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2021 Shakeout scenario for Quebec city, Canada

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Abstract

A ShakeOut exercise was planned to help understand potential impacts and prepare for a large earthquake in the Quebec City region, Canada. Scientific and technical knowledge was provided as the basis for a simple "drop, cover, hold on" procedure at home, school or workplace. More elaborated table top emergency exercises will also be developed for decision making by government departments and agencies. Evaluation of negative impacts was conducted for a 'what-if' M6.5 scenario earthquake with an epicentral distance of about 15 km from the Old downtown and a depth of 10 km. This hypothetical scenario was arbitrarily assigned a date, February 8th, when the outside temperature drops below -10 °C, and time, 3:00 pm, when most people are at school or work. Physical damage and social and economic losses were predicted using the ER2 user-friendly risk assessment tool. The analyses were run for site specific inventory of structural types of buildings and their occupancies, microzonation maps and ground motion maps for peak ground acceleration and spectral accelerations at periods of 0.3 and 1.0 seconds. The average number of injuries requiring medical care was estimated at more than 2,800 with 50 fatalities. The respective direct economic loss due to structural, non-structural and content damage to buildings was about $4.2B with more than 4,000 heavily damaged red-tagged buildings. Potential permanent ground displacements and damage to critical infrastructures were approximated and described qualitatively. A brief narrative of the disaster scenario is given at the end to summarize the activities, actions, decisions and solutions by the Crisis Management Team.

Key words: ShakeOut, inventory, vulnerability, damage, economic loss, human losses

1 Introduction

Quebec City is located in an intraplate region of low-to-moderate seismic activity in Eastern Canada. The past experience with earthquakes usually gives a false sense of security to the population. Earthquakes seldom happen, and even when they do, they are of relatively low intensity, last only a few seconds, and are too weak to cause any important damage. The largest known earthquake to have occurred within the Quebec City Metro area was the 1997 M4.7 Cap-Rouge earthquake (Figure . 1), with a depth of 22 km [1]. It caused limited non-structural damage concentrated to a few buildings in the epicentral area, e.g., fallen chimneys and parts of façade, cracked plaster, displaced shelves, etc. The other two noticeable events were the M4.0 1864 Beauport and M4.0 1964 Charlesbourg earthquakes. The largest ever recorded event in the region was the 1663 Charlevoix earthquake, about 150 km northeast of downtown Quebec City, with an estimated maximum perceived intensity X on the Mercalli scale, or with a moment magnitude between 7 and 8. The earthquake-generated shaking was felt sharply even several hundreds of kilometers away and caused a series of landslides along the St. Lawrence River.

There are numerous seismically vulnerable buildings, e.g., unreinforced masonry and heritage buildings, particularly in the Old Downtown [2]. Some of these buildings have already been retrofitted, however, most of them still remain unretrofitted. At the same time, the public awareness of potential earthquake risk is relatively low. Most of homeowners choose not to pay for insurance and the uptake of earthquake coverage is among the lowest in earthquake prone regions of Canada. A recent report from the Insurance Bureau of Canada estimates the number of homes with an insurance against the earthquake peril to only about 3-4 % [3].

Large earthquakes happen and if not adequately addressed, the loss of life and property can be significant leaving the local households on their own in the first several hours after the disaster. The possibility of a strong damaging earthquake in Eastern Canada, including the Quebec Metro area, has been identified by the industry and by the government [4, 5]. To help prepare for such rare events, Geological Survey of Canada has partnered with Public Safety Quebec to create a ShakeOut scenario aiming at understanding the potential short and long-term impacts of a strong earthquake in Quebec City. ShakeOut is an annual province-wide earthquake drill occurring each October in the Province of Quebec since 2013 [6]. It has been inspired by the ShakeOut exercise developed in 2008 in California to encourage the internationally recognized practice of "drop, cover, hold on" procedures. Participating individuals, schools and organizations use this opportunity to practice what they would do in case a large earthquake disrupts the daily life. The drill also serves to review emergency preparedness and action plans, and to secure spaces where people live, work, study, commute, etc.

