group of buildings with similar structural properties. Fragility curves combine the expected damage states of the given building type to a measure of the intensity of the seismic shaking. The developed seismic vulnerability modeling was inspired by the standard framework for performance-based engineering (Kircher et al. 1997, Moehle and Deierlein 2004, FEMA 2012).

Two dominant spectral accelerations at 0.3 and 1.0 seconds (Sa0.3s and Sa1.0s) are used as measures of the input shaking intensities to buildings with a short and long period of vibration, respectively. These spectral accelerations fully define a simplified 5%-damped elastic response spectrum for a given seismic scenario including local soil conditions. The maximal structural response of the considered building type, referred to as the 'performance point', is determined by the intersection between its structural capacity curve and the response spectrum adjusted for the inelastic structural damping associated with cyclic degradation (Kircher et al. 1997). The corresponding spectral displacement is then combined with a set of displacement based fragility curves for the considered building type to obtain the probability of being in each of the five potential damage states: none, slight, moderate, extensive, complete. Due to the similarity of the construction practices, the generic capacity curves and the displacement fragility curves used in this study are those standardized in FEMA (2012).

The next step consists in correlating the probabilistic damage states with the respective intensity measure. This allows for direct evaluation of the expected structural, non-structural and content damage given a ground motion scenario. To simplify the damage assessment and avoid the iterative process involved in determination of the performance point, an alternate solution process relying on a set of fragility curves expressed as explicit functions of the input intensity measure (Porter 2009) was adopted in this project. These functions are obtained for gradually increasing shaking intensity starting with low input spectrum yielding elastic displacement and ending with maximum reasonable input spectrum which generates fully plastic response on the capacity curve. The respective probabilistic damage states are computed for each successive step and arranged in tabular format together with the associated intensity. To further improve the damage assessment and decrease the computational effort, the discrete values were fitted with continuous lognormal cumulative probability functions (Abo-El-Ezz et al. 2014).

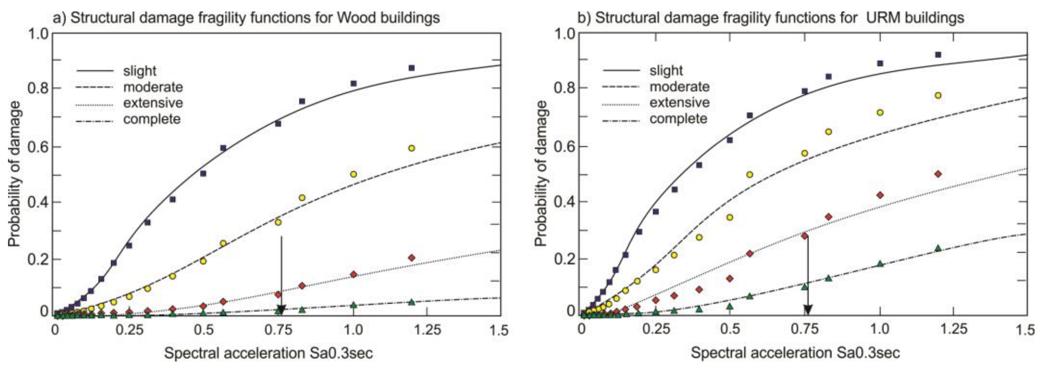

Fig. 2. *Fragility curves with closed form lognormal fit.*

The fragility curves shown as an example in Figure 2 provide a closed form solution for continuous prediction of probability of damage for low-rise wood light frame and unreinforced brick masonry building types for any Sa0.3sec compatible with a given earthquake scenario (magnitude, distance, soil class). Arrows indicate the Sa0.3=0.76g value used as an intensity measure in the following example. The developed algorithm was validated for the 128 building types considered in FEMA (2012). Once developed, these fragility curves represent a powerful tool for rapid seismic risk assessment.

