Abo-El-Ezz *et al.*
Advances in Bridge Engineering (2023) 4:3
https://doi.org/10.1186/s43251-023-00083-4

Advances in
Bridge Engineering

ORIGINAL INNOVATION

Open Access

Scenario-based earthquake damage assessment of highway bridge networks

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Abstract

In earthquake-prone regions, the evaluation of seismic impacts on bridges is crucial to mitigation, emergency, and recovery planning for highway networks. The degree of bridge damage determines the cost and time required for repairs and the level of post-earthquake functionality including disruption of transportation network, increased costs due to reduction of traffic flow and restricted access to emergency routes. The article presents the methodological development and implementation of an interactive web application for rapid geospatial assessment and visualisation of earthquake damage scenarios of municipal highway bridge networks based on open access datasets. The proposed framework consists of the following successive models: hazard, inventory, damage, and impact. The seismic hazard model generates spatial distribution of the shaking intensity for earthquake scenarios in terms of ground motion intensity measure using ground motion prediction equations based on seismic hazard model for Eastern Canada. The shaking intensities are then modified with local site amplification factors based on the Canadian highway bridge design code values. The inventory model provides a database of existing bridges based on open-access data which are then classified according to their seismic vulnerability. The damage model assesses seismic performance of classes of bridges by applying respective fragility functions represented as probabilistic relationships between the intensity measure and the degree of expected damage. The impact model evaluates the post-earthquake traffic-carrying capacity of the highway network based on the predicted damage including repair cost as a percentage of replacement cost of bridges and inspection priority. The web-application is demonstrated with a bridge network in Quebec City including 117 bridges subjected to 180 earthquake scenarios. The proposed methodology is particularly useful to facilitate direct communication of potential impacts to emergency managers and city transport officials.

Keywords: Earthquake scenarios, Fragility functions, Highway bridges, Damage assessment, Geospatial risk mapping

1 Introduction

Assessment of potential negative impacts to bridge networks is critical to mitigation, emergency, and recovery planning for transportation infrastructures. The capacity of a highway bridge network to carry traffic flow following a strong earthquake depends on the degree of damage, range of encountered cost, time required for repairs and the level of post-earthquake functionality (Wald et al. 2006; Werner et al. 2006; Padgett and DesRoches 2007; Wotherspoon et al. 2011; Lin et al. 2014). Complete or partial loss of functionality related to structural damage results in reduction or disruption of the transportation capacity, cost increase for detour or reduced traffic flow and, what is most important for the public safety, in restricted access to emergency routes. The decision to keep the traffic flow open or closed has to be made immediately following a strong earthquake event before conducting any detailed bridge-by-bridge inspection. As well, the pre-earthquake mitigation planning relies on the simulation of potential damage scenarios to identify the most vulnerable sections of the network where resources should be put to achieve cost-effective seismic retrofit. The common approach to seismic hazard assessment such as the probabilistic seismic hazard analysis (PSHA) is not necessarily tailored for post-earthquake emergency planning and management where the assessment of potential impacts from multiple earthquake events is the priority concern (Robinson et al. 2018). This is especially important in regions with limited information and data on damaging earthquake events, future earthquake probabilities and locations of active faults such as Eastern Canada (Atkinson and Adams 2013; Nastev et al. 2017; Abo El Ezz et al. 2019). PSHA is used to characterize for a given site the likelihood of exceeding some value of ground motion for a given period (e.g., a 2% chance of exceedance in 50 years) (McGuire 1995) and is widely used in determining the appropriate seismic design level in bridge codes such as the Canadian highway bridge design code (CSA 2014). On the other hand, effective planning and prioritization of mitigation activities requires the estimation of the scale and extend of future earthquake impacts and the locations where significant damage are most likely to occur according to the assessment of many earthquake scenarios.