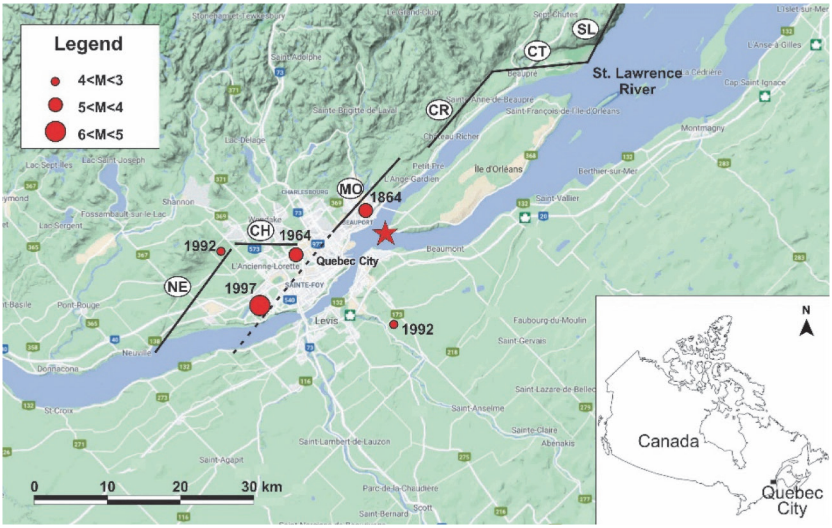

Figure 1. Location of the study area with major past earthquakes and local faults mentioned in the text: Neuville (NE), Charlesbourg CH), Montmorency (MO), Chateau-Richer (CR), Cap Tourmente (CT) and St. Lawrence (SL). The epicenter of the hypothetical M6.5 scenario is indicated with a red star

The objective of this paper is to describe the steps involved in the development of the 2021 ShakeOut exercise in the Quebec City region. The focus is on the development of a strong earthquake scenario and assessment of the potential physical damage to buildings and social and economic impacts. A brief narrative of the response to the disaster scenario is given at the end that summarizes the activities, actions, decisions and solutions by the Crisis Management Team.

2 Study area

Quebec City is located in a relatively quiescent region of the St. Lawrence rift system between the seismically much more active Western Quebec seismic zone, which encompasses Ottawa and Montreal, and the Charlevoix-Kamouraska seismic zone to the northeast [7]. The bedrock consists of Paleozoic shale and limestone along the St. Lowlands and mainly slate and sandstone of the Appalachian Orogen to the south [8]. They are floored by the Precambrian crystalline rocks of the Canadian Shield, principally igneous and high grade metamorphic rocks, which crop out in the northern part of the city. The Lowlands limit against the crystalline basement is marked by a series of northeast-striking faults: Neuville, Montmorency, Chateau-Richer, and St. Lawrence, and by shorter easterly striking Charlesbourg and Cap-Tourmente faults (Figure .1). These faults have traditionally been described as normal faults. The 1997 M4.7 Cap-Rouge earthquake was associated with the Neuville fault with an estimated average deep of 75° [1].

The stratigraphy of the Quaternary sediments is a result of the complex evolution of glacial, marine, estuarine and fluvial erosion and sedimentation systems. In the Lowlands, the Quaternary succession includes a varied suite of discontinuous surficial sediments typical of glaciated terrains. Glacial till is ubiquitous at the base of the stratigraphic column. It originates from the glacial abrasion of the Canadian Shield rocks and was deposited mainly during the last advance of the Laurentian glaciation, about 20,000 years ago. Additional distinctive features in the region are related to the Champlain Sea submergence, a marine incursion that occurred as a temporary inlet of the Atlantic Ocean. Formed at the close of the last deglaciation, it inundated the isostatically depressed St. Lawrence valley from about 13,000 years ago to about 10,000 years ago up to 200 masl. As a result of this submergence, the regional till is commonly covered by a blanket of marine clayey silts, concentrated in various topographic depressions. Younger sandy sediments were accumulated on top in beach, fluvial and deltaic environments. The surficial soils are very discontinuous laterally and often alternate vertically, in a way that local stratigraphic columns seldom contain more than two or three of these units. The presence or absence of the soft marine sediments exerts considerable control on ground shaking characteristics in the study area. The site classification of the local soil conditions was studied recently based on geophysical and geotechnical measurements and geostatistical modelling [9]. The shear wave velocity of the top 30m was used as the main parameter for these regional site classification according to the current provisions of the National Building Code of Canada NBCC 2015 [10].

