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RAPID SEISMIC RISK ASSESSMENT AT URBAN SCALE

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ABSTRACT

The primary objective of the present study is to overcome the current communication barriers between seismic risk experts on one side and decision makers from the public safety community on the other. A simplified methodology was developed for a first-hand assessment of the potential earthquake impacts as a combination of three major components: seismic hazard, inventory of buildings at risk and respective vulnerability models. Due to the similar construction practices, the same structural parameters as proposed by the US FEMA were used for 128 building types. Central to the vulnerability analysis is the concept of fragility function, which correlates the probability of exceedance of a specified damage state to the intensity of the seismic shaking. Fragility functions were developed based on the magnitude of the seismic scenario and the input spectral acceleration at a period of 0.3s (Sa0.3) and 1.0s (Sa1.0) as intensity measures (IM) of the seismic shaking. To accelerate the damage assessment, the distance and the local site effects are implicitly considered by the spatial distribution of IMs. In this way, tedious iterations for determination of the performance point are avoided and seismic scenarios for large urban centers can be run in a few minutes. The above approach was programmed into an easy to run web-application referred to as ER2 (rapid risk evaluation). Equipped with graphic user interface, ER2 allows non-expert users to run otherwise complex seismic risk scenarios at a 'press of a button' through a simple intuitive selection process.

Keywords: seismic risk; fragility function; urban scale; intensity measure; damage state

1. INTRODUCTION

In Canada, strong earthquakes with magnitude M≥7.0 have occurred in the past and, if not adequately addressed, the loss of life and property during future disastrous events can be enormous (PSC 2017). The conventional scientific knowledge of the hazard 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 the seismic hazard, people and infrastructure at risk and respective vulnerabilities. The risk assessment process comprising these three components is therefore central to achieving the overall safety. Recently, numerous computer models were developed for dynamic response of buildings and seismic loss analyses at urban and regional scales, e.g., Hazus-MH (FEMA 2012), OpenQuake (GEM 2017), SELENA (NORSAR 2017), etc. These technologically sophisticated computer models usually involve intensive data requirements, preparation and processing of both input data and results. Under such conditions, they are intended first of all for use by a small number of scientists and technical experts, and are generally ill-suited for adjustments allowing custom adaptation or for application by the broader non-expert public safety community. Risk assessment results remain therefore obscure and largely inaccessible and communicating the seismic risk to local stakeholders, so that they indeed understand their exposure and vulnerability, represents an outstanding challenge.
The primary motivation of this research is to overcome the current communication barriers between the risk

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experts on one side and decision makers on the other. The objective is twofold: to propose relatively rapid methods for seismic risk assessment at urban scale, and to develop software in a way that they can be used relatively easily by non-experts. A simplified methodology was developed for a first-order computation of the potential negative impacts with vulnerability analysis based on the concept of hazard-compatible damage functions which correlate directly the intensity of the seismic shaking to the probability of exceedance of a specified damage state. For a relatively rapid and user-friendly risk assessment, the methods were prototyped into an interactive web-based application, ER2. It allows non-expert users to run otherwise complex risk scenarios at a 'press of a button' through a simple intuitive selection process.

This paper describes the methodological development of ER2 and part of the ongoing activities. Seismic risk assessment methods and comprehensive sets of stored site-specific databases are discussed, among which are: generation of ground motion scenarios considering simplified point source or finite fault assumption, prediction of potential attenuation with distance and local site amplification, standardized inventory of structural properties and occupancy of exposed buildings, dynamic response and evaluation of the seismic vulnerability. An application example of a M7 earthquake scenario about 20 km from downtown Quebec City is given at the end.

2. RISK ANALYSIS PROCESS

The seismic risk assessment process involves the quantification of the three major input components: seismic hazard, inventory of assets at risk and respective vulnerability, and of the resulting negative impacts. The seismic hazard is defined with the earthquake magnitude, focal distance and the different types of local soil conditions at a particular location. The assets at risk, in this case, are the existing buildings combined with the population in the affected area. The vulnerability represents the physical, economic and social susceptibility to damage as function of the intensity of the earthquake motion. The expected degree of damage and loss are obtained in terms of physical damage, economic losses as percentage of reconstruction costs and social losses are determined with the number of casualties and homeless people.

