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A Web-Based Tool for Scenario-Based Seismic Risk Assessment

Ahmad Abo-El-Ezz[1], Alex Smirnoff[1], Miroslav Nastev[1], Marie-José Nollet[2], Nicholas Gibb[1], Heather McGrath[3]

[1] Geological Survey of Canada, Natural Resources Canada – Quebec, QC, Canada.
[2] École de technologie supérieure – Montréal, QC, Canada.
[3] Natural Resources Canada – Ottawa, ON, Canada.

ABSTRACT

Numerous computer models have been developed for seismic loss analyses at urban and regional scales. They seem, however, ill-suited to custom applications in the specific Canadian hazard and exposure settings and, more importantly, inadequate for utilization by the broader non-expert public safety community. Therefore, communication of the potential seismic risk results to local stakeholders, such that they can properly understand their own exposure and vulnerability, represents an outstanding challenge. The primary objective of the present study is to describe the methodological development of the Rapid Risk Evaluator (ER2), a relatively rapid and user-friendly risk assessment application, currently being programmed to overcome the existing communication barriers between risk experts and decision makers. A simplified methodology was developed for a first-order computation of earthquake negative impacts. It conducts vulnerability analyses based on the concept of hazard-compatible damage functions that directly correlate the intensity of the seismic shaking to the probability of exceedance of a specified damage state. This approach allows for risk assessment of any given seismic scenario in large urban centers within a minute. To facilitate the use of ER2 by decision makers, the theoretical methods were expanded into an interactive web-based application. This paper describes the development of ER2 and the ongoing activities on enhancing its capacity. ER2 includes pre-computed site-specific databases containing ground motion scenarios, prediction of potential attenuation with distance and local site amplification, standardized inventories of structural properties and occupancy categories of buildings, and assessment of their seismic response and vulnerability. An example of a hypothetical earthquake event within Quebec City limits is presented to illustrate the user interface and capabilities of the application.

Keywords: Seismic risk, fragility curves, loss estimation, risk communication.

INTRODUCTION

In Canada, strong earthquakes with magnitude $M \geq 6.0$ have occurred in the past and, if not adequately addressed, the loss of life and property during future disastrous events can be enormous [1]. 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. Numerous computer models were developed last decade for seismic loss analyses at urban and regional scales, e.g., Hazus-MH [2], OpenQuake [3], SELENA [4]. 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 applications 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 experts on one-hand side and decision makers on the other. The objective is twofold: to propose relatively rapid approach for seismic risk assessment at urban scale, and to develop software in a way that they can be used 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 [5]. 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 sources or finite fault assumptions, 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 example of ER2 applied to a hypothetical earthquake event about 7 km from the Old Quebec City is presented to illustrate the simplicity of the user interface and capabilities of the application.

FRAMEWORK FOR RISK ASSESSMENT

The seismic risk assessment process involves the quantification of three major input components (Figure 1): seismic hazard, inventory of assets at risk and respective vulnerability, and of the resulting impacts. The seismic hazard is determined with earthquake magnitude, focal distance and local soil conditions. The assets at risk, in this case, are the existing buildings combined with the population distribution 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 negative impacts are obtained in terms of physical damage, economic losses as percentage of reconstruction costs and social losses (shelter needs, number of injuries and casualties).