2.1 Assets at risk

Buildings represent important sector within the urban built environment and their performance under earthquake loading is critical to the overall seismic resilience of the community. An inventory of the existing buildings was generated interpreting data from the Quebec City municipal property database, Statistics Canada 2016 census database [11] and from a limited street survey used for validation purpose. Inventory data was aggregated at the census tract level, a geographic area with a population between 2,500 and 8,000 people, smaller in downtown area and larger in the neighbourhoods. The following criteria were used for to categorize the buildings: construction material; structural system: frame or wall structure; seismic design code: pre-code, low-code, mid-code or high-code; height: low-rise 1–3 stories, mid-rise 4–7 stories, or high-rise 7+ stories; and occupancy class [2]. The total number of inventoried buildings in the study area is 211,929 with a replacement cost of about $110B. Detailed inventory results for seven downtown census tracts identify two most common structural types mainly with residential occupancy (Table 1): low-rise unreinforced masonry (URM Brick; about 17 %) and low-rise wood light frame (W1; about 75 %), whereas reinforced concrete and steel structures account for <8 % combined.

Table 1. Building inventory for downtown Quebec City

Construction material		Wood		Concrete					Steel					Masonry			
																URM	
		W1	W2	C1	C2	C3	PC1	PC2	S1	S2	S3	S4	S5	RM1	RM2	Brick	Stone
Occupancy class	Res	11860	0	229	8	2	6	7	62	27	0	5	4	4	2	2009	102
	Com	265	17	26	34	0	51	10	186	255	0	12	39	39	40	583	63
	Ind	0	9	5	3	0	3	2	25	20	10	1	6	6	5	34	1
	Rel	0	7	1	1	0	0	0	3	3	0	0	4	4	5	0	34
	Gov	0	0	0	0	0	1	1	3	4	0	0	0	0	0	11	3
	Edu	0	3	3	2	0	0	3	10	14	0	1	0	0	0	21	0
Height	1- 3	12119	36	21	38	1	61	10	199	254	10	4	46	46	52	2384	160
	4-7	6	0	34	6	1	0	13	70	41	0	3	7	7	0	274	43
	8+	0	0	209	3	0	0	0	20	28	0	12	0	0	0	0	0
Total		12125	36	264	47	2	61	23	289	323	10	19	53	53	52	2658	203

In Canada, unreinforced brick masonry buildings date back before 1940 when the first seismic design provisions were introduced. These buildings were designed to resist gravity loads with poor resistance to lateral seismic loading. Their main structural components are the load-bearing walls which transfer primarily gravity loads to the building foundation. Bearing walls are vulnerable to in-plane shear, resulting in typical diagonal cracks, and to out-of-plane bending, which can lead to collapse. For each floor, the relatively flexible floor/ceiling system consists of wooden joists placed or loosely tied at the top edge of the walls. They represent the structural elements capable of distributing the horizontal inertia loads to the bearing walls. Some of the masonry buildings have been retrofitted applying standard techniques: restoring the physical integrity of the masonry by replacing deteriorated mortar from joints with new mortar, and anchoring and tying of individual structural elements (walls, floors) with tension and/or shear anchors thus increasing the overall stiffness and tensile resistance. However, most still remain unretrofitted. On the other hand, the wood light-frame single-family or multifamily buildings have been widely built across Canada starting from the second half of the 20th century. The wooden floor frame is attached to the foundation walls made of poured concrete, unreinforced concrete blocks or rarely with stone walls. The floor structure is built with wooden joists that frame the floor on which stud wall frames are erected in sections. The modern light wood frame structures rely on wood based shear walls, e.g., plywood sheeting, as the lateral force resisting system.