2.3 **Ongoing work**

A seismic risk assessment tool referred to as Rapid Risk Evaluation (ER^2) is currently being developed to include both ShakeMap and vulnerability algorithms. ER^2 consists of two software components for two distinct types of use. The first one focuses on near real-time risk analysis following a major earthquake event. It fills in the current gap in the federal government’s capacity to automatically generate and display potential impacts of major earthquakes, informing the greater emergency management and public safety community. Continuous connection to the national and local seismograph networks will be implemented and spatial distribution of seismic parameters and their attenuation with distance will be calibrated against acquired real-time data. Damage as well as economic and social losses will be generated afterwards based on the calibrated ShakeMap. The interconnected set of algorithms will be installed and tested on NRCan servers in Ottawa.

The second planned component of ER^2 will support scenario seismic hazard and risk analyses. A web-based platform with national coverage and comprehensive databases is planned to be offered to the non-expert public safety community. A simple prototype of the custom input window is shown in Figure 3. 128 building types and 33 occupancy classes are available to the user through a dropdown menu. The tool calculates the probability of the building components (structural system, non-structural acceleration-sensitive part and non-structural drift-sensitive) to be in each of the five damage states. Based on these probabilities, indoor casualties in four severity levels and economic losses sustained by building components and contents are calculated. The mean damage factor (MDF), defined as a fraction of the replacement cost, and the coefficient of variation (COV) are also reported.

An example scenario for a low-rise pre-code wood building (W1-p) is shown in Figure 3. The single family building with a total value (structure and content) of $300,000 is exposed to the same M6.0 scenario, shown in Figure 1, with epicentral distance of 10 km and soft soil conditions (site class E). The summary report shows that low human casualties are likely to result from this scenario (0.25%), however, the total economic losses could reach about $20,000. Figure 4 graphically demonstrates the distribution of structural damage state probabilities and the probabilities of injury severity-levels for a low-rise wood-frame residential building subjected to an earthquake scenario of M6.0 and distance 10km on site class E ($V_S \leq 180$ m/s).

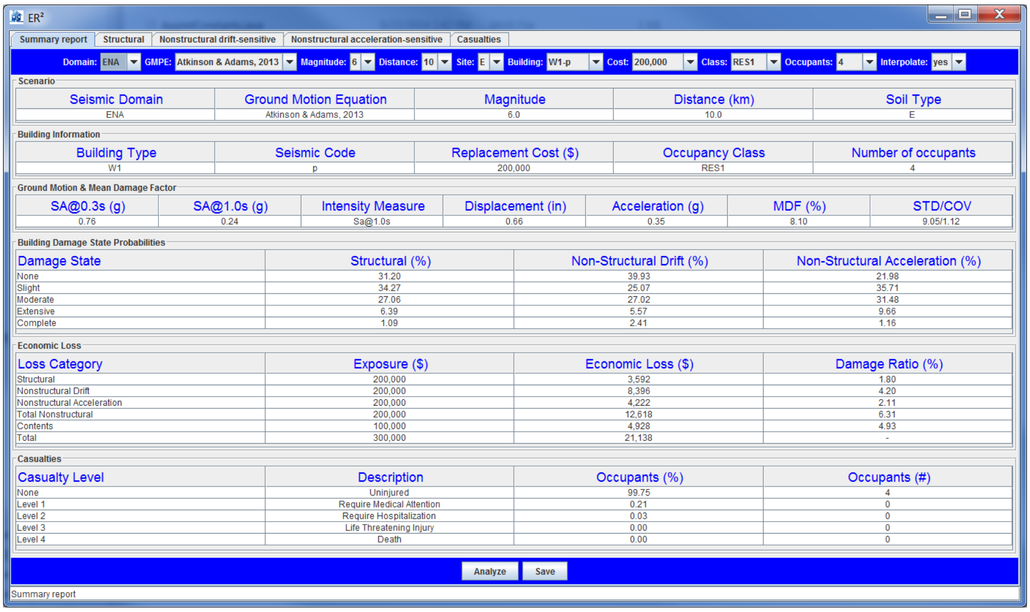

Fig. 3. *ER^2 toolbar for input parameters (top), and the standard ‘Summary Report’ form.*

The generated results for probability of structural damage state and casualties were further validated with those obtained with the HAZUS-MH earthquake model (FEMA 2012). The observed average deviation for 30 different seismic scenarios for 128 building types (7,680 tests) is ≤0.03% for casualties and ≤1.03% for structural damage.