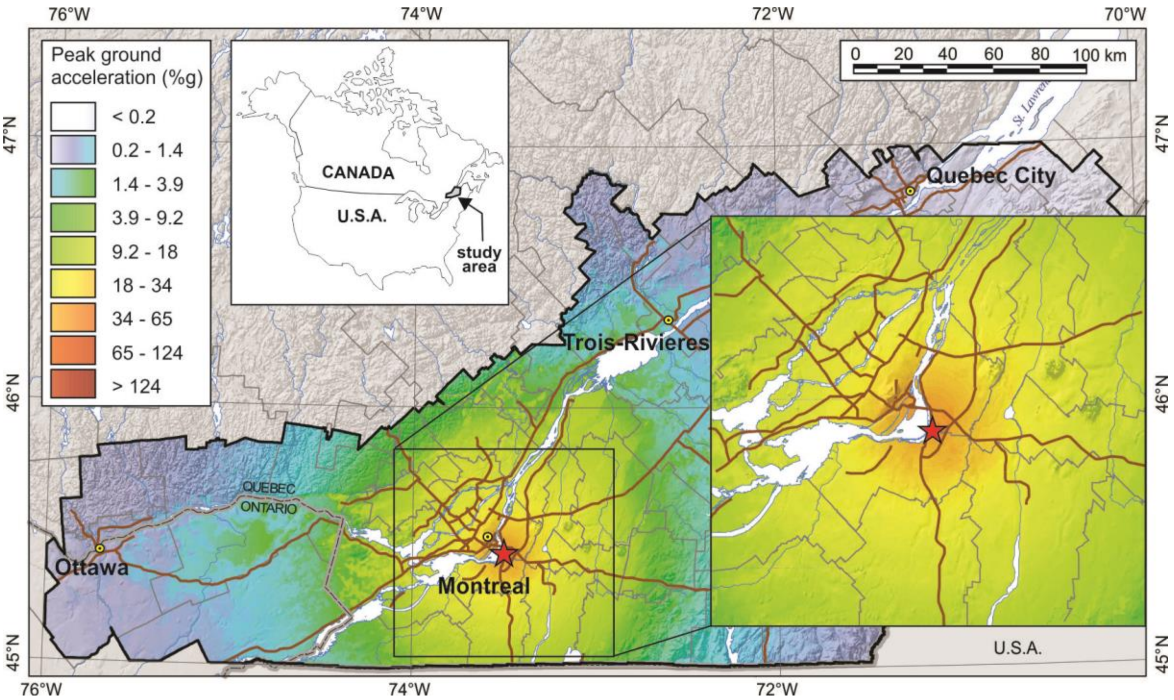

Figure 1. Peak ground acceleration for Montreal M6.0 point source scenario with depth of 10km

2.1 Seismic scenarios

An algorithm has been developed with a shakemap generation capacity for earthquake events with specified magnitude, distance and simple fault geometry. It applies the new generation of ground-motion prediction models for reference response spectral accelerations on rock including PGA and PGV: AA13 for Eastern Canada (Atkinson and Adams 2013), which is being proposed in the National Building Code of Canada NBCC 2015 (NRC 2016); and AB10 for Southern Europe and the Mediterranean (Akkar and Bommer 2010). Since both equations are calibrated for equivalent point source model, finite fault dimensions can also be considered, ignoring focal mechanisms, to generate appropriate motion parameters using the closest distance from each site. The epistemic uncertainty can be captured by the provided confidence levels.

The ground motion is then corrected for the local soil conditions with the amplitude and frequency dependent site amplification factors with respect to the computed average V_{S30} at each site as defined by the NBCC 2015. The other option is to use the nonlinear site amplification embedded in the attenuation prediction equations.