2.2 Vulnerability

The input shaking intensity for dynamic response analyses of the building inventory was defined with the peak ground acceleration PGA and with spectral accelerations at periods of 0.3 and 1.0 second, Sa0.3s and Sa1.0s, respectively. Whereas Sa0.3s and Sa1.0s are used for damage assessment to both structural and non-structural components, the PGA value contributes to estimate damage to non-structural acceleration sensitive components only. According to the capacity spectrum method CSM, the performance point solution requires that both the building's specific capacity curve and the seismic demand be represented in the spectral acceleration vs. spectral displacement domain, Sa-Sd [12, 13]. The performance point is obtained when the effective damping of the capacity curve equals that of the demand spectrum at their intersection. Depending on the shaking intensity, the performance point can fall on the constant acceleration portion of the demand spectrum, determined with Sa0.3s in this case, yielding usually low degree of damage. When the performance point occurs in the constant velocity domain of the spectrum, Sa1.0s, the stronger shaking engenders a higher degree of damage. The performance point is used to calculate the respective discrete damage state probabilities through a set of building specific fragility curves. Five physical damage states are defined: none, slight, moderate, extensive, complete, each with own median threshold and a lognormal standard deviations [14]. Casualties are mainly correlated to the collapse state calculated as percentage of the completely damaged buildings.
The standard CSM, however, is a tedious and time consuming method, which takes several hours to run. To accelerate the process of damage assessment, a non-iterative algorithm was proposed based on the development of fragility curves correlated directly to the shaking intensity, e.g., PGA, Sa0.3s and Sa1.0s [15]. They are generated for a given seismic scenario (magnitude-distance) adjusted for local site conditions. The fragility curves are developed gradually increasing the input acceleration from low spectral values and elastic displacement, to reasonably high spectral values, for which plastic response is obtained on the far end of the capacity curve [16]. First, the specific performance point parameters are defined: spectral displacement Sd, spectral acceleration Sa and effective damping ratio. The respective demand spectrum is then correlated to the 5 % damped input response spectrum defined from the seismic scenario. Next, Sd is linked to the set of displacement based fragility curves for the given building type to obtain the probability of being in each of the potential damage states. In the last step, the probabilistic damage states are correlated to the shaking intensity defined with the input spectrum parameters.
The above rapid method allows for a direct assessment of the structural and non-structural damage. The damage functions that correlate the intensity of the seismic shaking, herein given with Sa03s, to the probability of a given damage state for both building types are shown in Figure . 2.

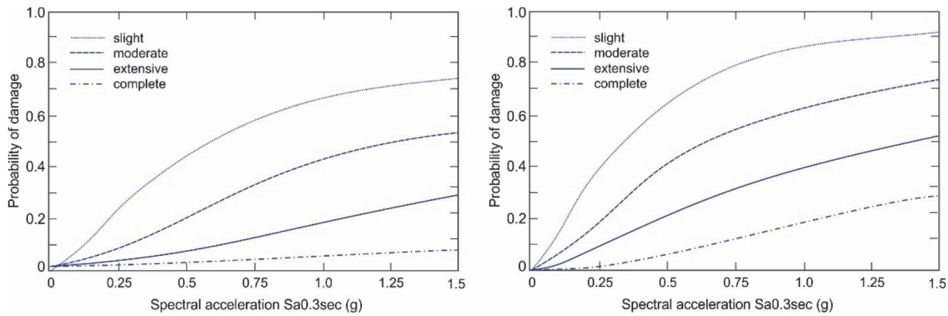

Figure 2. Damage functions with discrete damage states for low-rise: a) light wood frame buildings, and b) unreinforced brick masonry buildings

3 Seismic scenario

A series of different earthquake scenarios were first created by Public Safety Quebec. The retained hypothetical scenario was chosen so that it would affect both shores of the St. Lawrence River stretching the response capacity of the emergency management organizations to their limit. The earthquake occurs on the Montmorency fault with M6.5 and a shallow crustal depth of 10km, compatible with the current NBCC 2015 seismic hazard. The epicenter is located at the southern tip of Ile d'Orleans, an elongated island just across the Old Quebec City (Figure 3a). The probability of such an event is evaluated low, in the range of 0.1-1 % per year, or with a return period between 100 and 1000 years. The current ground motion predication equation GMPE for the seismotectonic features of Eastern Canada was applied to predict the expected ground motion amplitudes as functions of magnitude and distance [17]. The reference soil conditions for site-class C, very dense soil to soft rock with shear wave velocity in the range between 360 and 760 m/s, are considered in this GMPE. The ground motion parameters were then adjusted for the local soil conditions. The spatial distribution of the input shaking intensity defined with PGA and the spectral accelerations Sa0.3s and Sa1.0s was calculated at the centroid of each census tract (Figure 3).

The analyses were carried out with the earthquake module of ER2 Rapid Risk Evaluator, a seismic risk assessment tool which applies the above rapid damage assessment method. ER2 is a user-friendly multi-hazard risk assessment tool with intuitive GUI and integrated open-source GIS [16, 18]. The negative impacts, generated for each of the considered 209 census tracts with more than 800,000 inhabitants, are given in Table 2.