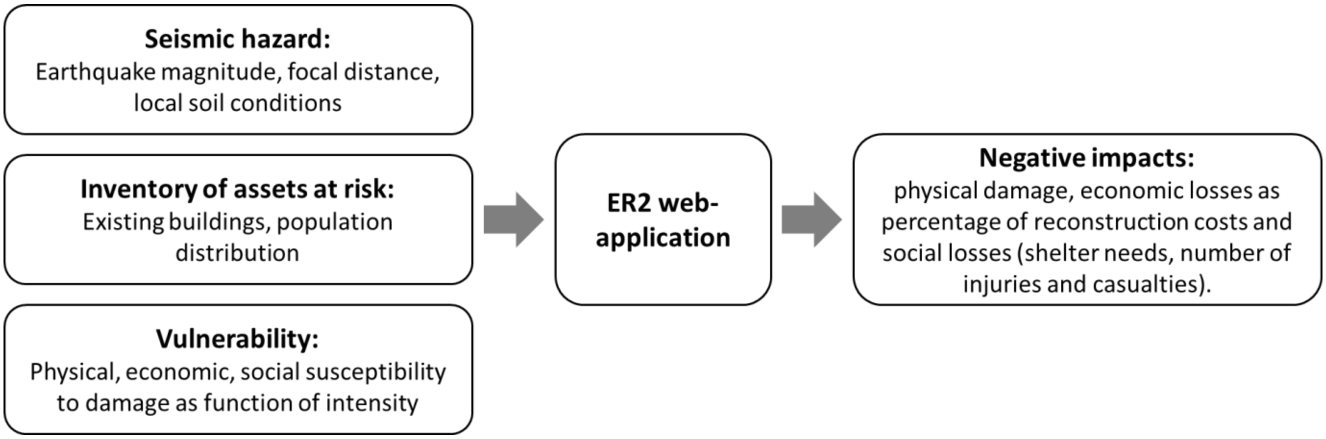

Figure 1. Framework for seismic risk assessment.

Seismic Scenarios

To generate shake maps for user defined earthquake events, an algorithm has been developed with specified magnitude, distance and hypocenter depth as input parameters. It applies the latest generation of ground-motion prediction models, e.g. AA13 GMPE [6], for reference response spectral accelerations on stiff soils. It provides the needed peak ground acceleration value (PGA) and 5% damped spectral accelerations at periods of 0.3 and 1.0 s (Sa0.3 and Sa1.0) as IMs. Probabilistic scenarios are conducted using the embedded national database with specified return periods of 100, 250, 475, 750, 1000, 1500, 2000 and 2475 years as suggested by seismic hazard maps of the 2015 National Building Code of Canada (NBCC2015) [7].

Next, the ground motion determined for reference site condition is corrected for local soil conditions. The current version of ER2 supports a site amplification option. It uses standard amplitude and frequency dependent site amplification factors computed for five broad site categories with specified ranges of the average shear wave velocity Vs of the top 30 meters (in decreasing order): hard rock (A; Vs30>1500m/s), rock (B; 760<Vs30<1500m/s), very dense soil and soft rock (C; 360<Vs30<760m/s), stiff soil (D; 180<Vs30<360m/s), and soft soil (E; Vs30<180m/s) according to the current NBCC 2015 [8]. To determine the spatial distribution of the site classes, a 3D geological model has been developed for a study area extending from Quebec City to Toronto. Representative Vs were assigned to the stratigraphic units next [9]. The ground motion intensity measures (IMs), PGA, Sa03 spectral acceleration at 0.3s, and Sa10 spectral acceleration at 1.0s, are computed at the centroid of each census tract. They fully define a simplified 5%-damped elastic response spectrum for a given seismic scenario including local soil conditions. The example shake map shown in Figure 2 applies the AA13 GMPE to obtain the spatial distribution of the PGA for M6 point source scenario located in the center of Quebec City with hypocentral depth of 10km.