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. The study area was previously divided into 250x250 grid cells, each characterized with a single soil stratigraphy, shear velocity profile and V_{S30} value.

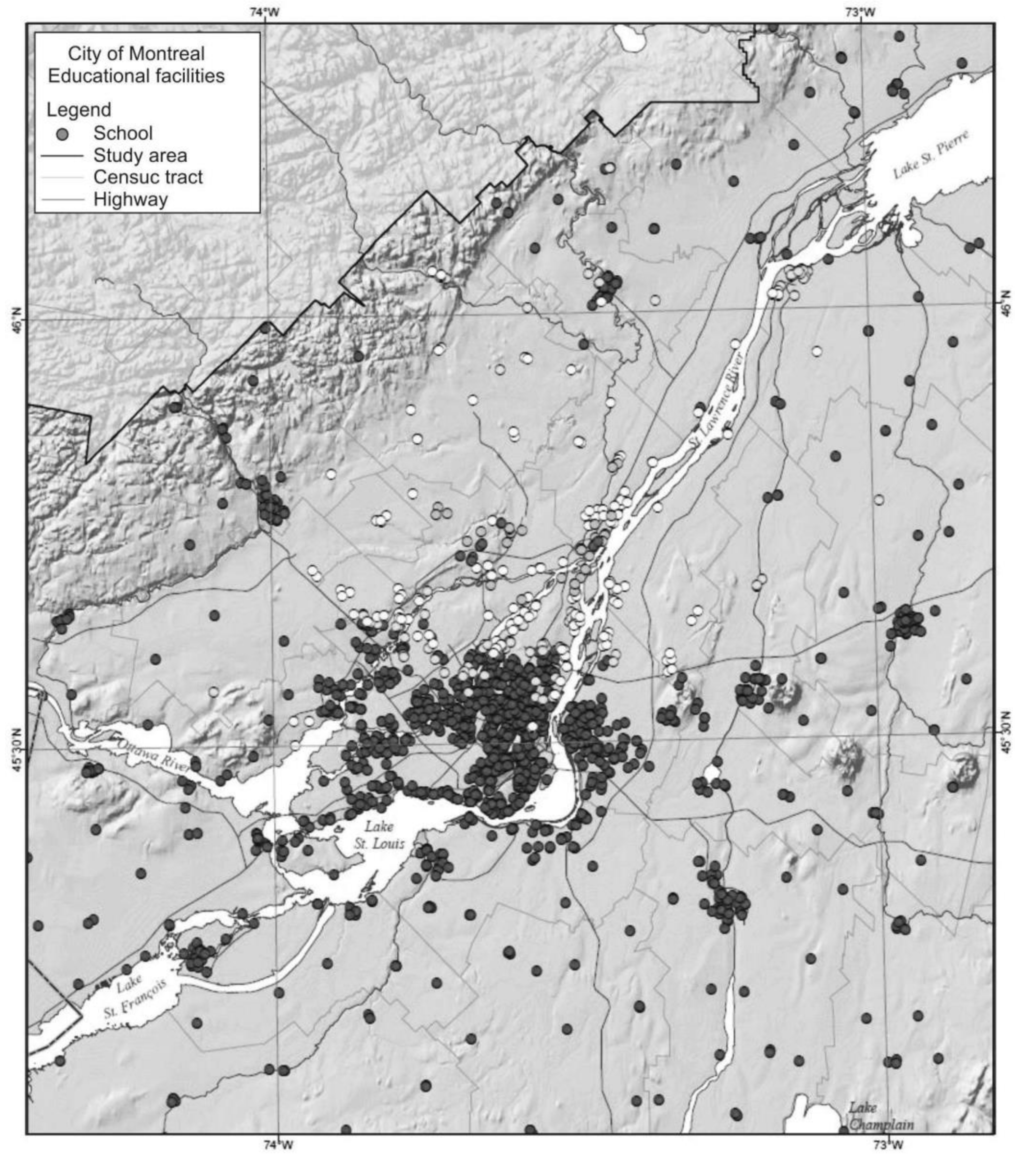

Figure 2. Montreal schools are the type of essential facilities which may generate highest losses and require strong focus during risk reduction actions