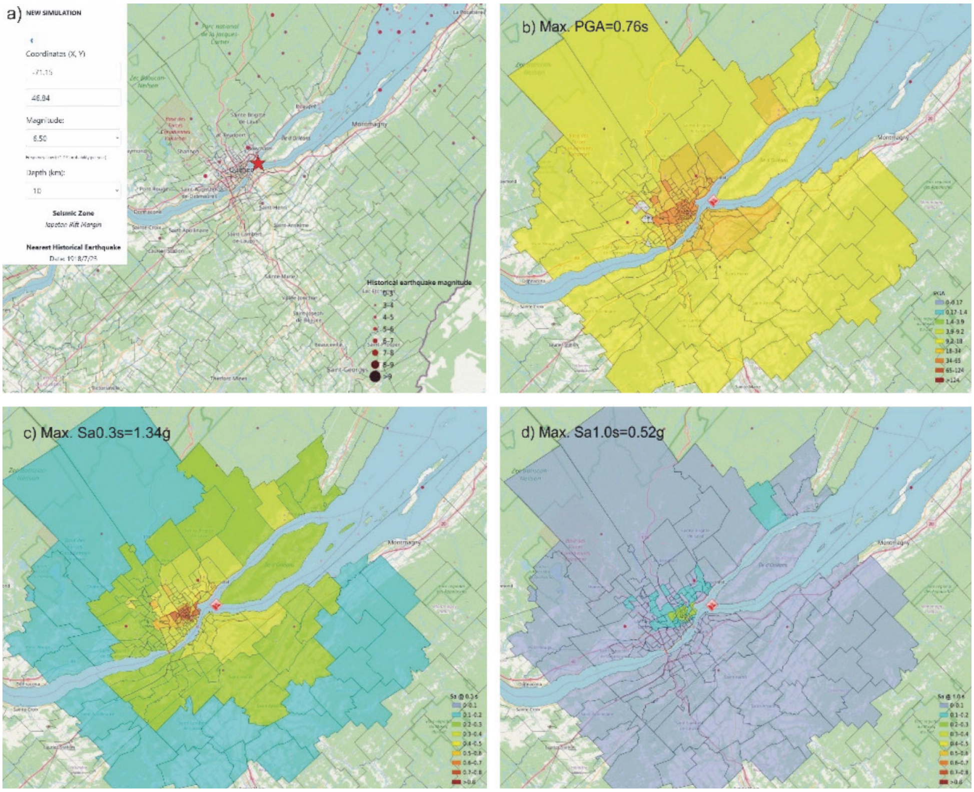

Figure 3. Hypothetical earthquake scenario: a) M6.5 and Depth = 10km; and spatial distribution of the seismic shaking intensity for: b) PGA, c) Sa0.3s and d) Sa1.0s

Table 2. Predicted physical damage, economic and human losses

Economic loss								
Number of tracts	Total buildings	Total exposure	Economic loss	Number of buildings in each damage state				
				No	Slight	Moderate	Extensive	Complete
209	211,929	$110,489M	$4,270M	155,238	36,115	16,184	3,375	1,017
Casualties								
Night time (2am)			Day time (2pm)			Commuting time (5pm)		
Indoors	Injuries	Fatalities	Indoors	Injuries	Fatalities	Indoors	Injuries	Fatalities
811,041	1,895	47	712,349	2,848	50	578,314	1,730	20

The results show that in average about 73 % of the considered buildings would experience no perceptible damage, whereas approximately 2 % (4,392 buildings) are expected to be red tagged and sustain at least extensive damage or damage beyond repair. The economic loss is about 4 % of the total value of the building stock. Most of the damage is due the non-structural damage, more than 80 %. The light wood frame structures show best performance, whereas most of the damage occurs in the masonry houses, where more than 30 % of the buildings would sustain various levels of damage. The time of the day when the earthquake occurs affects social consequences only since the population can be located in different types of buildings or commuting. The average number of injuries requiring medical attention vary between 1730 and 2,848, and up to 50 deaths can be expected. Obviously, the human and economic losses will likely be higher, since the model doesn't consider potential damage and casualties due to geohazards associated with shaking (e.g., landslides), induced urban fires (e.g., gas pipes ruptures), or other accidents that might occur during and following the earthquake (e.g., car accidents, heart attacks, etc.).