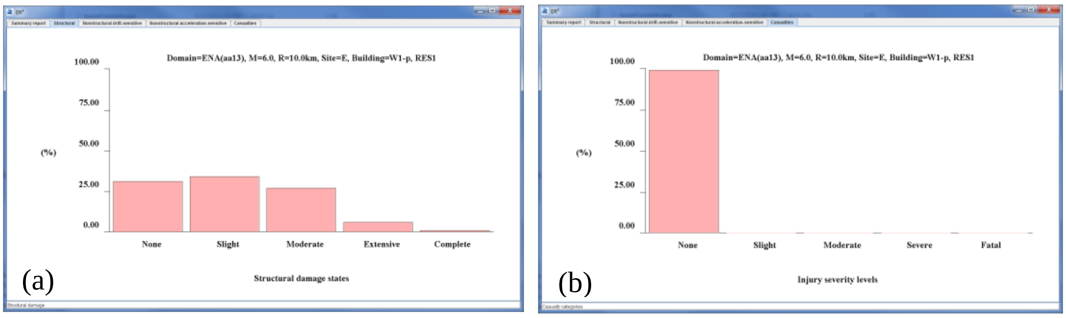

Fig. 4. *Distribution of probabilities: (a) structural damage states and, (b) casualty levels*.

3 BUILDING INVENTORY

The inventory of exposed buildings was generated at a local (building) scale by sidewalk and virtual desktop surveys, and at an urban scale by interpretation of data from municipal property assessment databases. In terms of structural building type information, the first approach relies heavily on the surveyor's experience but generates a more detailed building-specific inventory, whereas the second approach is faster, but generates an aggregated inventory at the census tract level.

An innovative tool for rapid building-by-building inventory, referred to as Urban Rapid Assessment Tool (Urban RAT), has been developed as an integrated ArcGIS-Google-Android system. It contains two software components: (i) Urban RAT Desktop that is used on a computer workstation for virtual environment building surveys within the ArcGIS software environment; and (ii) Urban RAT Mobile, a digital sidewalk survey tool in the form of a Google Android 'app' allowing for rapid collection of the same building parameters as the desktop system (Sawada et al 2014). Both components facilitate rapid and comprehensive data collection of numerous engineering parameters, e.g., location, year of construction, floor surface, occupancy, construction quality, design quality, design code, design redundancy, structural walls, weak column, vertical and plan irregularity, space between adjacent buildings, etc., as specified in FEMA 154 (ATC 2002) and FEMA 310 (ASCE 1998).

3.1 Urban RAT desktop

Urban RAT desktop has three subcomponents. The first subcomponent is a custom toolbar containing the tools for adding new points, editing existing points and adding multiple points of the same type associated with a particular building. The second and third are two custom forms containing the data entry form and the virtual environment (Figure 5a). The incorporation of form-based validation in the desktop application minimizes data entry errors by limiting user choices to dropdown/pick-lists and allows form auto-fill for multiple identical structures, thereby increasing data entry efficiency in homogenous neighborhoods. Google Street View automatically opens in a new window to the selected location. Urban RAT desktop provides the mechanisms to retrieve and manipulate (i.e. pan, zoom, move location) the panoramic imagery. The integration of Google Street View reduces the time required to visually parameterize a building. The submitted form data is automatically entered directly into a spatial data attribute table.

3.2 Urban RAT mobile

Urban RAT Mobile was developed for street survey and/or for cases where the surveyor decides that there are insufficient vantage points in Google Street View (Figure 5b). In these cases, surveyors visit the neighborhood and make their observations while avoiding unnecessary paper forms. Additional mapping and data management functions allow the surveyor to review and edit existing assessments. The tool runs on any Android tablet with GPS and the device's camera can be used to record geotagged photographs of the structure being assessed. All collected data is stored locally on the device and can be uploaded to the main ArcGIS program when the user returns to the office.