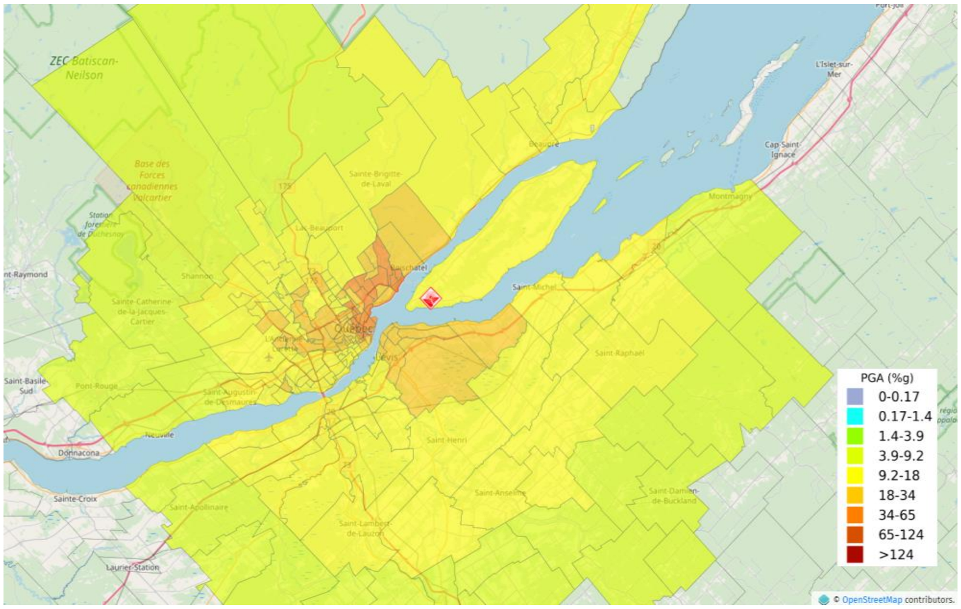

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Figure 2. PGA for Quebec City M6.0 point source scenario with hypocentral depth of 10km.

Inventory

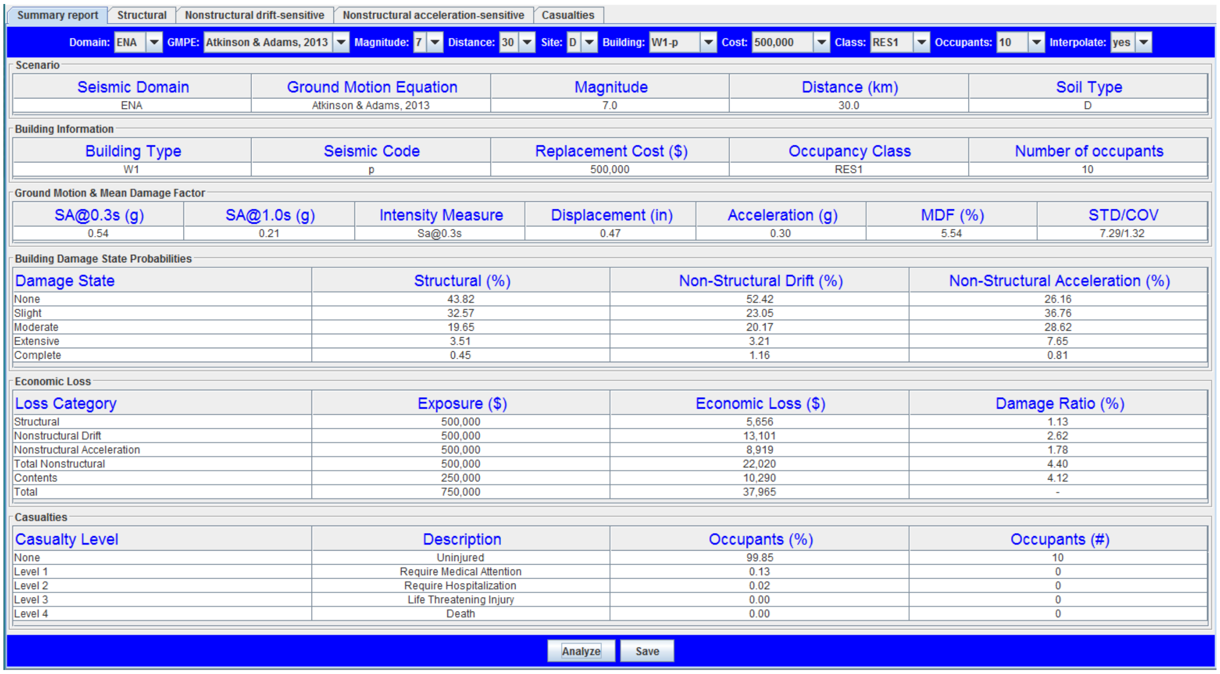
The inventory of exposed buildings and population is the second major input parameter. Respective databases were generated by sidewalk and virtual desktop surveys, by interpreting data from municipal property assessment databases [10], and derived from census information [11]. The needed information consists of parameters related to the structure (location, year of construction, square footage, number of stories, design code) and occupancy type (residential, commercial, industrial, agricultural, governmental). The population distribution is considered at three different 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.