4 Scenario outline

The specified seismic scenario with M6.5 and the quantitative assessment of the potential negative impacts provided the first step in the planning of the 2021 ShakeOut exercise in Quebec City. A range of earthquake induced hazards and impacts, e.g., damage to essential and transportation facilities were not considered in the risk assessment process. Since they may be critical for the emergency response, experts from other departments were consulted. For example, the Quebec Ministry of Transport was tasked to identify the most probable areas where landslides could occur. This process ensures that comprehensive set of potential impacts accurately reflects what may happen should a strong earthquake strike the region. As well, the scenario responds well to the needs of the operators of various infrastructures and networks to test the capacities in case of emergency.

To make the overall results more easily accessible for the participants, a fictional narrative was developed. It will guide the public drills and emergency response exercises throughout the metro area. A brief summary of the ShakeOut narrative is given in Table 3.

Table 3. Predicted physical damage, economic and human losses

What is the event	A strong earthquake of magnitude 6.5 has occurred in Saint-Jean-de-l'Île-d'Orléans, at the southern tip of the Île d'Orléans. Aftershocks are expected.
Date of the event	15:05pm EST Monday, February 8, 2021
Weather conditions	-5 °C day time and -12 °C night time, with a mean temperature of -9 °C
Affected region	Both shores of the St. Lawrence River are affected together with the Île d'Orléans
Is there any urgent need for action?	Yes. All civil security stakeholders (citizens, businesses, municipal authorities and government) must intervene immediately!
What is the scale and severity of the emergency and the degree of risk associated with it?	This is a major disaster involving more than one municipality in m than one region. First estimates are that the damage to buildings and infrastructure is high. There are numerous injured people and killed people. A number of essential services are also affected. The date and the time of day complicate the operations. Hurry up with your intervention!
How was it learned that the disaster has occurred?	The earthquake was felt by the population and direct damage was widespread. An event briefing was issued by the Government Operations Center for the government partners involved in the emergency response.
What is the type and severity of reported damage?	· Several hundreds of injured people requiring medical treatment, dozens of fatalities, missing people and orphaned children. · Impacts on social and psychological life of individuals, families, employees. · Important damage to buildings structural and non-structural components and content. Partial collapse of older buildings. · Interruptions and low pressure in drinking water supply, occasional large pools of water on the streets. Damage to wastewater and sewer pipes. Structural damage to pumping station and water treatment plant · Major ground movements are observed, landslides and liquefaction · Fires are caused by toppled equipment, collapsed power lines, burst gas pipes · Restricted access to transportation facilities (roads, railways, bridges), fallen debris in the streets, damaged roadways. Damaged interchanges and ramps to Pierre-Laporte and Quebec bridges. A few rail or road accidents occurred. Flight and ferries services are suspended. Problems with repatriation of foreign travelers (tourists, business trips, farm workers, etc.) · Electrical failures, loss of power and telecommunication systems Industrial accidents along the Énergir Pipeline on the South shore and the Valero Oil Refinery in Lévis. Release of hazardous materials into the environment due fuel tank breaches, gas and oil pipeline bursts, etc.
Which intervention measures have already been taken?	· Municipal coordination centers have been opened. · Civil security advisers are already on the ground to provide support · Regional Government Coordination Center is open to ensure coordination and communication between the government departments and agencies involved in the emergency response. · Liaison officers from each of the government departments and agencies have been appointed.

5 Conclusions

The specified M6.5 seismic scenario provided a quantitative assessment of the potential negative impacts in the Quebec City region. The probability of a major earthquake striking the region is relatively low. Even if such event occurs with similar magnitude, its location, the involved fault and depth, will likely be very different from the one retained for this ShakeOut exercise. The predicted negative impacts, however, can be expected to be in the order of magnitude with respect to the affected buildings, infrastructures and human losses. The authoritative estimates indicate the areas that may be exposed to higher seismic risk and the type and number of structures with inadequate design prone to more vulnerability. The negative impacts can certainly be reduced through improved emergency preparedness, such as this exercise, and through a long process of mitigation planning.