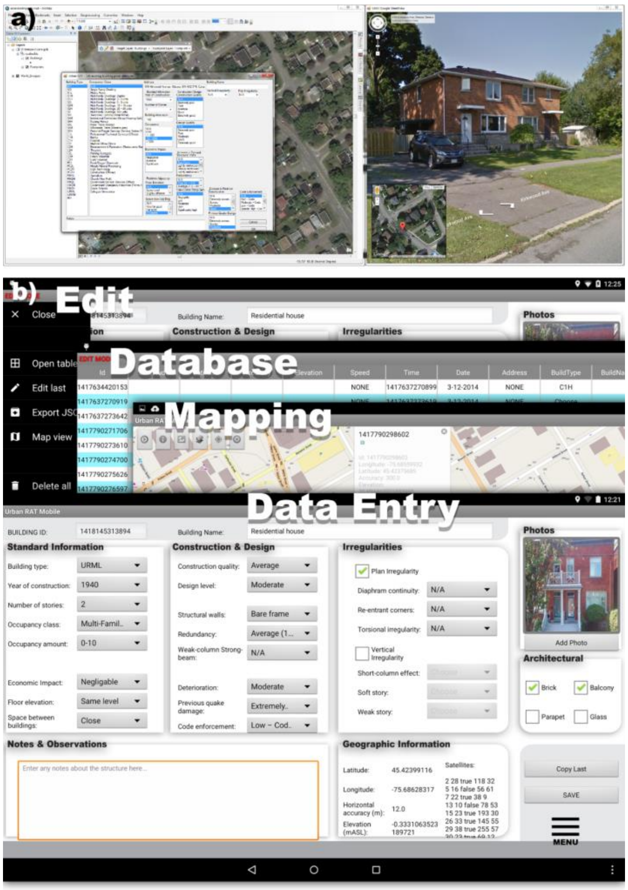

Fig. 5. *Virtual environment: (a) ArcMap with a layer that accepts new building points and a high resolution aerial basemap included with ArcGIS, and (b) mobile android app*.

Both components shown in Figure 5 feed data into a common inventory database and use basemap data available within the applications (World Imagery Source: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community (map data ©2014 Google, DigitalGlobemap, ©OpenStreetMap contributors).

The Urban RAT suite was first implemented to inventory the downtown core of the City of Ottawa. By 2014, over 44,000 buildings have been assessed; a map showing the distribution of building types in downtown Ottawa is presented in Figure 6. The virtual data collection began in the downtown core, a rich mix of historical and modern structural building systems. The time necessary for data collection was about 3 to 5 min/bldg for Urban RAT Desktop and 8-10 min for Urban RAT Mobile. This is considerably faster compared to the traditional sidewalk surveys which take about 20 min/bldg. Urban RAT is currently being extended to collect information on additional building parameters needed for flood risk assessment, e.g., first floor height, basement type, and foundation type.

4 CONCLUSION

The ongoing and proactive efforts to develop methods and tools for natural hazard risk analyses in Eastern Canada are discussed. Presently, earthquakes and floods are considered, however, other hazards may be added in the future. In case of earthquake shaking, the probabilities of structural and non-structural damage potential are computed as a direct function of spectral accelerations at 0.3 and 1.0 seconds. This rapid method is currently being combined with a ShakeMap generation capacity for near real-time damage assessment. An innovative tool for inventory of exposed buildings is also discussed: Urban RAT which integrates an ArcGIS-Google-Android system for building-by-building desktop and street surveys. It was applied and validated for building inventories in Ottawa (ON) and Quebec City.