2.2 Building inventory

The inventory of exposed buildings is the second major input parameter. It can be generated at a local (building) scale by sidewalk and virtual desktop surveys (Ploeger et al. 2016), at an urban scale by interpreting data from municipal property assessment databases - community open datasets (Nollet et al. 2012) or and at the national scale derived from census information, governmental agency data and/or applying statistical procedures (Ulmi et al. 2014). In terms of efficiency of information collection, the first approach relies heavily on the surveyor's experience but generates a more detailed building-specific inventory, whereas the second and third approaches are faster, but generate an aggregated inventory at the census tract level. The needed information consists of structural parameters (location, year of construction, floor surface, number of stories, design code), occupancy (residential, commercial, industrial, agricultural, governmental, etc.) and population distribution in three times of the day (daytime when most of the working population is expected to be in offices; daytime when part of the population is commuting home; and night-time, when most of the population is at home in residential neighborhoods).

An example map showing the distribution of school buildings in the City of Montreal is presented in Figure 2. For the time being, building inventory data is available for only a part of Eastern Canada between Ville de Saguenay and Toronto. For other regions users are prompted to introduce their own datasets in a predefined format.

2.3 Vulnerability to seismic shaking

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 (Sa0.3 and Sa1.0) are used 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 in Canada and the US, the fragility data were developed for the 128 generic building classes using the standardized capacity parameters and the definitions of the damage states (FEMA 2012).

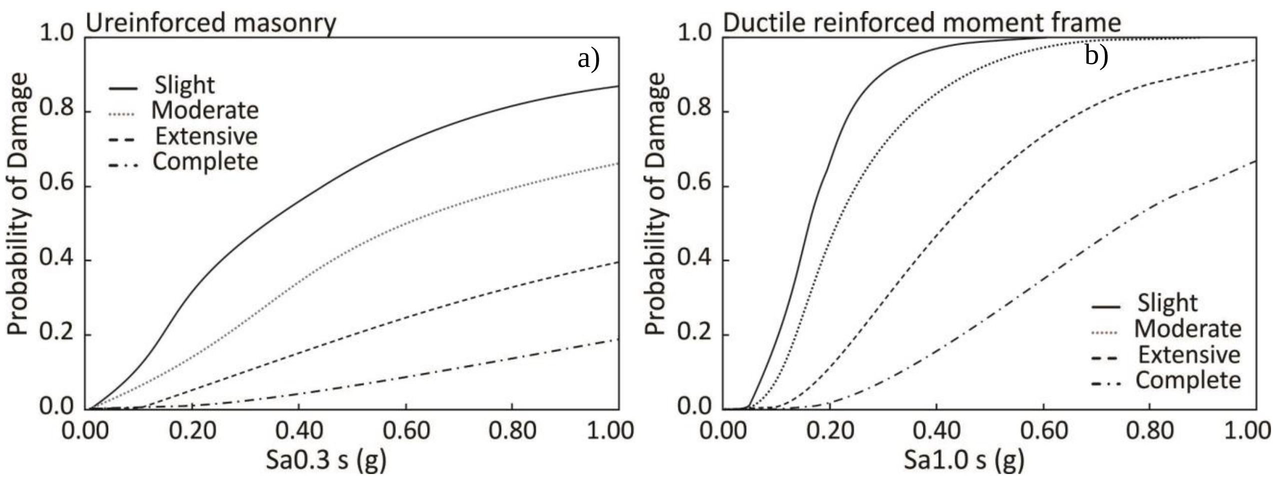

Figure 3. Fragility curves with closed form lognormal fit conditioned to spectral acceleration a) Sa0.3 for unreinforced masonry buildings and b) Sa1.0 for ductile moment frame low-rise buildings

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 shaking intensity was adopted in this project. These functions are obtained for gradually increasing intensity ending with a maximum reasonable input spectrum value which generates fully plastic response on the capacity curve (Porter 2009). 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, Nastev et al 2017)). The fragility curves shown in Figure 3 provide a closed form solution for continuous prediction of probability of damage to buildings. Once developed, these fragility curves represent a powerful tool for rapid seismic risk assessment.