This article presents the development of a framework for rapid geospatial assessment of earthquake damage scenarios of highway bridge networks and its implementation in a proof-of-concept interactive web-application. The proposed methodology intends to facilitate direct communication of potential impacts to emergency managers and city transport officials. The underlying methodology is based on the generation of precalculated damage scenarios for multiple-earthquake events compatible with the regional seismicity of Eastern Canada with considerations to sources of uncertainties inherent in the assessment process. This includes the development of a computational tool for rapid retrieval and visualisation of the precalculated damage scenarios based on the integration of multiple computational models and datasets including: ground motion prediction model that is compatible with the seismicity in Eastern Canada (Halchuk et al. 2014) which represent the basis for seismic hazard design input in the Canadian highway bridge design code (CSA 2014), local site classes based on geologic and geotechnical mapping and corresponding local site amplification factors, bridges inventory and classification based on seismic vulnerability of classes of bridges using open-access datasets, seismic fragility functions relating the expected damage to a ground motion intensity measure (IM) such as the peak ground acceleration (PGA) and impact model which evaluates the post-earthquake traffic-carrying capacity of the highway network based on the predicted damage including repair cost as a percentage of replacement cost of bridges and inspection priority. This calculation process provides a rapid access (within seconds) to a suite of earthquake scenarios and results for end users. Existing tools such as Hazus (FEMA 2020) and ShakeCast (Lin et al. 2014) are used for regional scale risk assessment of highway bridges in the United States. On the other hand, they require extensive data preparation and specific requirements for their software integration with local bridge information and are not necessarily compatible with the Canadian seismic hazard parameters. The proposed web-application represents an advantage compared to existing tools with the above challenges to non-expert end-users by providing ready-to-use interactive risk information for multiple scenarios. Using visualization techniques on the web, users can access damage results without specific software download or technical expertise. In addition, the proposed methodology provides a framework for utilizing open access datasets in the risk assessment process.

The computational framework for earthquake damage assessment of bridges is first presented, followed by detailed description of the successive steps in the modelling process including seismic hazard, inventory, damage, and impact models. The various open access input datasets for each model for a case study region in Quebec City, Canada are presented and discussed to demonstrate the capacity of the proposed modelling methodology. At the end, a comparative analysis of potential earthquake damage for increasing levels of seismic hazard is presented.

2 Risk assessment framework

The proposed framework for scenario based seismic risk of highway bridge networks consists of the following successive models: hazard, exposure, damage, and impact. The seismic hazard model generates spatial distribution of the shaking intensity for earthquake scenarios in terms of a ground motion IM; the inventory model provides a database of bridge classes defined according to construction material, structural systems and seismic design level; the damage model assesses seismic performance of the bridge classes in the network applying respective fragility functions represented as probabilistic relationships between the IMs and the simulated degree of expected damage; and the impact model evaluates the post-earthquake traffic-carrying capacity of the highway network based on the predicted damage including repair costs of bridges, road closures and post-earthquake inspection priority. Open-access datasets were used for the demonstration case study in Quebec City including ground motion prediction database, microzonation map to define the site classes at each bridge location and bridge inventory data. In the following section, each model input data and output parameters are explained using the case study highway bridge network.

2.1 Seismic hazard model

The seismic hazard is determined with the shaking intensity at each bridge site based on a closed-form ground motion prediction equation (GMPE). The GMPE lookup tables for Eastern Canada (Atkinson and Adams 2013), used to develop the seismic hazard model of Canada outlined in (Halchuk et al. 2014) which represents the basis for seismic hazard design input in the Canadian highway bridge design code (CSA 2014), is applied for reference peak ground acceleration (PGA) at rock level. In this study, PGA is considered the IM for the subsequent steps in the risk modelling since most fragility functions in the literature were developed for PGA (Tsionis and Fardis 2014) and it has been demonstrated that it provides optimal correlation with damage for a portfolio of bridges