As the building construction practices in Canada and in the United States are similar [12], the same building taxonomy and parameters were employed as in Hazus [13]. Accordingly, there are 16 basic structural types depending on the construction material (e.g. wood, steel, concrete, masonry) and the dominant lateral force resisting system (e.g. bearing wall, shear wall, moment frame with infill walls). Three general height categories are considered to reflect the variation of the fundamental period of the building: low (one to three stories), medium (four to seven stories) and high-rise (more than seven stories). The expected resistance to seismic loads is assigned with one of the following seismic design levels: pre-code, low-code, moderate-code and high-code (e.g., pre-1941, 1941–1970, 1970–1990, and post-1990). The default building inventory in ER2 was aggregated at the census tract level.

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 particular IM. The developed seismic vulnerability modelling was inspired by the standard framework for performance-based engineering [13][14]. The maximum structural response of the considered building type is referred to as the ‘performance point’. It is determined by the intersection between its structural capacity curve and the response spectrum adjusted for the inelastic structural damping associated with cyclic degradation [15]. 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. The next step consists in correlating the probabilistic damage states with the respective intensity measure. This allows for direct evaluation of the expected structural and non-structural damage given a ground motion scenario. To accelerate 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. These functions are obtained for gradually increasing intensity ending with input spectrum value which generates fully plastic response on the capacity curve [16]. The respective probabilistic damage states are computed for each successive step and arranged in tabular format together with the associated intensity [5].

The building damage estimates are determined as probabilities of being in each damage state. They are then translated into direct economic losses expressed as percentages of the replacement costs of buildings. Direct economic losses are estimated based on the concept of damage factors (DF), which correlate the cost of repairs for each damage state (i.e. slight, moderate, extensive, and complete) to the replacement cost of the building. The respective mean damage factor (MDF) is then computed as the ratio between the expected repair cost value and the replacement cost of the building. Direct social losses are estimated in terms of the expected number of injuries and fatalities. It is related to the probability of being in one of the structural damage states including the probability of collapse. Four casualty levels are considered [13]: severity 1: injuries requiring basic medical aid, but without hospitalization (treat and release); severity 2: injuries requiring medical attention and hospitalization, but not considered to be life-threatening; severity 3: casualties that include entrapment and require expeditious rescue and medical treatment to avoid death; and severity 4: fatalities. Figure 3 shows an example of damage and loss estimation of a single building type (W1, pre-code wood light frames) subjected to ground motions from a M7R30km scenario.



Domain: ENA GMPE: Atkinson & Adams, 2013 Magnitude: 7 Distance: 30 Site: D Building: W1-p Cost: 500,000 Class: RES1 Occupants: 10 Interpolate: yes

Scenario

Seismic Domain	Ground Motion Equation	Magnitude	Distance (km)	Soil Type
ENA	Atkinson & Adams, 2013	7.0	30.0	D

Building Information

Building Type	Seismic Code	Replacement Cost ($)	Occupancy Class	Number of occupants
W1	p	500,000	RES1	10

Ground Motion & Mean Damage Factor

SA@0.3s (g)	SA@1.0s (g)	Intensity Measure	Displacement (in)	Acceleration (g)	MDF (%)	STD/COV
0.54	0.21	Sa@0.3s	0.47	0.30	5.54	7.29/1.32

Building Damage State Probabilities

Damage State	Structural (%)	Non-Structural Drift (%)	Non-Structural Acceleration (%)
None	43.82	52.42	26.16
Slight	32.57	23.05	36.76
Moderate	19.65	20.17	28.62
Extensive	3.51	3.21	7.65
Complete	0.45	1.16	0.81

Economic Loss

Loss Category	Exposure ($)	Economic Loss ($)	Damage Ratio (%)
Structural	500,000	5,656	1.13
Nonstructural Drift	500,000	13,101	2.62
Nonstructural Acceleration	500,000	8,919	1.78
Total Nonstructural	500,000	22,020	4.40
Contents	250,000	10,290	4.12
Total	750,000	37,965	-