3. ER2 SOFTWARE

A seismic risk assessment tool referred to as Rapid Risk Evaluation (ER2) is currently being developed to include both shakemap and vulnerability algorithms. ER2 consists of three software components for three distinct types of use: near real-time regional seismic risk assessment, customized computation of earthquake negative impact to a single building and user-friendly web-application for seismic scenario risk modeling. Results consist of structural damage, drift and acceleration sensitive non-structural damage, economic losses and casualties.

3.1 Near-real time computation

The first component of ER2 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 is implemented and spatial distribution of seismic parameters and their attenuation with distance is calibrated against acquired real-time data. Damage as well as economic and social losses are generated next based on the calibrated shakemap. The interconnected set of algorithms is installed and tested on NRCan servers in Ottawa.

3.2 Single building consideration

The second component of ER2 supports scenario seismic hazard and risk analyses for a single building type. This module was developed mainly for validation purposes against other risk assessment software (e.g., advanced engineering building module; FEMA 2012) and for comparative analyses between damage probability results for different building classes. A simple prototype of the custom input window is shown in Figure 4. The 128 building types and 7 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 components and non-structural drift-sensitive components 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 4. 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).

3.3 ER2 as an interactive web-application

A web-based application with national coverage and comprehensive databases is planned to be offered to the non-expert public safety community. To demonstrate the potential capabilities of the proposed web-application, a prototype illustrating a seismic risk scenario has been built that is discussed herein. The work on the System Requirements Specification and the System Design documentation for the application is in the final stage of development. The programming of the beta version is underway using the Java programming language and PostgreSQL database as the back-end (interface between the user and the data access layer). The interactive web-application will be freely accessible via internet, with no need for any commercial software or advanced GIS (geographic information system) or engineering knowledge. To this end the Federal Geospatial platform will be used to provide a link to the application in line with Canada's Action Plan on Open Government (Nastev et al 2017).