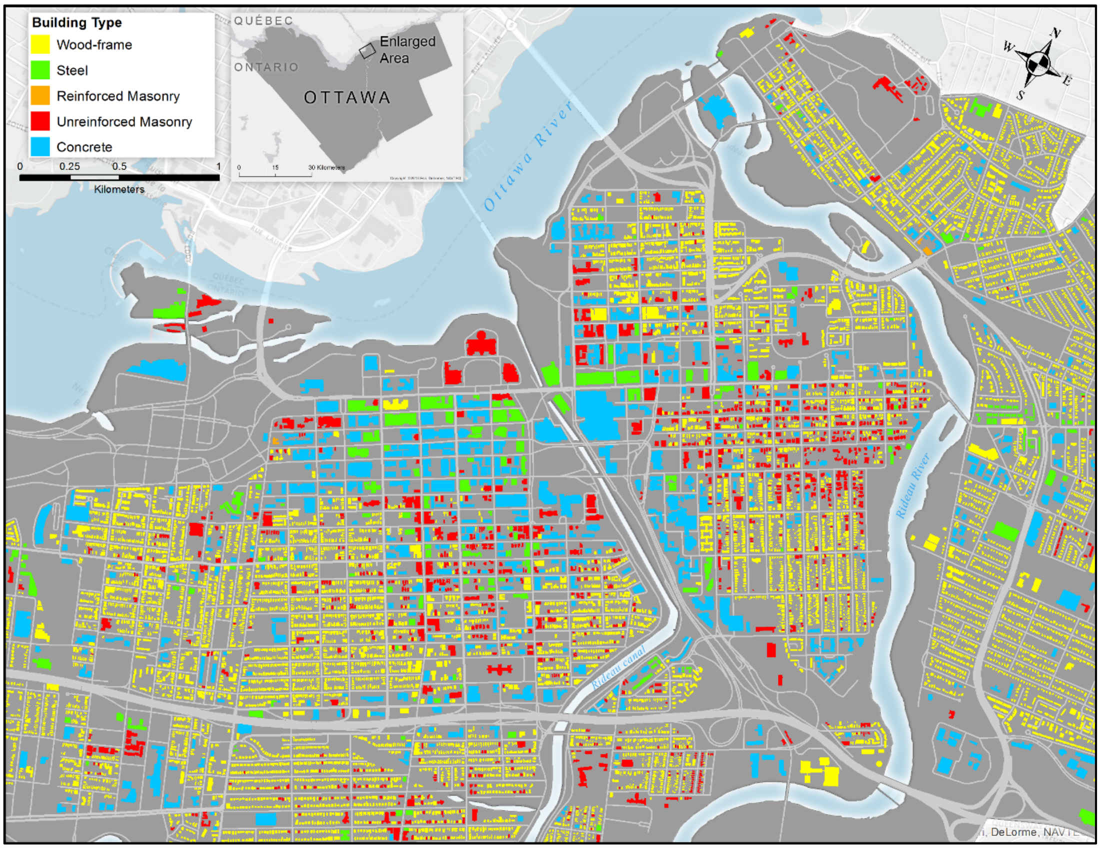

Fig. 6. *Building types in downtown Ottawa (basemap data ©2013 Esri, DeLorme, NAVTEQ).*

The discussed methods and tools for natural hazard risk analyses present an opportunity for the rapid calculation of potential losses in the pre- and post-disaster period. One of the goals of these developments and communication of results is to facilitate informed decision making and offer 'press of a button' simplicity to a multitude of users. It is endeavored that the developed inventory tools, and seismic risk applications will be combined in a single national risk assessment portal, with an option for adding additional natural hazards. The portal will be primarily intended for emergency management officials to support informed decision making with the purpose of reducing risk and minimizing potential losses. To this end, collaboration has been initiated with several municipalities to gain the necessary feedback from the local public safety community in order to design a practical and effective set of tools.