Casualties

Casualty Level	Description	Occupants (%)	Occupants (#)
None	Uninjured	99.85	10
Level 1	Require Medical Attention	0.13	0
Level 2	Require Hospitalization	0.02	0
Level 3	Life Threatening Injury	0.00	0
Level 4	Death	0.00	0

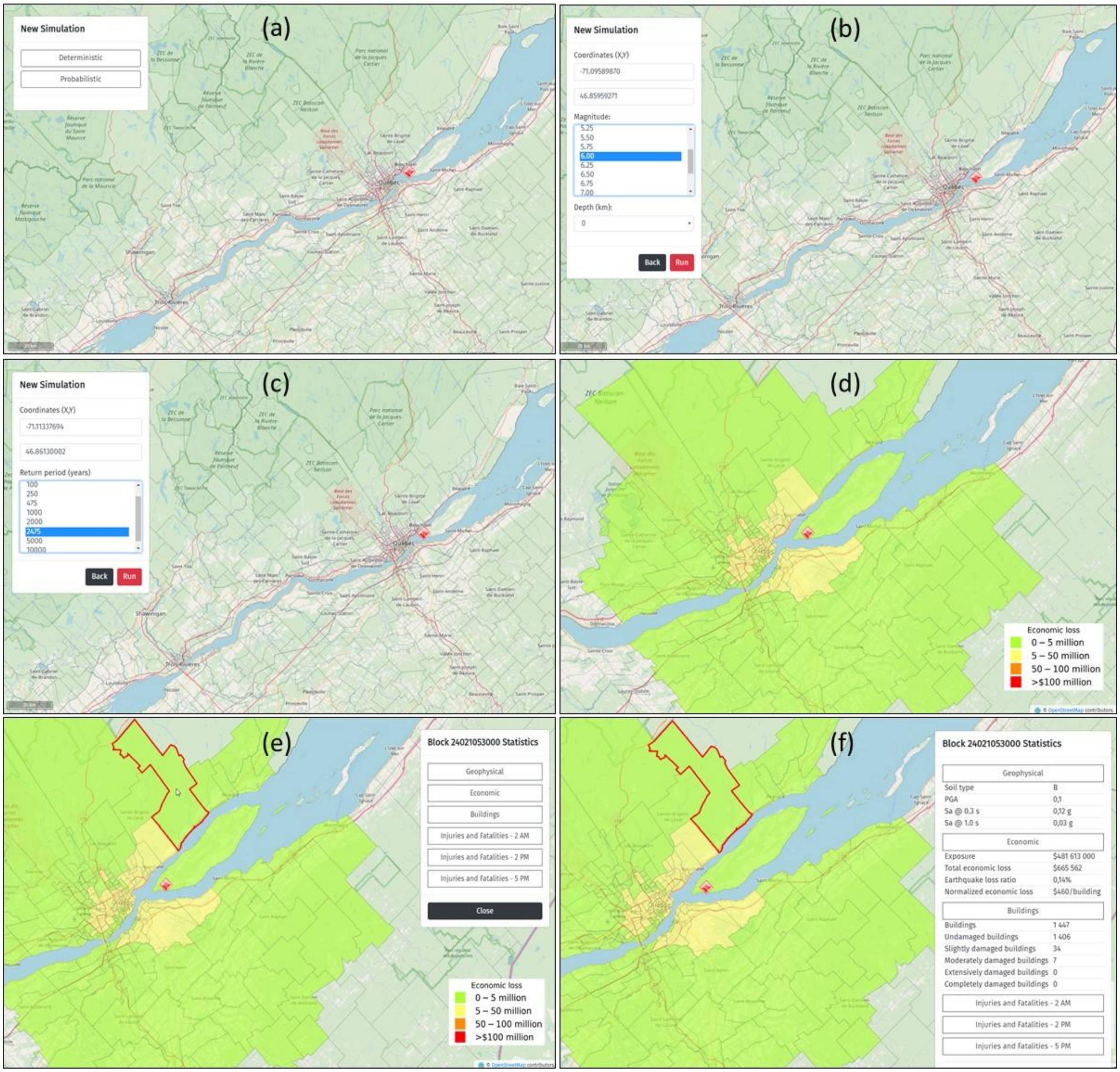
Figure 3. A screen view of damage and loss estimation of a single building type.