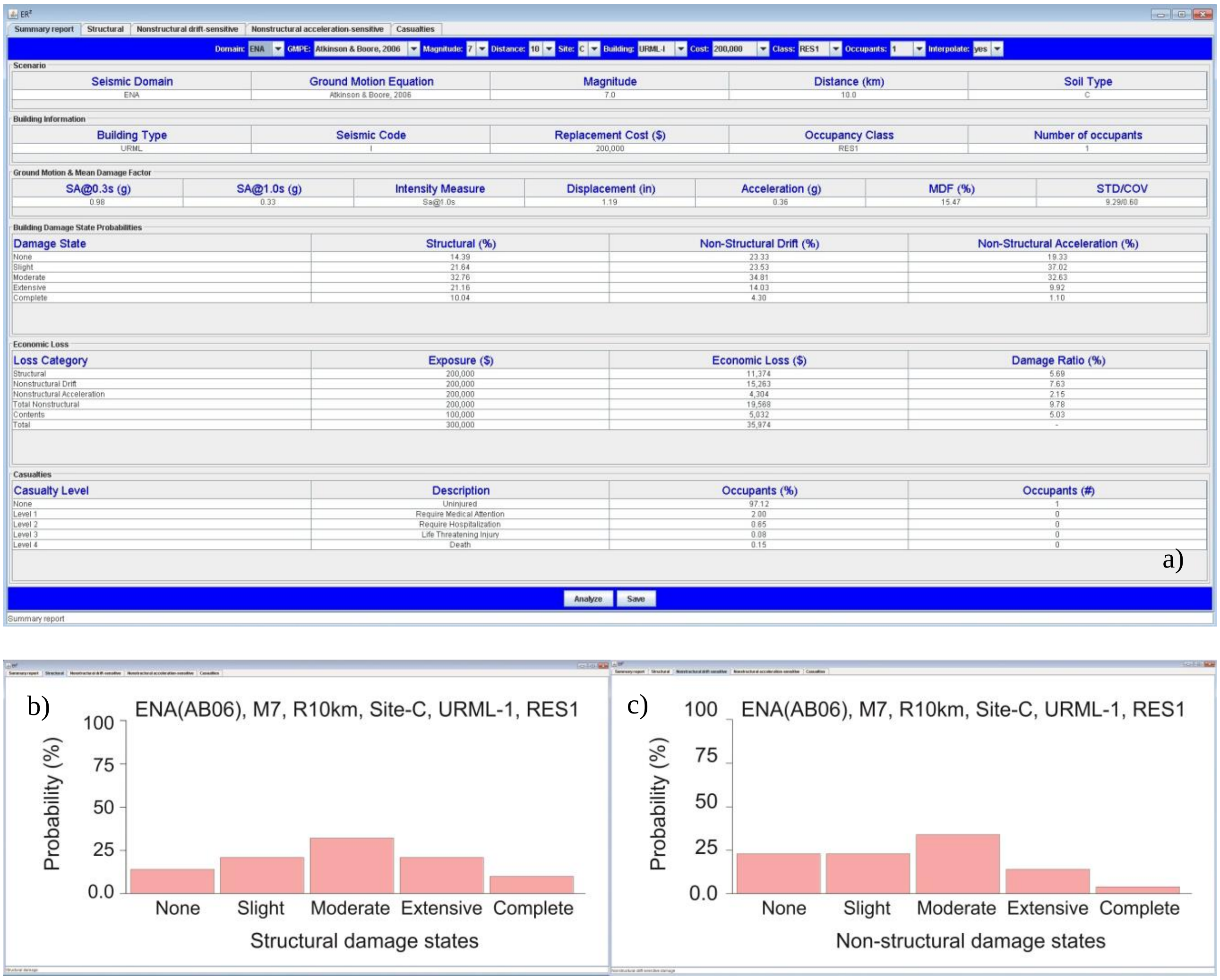

Fig. 4. Computation of seismic damage to single building in ER2: a) toolbar for input parameters and the standard 'summary report' form, and probability distribution of: b) structural and c) non-structural damage states

The example presented in Figures 5 considers the Quebec City magnitude M7.0 scenario. This scenario is comparable to the NBCC 2015 probability of exceedance of 2% in 50 yr. The web-application starts with an interactive window requesting the user to select the hazard type. For deterministic what-if seismic scenarios, the user is prompted to select the epicenter of the scenario and assign the desired magnitude. Recommended reasonable what-if scenarios are those obtained from the deaggregation of the national hazard map. A disclaimer will let users know that in Eastern Canada those scenarios are in the range of M6 with 10-15 km distance from downtown, and M7.25 with 25-35 km distance from downtown.

The software automatically computes the extent of the study area and the number of affected buildings and/or census tracts as a function of the magnitude. In this case, the risk analysis was carried out for a radius of about 45 km around the epicenter. The application automatically generates the inventory of buildings in the selected study area: population and number, type and occupancy of buildings aggregated at the census tract level. By clicking on the screen, the user will be able to verify the inventory for each census tract, to modify it if necessary or to introduce their own values, and to save it for further use.