ACKNOWLEDGEMENTS

This work was partially supported by the NRCan's Public Safety Geoscience Program and by the Canadian Safety and Security Program (CSSP) which is led by Defense Research and Development Canada's Centre for Security Science, in partnership with Public Safety Canada. The CSSP is a federally-funded program to strengthen Canada's ability to anticipate, prevent/mitigate, prepare for, respond to, and recover from natural disasters, serious accidents, crime and terrorism through the convergence of science and technology with policy, operations and intelligence.

REFERENCES:

Abo-El-Ezz, A., Nollet, M.J. & Nastev, M. 2014. Methodology for rapid assessment of seismic damage to buildings in Canadian settings. *Geological Survey of Canada*, Open File 7450, Ottawa, 41 p.

ASCE. 1998. FEMA 310: Handbook for the Seismic Evaluation of Buildings - A Prestandard. Prepared for the *Federal Emergency Management Agency*, Washington, D.C.

ATC (Applied Technology Council). 2002. FEMA 154: Rapid Visual Screening of Buildings for Potential Seismic Hazard: A Handbook. (Second edition), prepared for the *Federal Emergency Management Agency*, Washington, D.C.

Atkinson, G.M. & Adams, J. 2013. Ground motion prediction equations for application to the 2015 Canadian national seismic hazard maps. *Canadian Journal Civil Engineering*, 40: 988-998.

Boore, D.M. & Atkinson, G.M. 2008. Ground-motion prediction equations for the average horizontal component of PGA, PGV, and 5%-damped PSA at spectral periods between 0.01 s and 10.0 s. *Earthquake Spectra*, 24, 99-138.

FEMA (Federal Emergency Management Agency). 2012. Hazus-MH 2.1 – Earthquake Model User Manual. Washington, D.C., 863 p.

GEM (Global Earthquake Model). Openquake Platform. Pavia, Italy, https://github.com/gem/oq-platform (Feb. 15, 2015)

Howlett, D. 2013. Regional-scale three-dimensional geological modeling of the St. Lawrence and Ottawa Valleys for geohazard assessment. Undergraduate thesis, Department of Earth and Environmental Sciences, University of Waterloo, 46 p.

ICLR (Institute for Catastrophic Loss Reduction). 2003. "An Assessment of Flood Risk Management in Canada." Research paper series – No. 28, Toronto, Ontario, 71 p.

Kircher, C.A., Reitherman, R.K., Whitman, R. & Arnold, C. 1997. Estimation of earthquake losses to buildings. *Earthquake Spectra*, 13(4), 703–720.

Moehle, J., & Deierlein, G. G. 2004. A framework methodology for performance-based earthquake engineering. Proceedings of the 13th World Conference on Earthquake Engineering, Vancouver, British Columbia, 13 p.

Nastev, M. 2014. Adapting Hazus for seismic risk assessment in Canada. *Canadian Geotechnical Journal*, 51(2), 217-222.

NRC (National Research Council of Canada). 2010. National Building Code of Canada - NBCC 2010. Ottawa, Ontario.

ERN-AL (Natural Risk Evaluation - Latin America). 2015. CAPRA Probabilistic Risk Assessment Initiative. http://www.ecapra.org/sites/default/files/softwares/Setup_ERN-Inundaci%C3%B3n%20v2.1_100812.rar (Feb. 15, 2015).

NORSAR (Norwegian Seismic Array). 2015. The SELENA-RISe Open Risk Package. Kjeller, Norway, http://sourceforge.net/projects/selena/files/ (Feb. 15, 2015)

Porter, K. A. 2009. Cracking an open safe: Hazus vulnerability functions in terms of structure independent spectral acceleration. Earthq. Spect., 25, 361–378.

Public Safety Canada. The Canadian Disaster Database. Ottawa, Ontario, https://www.publicsafety.gc.ca/cnt/rsrcs/cndn-dsstr-dtbs/ (Feb. 15, 2015)

Sawada, M., Ploeger, S.K., Elsabbagh, A., Saatcioglu, M., Rosetti, E. & Nastev, M. 2014. Integrated desktop/mobile GIS application for building inventory. Geological Survey of Canada, Open File 7345, 35 p.