ER2: INTERACTIVE WEB-APPLICATION

Interactive web-based application was developed for use by non-expert public safety community. It will be freely accessible via internet in 2019, with no need for any commercial software or advanced geographic information system (GIS). The objective is to provide first-order estimates of potential physical damage, economic and social losses resulting from seismic hazards. Background data includes seismic scenarios, inventory of buildings and vulnerability databases that are stored on a dedicated server for the current version of the application. Data retrieval process and selection of the different options are accompanied by intuitive on-screen prompts that guide the user through different functionalities.

Application of ER2 is illustrated for a hypothetical earthquake event within Quebec City limits. It starts with opening of a new simulation dialog box. It provides an easy way to navigate the map and to prepare the planned scenario (Figure 4a). For simple point source scenario, single clicking on the map selects the epicenter location (Figure 4b). Here, the point source is located about 7 km from the Old Quebec City. A magnitude M6.0 is selected with hypocentral depth of 10km. The studied region is auto-determined with a corresponding radius (e.g., 50km) adjusted to the boundaries of the affected census tracts. The closest distance to the centroid of census tract is measured and applied in the calibrated point source model of the GMPE to obtain the IMs of the considered scenario. For probabilistic scenarios, the user clicks on the map to choose the location of the center of the study and selects the return period (Figure 4c). For the illustrated scenario, a return period of 2 475 years, or 2% in 50 years, is selected. The needed IMs are retrieved directly from the stored database of each return period.

The red “Run” button initiates the simulation. Within the study area in Eastern Canada, all IMs are adjusted for the local site conditions. The application then automatically retrieves the aggregated inventory data across each of the affected census tracts and determines the damage states and the corresponding economic and social losses of existing building types with respect to the IMs. Following the completion of the analyses, the user is prompted to select and display the resulting map layers and simulation statistics for the entire study area (Figure 4d) where the aggregated direct economic losses on the census tract level are shown. The tool can also show more details related to the scenario for a specific census tract (Figure 4e,f) including the shaking intensities, direct economic loss, number of buildings in each damage state (no damage, slight, moderate, extensive, complete) and the number of injuries and fatalities. The user has the option to download and save the analysis results and summary reports.



New Simulation

Coordinates (X,Y)
-71.09589870
46.85959271
Magnitude: 6.00
Depth (km): 0

New Simulation

Coordinates (X,Y)
-71.11337694
46.86130002
Return period (years) 2475

Block 24021053000 Statistics

Geophysical	
Soil type	B
PGA	0,1
Sa @ 0.3 s	0,12 g
Sa @ 1.0 s	0,03 g
Economic	
Exposure	$481 613 000
Total economic loss	$665 562
Earthquake loss ratio	0,14%
Normalized economic loss	$460/building
Buildings	
Buildings	1 447
Undamaged buildings	1 406
Slightly damaged buildings	34
Moderately damaged buildings	7
Extensively damaged buildings	0
Completely damaged buildings	0

Figure 4. Example of ER2, running a M6 with 10km depth point source seismic scenario for Quebec City and respective results. The epicenter location is indicated with a red rhombus.

ONGOING DEVELOPMENTS

Ongoing developments of ER2 include finite-fault model implementation for the simulation of earthquake rupture and the estimation of the IMs, consideration of the epistemic uncertainty in the shaking intensity introducing the GMPE's upper and lower bound, vulnerability of the transportation networks including highway bridges fragility functions.

CONCLUSIONS

The ongoing and proactive efforts to develop the interactive web-application for seismic risk assessment tool, ER2, were presented. One of the goals of these developments is to facilitate informed decision-making and offer simplified access of the public safety community to estimates of potential physical damage, economic and social losses resulting from seismic hazards. 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 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. 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 replacement costs and social losses are determined with the number of injuries and fatalities. Equipped with graphic user interface, ER2 web-application allows non-expert users from the public safety community to run otherwise complex seismic risk scenarios through a simple intuitive process.

ACKNOWLEDGMENTS

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