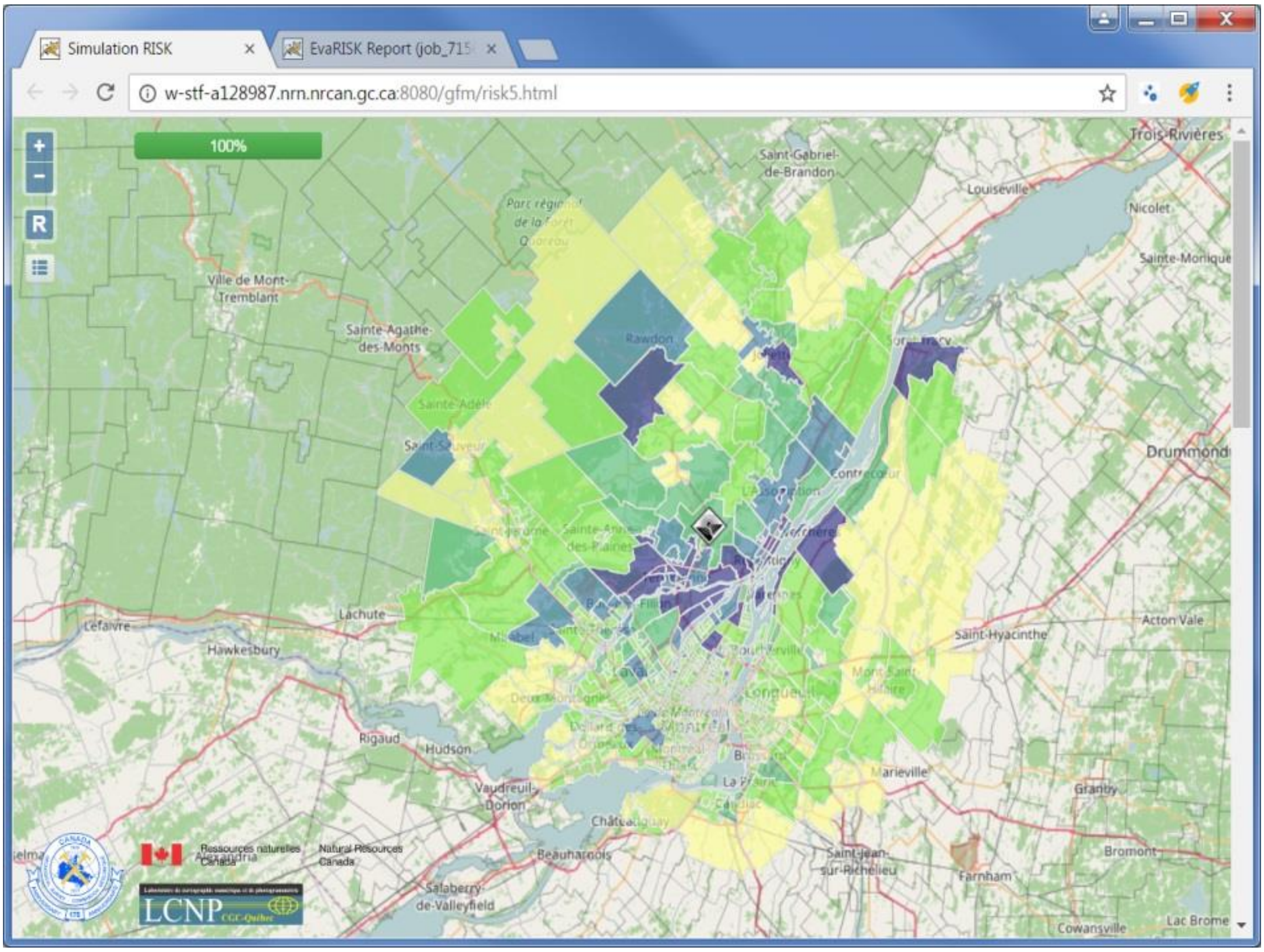

Figure 5. Prototype of the ER2 web-application window showing the normalized economic losses per census tract

4. CONCLUSIONS

The ongoing and proactive efforts to develop methods and tools for seismic risk analyses in Eastern Canada are discussed. One of the goals of these developments and communication of results is to facilitate informed decision making and offer ‘press of a button’ simplicity. The considered seismic risk assessment process involves the quantification of the three major input components: seismic hazard, inventory of assets at risk and respective vulnerability, and of the resulting negative impacts. The seismic hazard is defined with the earthquake magnitude, focal distance and dimensions, and the different types of local soil conditions at a particular location; the assets at risk, in this case, are the buildings combined with the population present in the affected area; and the vulnerability represents the physical, economic and social susceptibility to damage. 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. The expected degree of damage and loss are obtained in terms of physical damage, economic losses as percentage of reconstruction costs and social losses are determined with the number of casualties and homeless people.

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