References

[1] Nadeau, L., Lamontagne, M., Wetmiller, R.J., Brouillette, P., Bent, A., Keating, P. (1998) Preliminary results and tectonic setting of the Cap-Rouge earthquake of November 5, 1997, Quebec. Current Research 1998-E; Geological Survey of Canada, p. 105-115, https://doi.org/10.4095/209947

[2] Nollet, M.J., Désilets, C., Abo-El-Ezz, A., Nastev, M. (2012). Approche méthodologique d'inventaire de bâtiments pour les études de risqué sismique en milieu urbain. Geological Survey, Open File 7260, 93 pages, https://doi.org/10.4095/292281

[3] IBC Insurance Bureau of Canada (2016). Earthquake: Be prepared, not scared. 12 p. https://infoassurance.ca/getattachment/5878f093-3fb5-4e89-83ef-ad986268e3a3/Tremblement-de-terre-Soyez-pret-et-non-inquiet.aspx, (accessed 20th December 2020).

[4] IBC Insurance Bureau of Canada, 2013. «Étude d'impact et des coûts d'assurance et coûts économiques d'un séisme majeur en Colombie-Britannique et dans la région du Québec et de l'Ontario». AIR Worldwide. http://assets.ibc.ca/Documents/Studies/IBC_EQ_Study_Summary_FR.pdf (accessed 20th December 2020).

[5] Abo El Ezz, A., Nollet, M.J., Nastev, M. (2015): Assessment of earthquake induced damage in Quebec City, Canada. International Journal of Disaster Risk Reduction, 12: 16-24, https://doi.org/10.1016/j.ijdrr.2014.11.004

[6] PSQ Public Safety Quebec https://www.grandesecousse.org/quebec/ (accessed 20th December 2020).

[7] NRCan Earthquakes Canada https://earthquakescanada.nrcan.gc.ca/, (accessed 20th December 2020).

[8] Globensky, Y. (1987). Géologie des basses-terres du Saint-Laurent. Direction Generale de la Recherche Geologique et Minerale, map# MM 85-02.

[9] Nastev, M., Parent, M., Ross, M., Howlett, D., Benoit, N. (2016). Geospatial modeling of shear-wave velocity and fundamental site period of Quaternary marine and glacial sediments in the Ottawa and St. Lawrence Valleys, Canada. Soil Dynamics and Earthquake Engineering, 85: 103-116, https://doi.org/10.1016/j.soildyn.2016.03.006

[10] NRC National Building Code of Canada 2015 (2016). National Research Council Canada, Ottawa, Canada.

[11] StatsCanada 2016 https://www12.statcan.gc.ca/census-recensement/2016/dp-pd/prof/index.cfm?Lang = E (accessed December 2020).

[12] ATC-40 Applied technology Council (1996). Seismic evaluation and retrofit of concrete buildings – Volume 1. Report No. SSC 96-01, Seismic Safety Commission, Redwood City, CA.

[13] Kircher, C.A., Nassar, A.A., Kustu, O., Holmes, W.T. (1997). Development of building damage functions for earthquake loss estimation. Earthquake Spectra, 13(4): 663–682. https://doi.org/10.1193/1.1585974

[14] FEMA (2012). HAZUS-MH: Multi-hazard Loss Estimation Methodology Earthquake Model - Technical manual. Federal Emergency Management Agency, National Institute Building Science, Washington, D.C.

[15] Porter, K. (2009). Cracking an open safe: more HAZUS vulnerability functions in terms of structure-independent intensity. Earthquake Spectra, 25(3): 607–618, https://doi.org/10.1193/1.3153330

[16] Abo El Ezz, A., Smirnoff, A., Nastev, M., Nollet, M.J., McGrath, H. (2019). ER2-Earthquake: Interactive web-application for urban seismic risk assessment. International Journal of Disaster Risk Reduction (3.6), Elsevier, 34:326-336. https://doi.org/10.1016/j.ijdrr.2018.12.022

[17] Atkinson, G. and Adams, J. (2013). Ground Motion Prediction Equations for Application to the 2015 Canadian National Seismic Hazard Maps. Canadian Journal of Civil Engineering, National Research Council Canada NRC, 40(10): 988-998, https://doi.org/10.1139/cjce-2012-0544

[18] Nastev, M., Nollet, M.J., Abo El Ezz, A., Smirnoff, A., Ploeger, S.K., McGrath, H., Sawada, M., Stefanakis, E. (2017). Methods and tools for natural hazard risk analysis in Eastern Canada – Use of knowledge to understand vulnerability and implement mitigation measures. American Society of Civil Engineers ASCE, Natural Hazards Review, 18(1): 1535-1543. 10.1061/(ASCE)NH.1527-6996.0000209