(Padgett et al. 2008). The uncertainty in the IM was captured with the provided upper and lower bounds dataset in (Atkinson and Adams 2013). At each bridge site, the distance from the epicentre is estimated to the bridge location coordinates and the rock IM is automatically modified for local site conditions with amplitude and frequency dependent site amplification factors as functions of the average shear wave velocity to a depth of 30 m (Vs30) as defined in the Canadian highway bridge design code (CSA 2014) including: hard rock (A; Vs30 > 1500 m/s), rock (B; 760 < Vs30 < 1500 m/s), very dense soil and soft rock (C; 360 < Vs30 < 760 m/s), and stiff soil (D; 180 < Vs30 < 360 m/s). In order to estimate the corresponding site class at a bridge location, an open access microzonation map developed for Quebec City was used (Leboeuf et al. 2013) (Fig. 1). The GMPE, initially available as discrete values in lookup tables for Vs30 = 760 m/s (B/C boundary), is approximated through regression analysis to a closed-form solution to facilitate its implementation as a function of the magnitude (M) and the epicentral distance (R_{epi}) as shown in eqs. 4, 5 and 6 for the median PGA for Eastern Canada for magnitude range from 5 to 7.25 and epicentral distance up to 40 km. Fig. 2 shows the range of predicted median PGA values per scenario (i.e., the median of the shaking intensity for a given scenario at 117 bridge sites). In this study, 180 shaking scenarios were considered, including three earthquake magnitudes (M5, M6 and M7), three GMPE representing the lower bound (eqs. 1, 2 and 3), median (eqs. 4, 5 and 6) and upper bound (eqs. 7, 8 and 9) estimate of the considered IM (Atkinson and Adams 2013) and 20 epicentres to consider the uncertainty in future earthquake locations based on the 10 km grid spacing of the Geological Survey of Canada seismic hazard model (NRCAN 2015).

$$PGA_{lower} = e^{[(-0,1159 \times M^2 + 2,0446 \times M - 9,265) + ((0,0047 \times M^2 - 0,0437 \times M + 0,0418) \times R_{epi})]}, , 5 \leq M < 6.5 \quad (1)$$

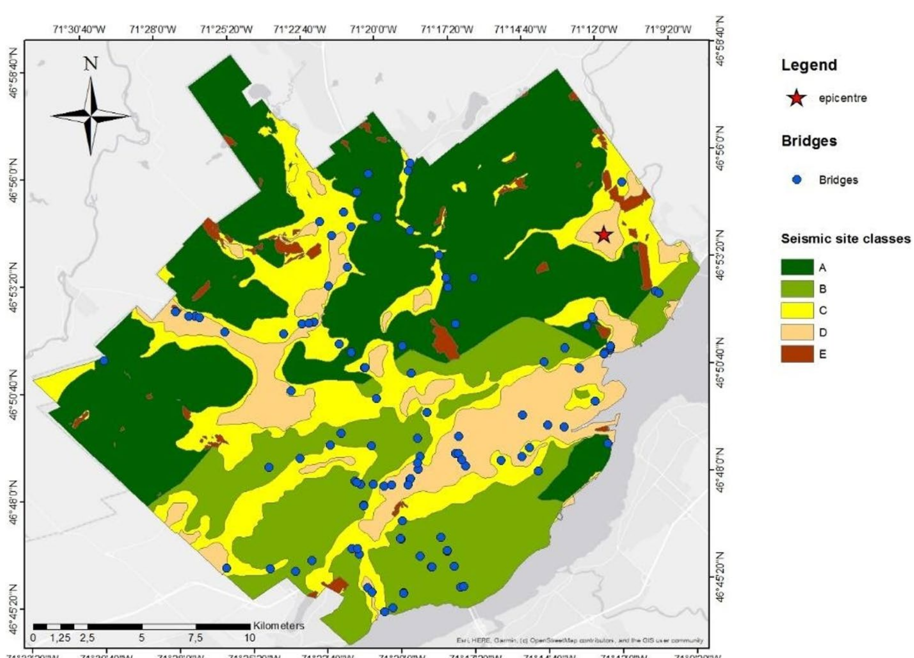

Fig. 1 Seismic site classes map for Quebec City

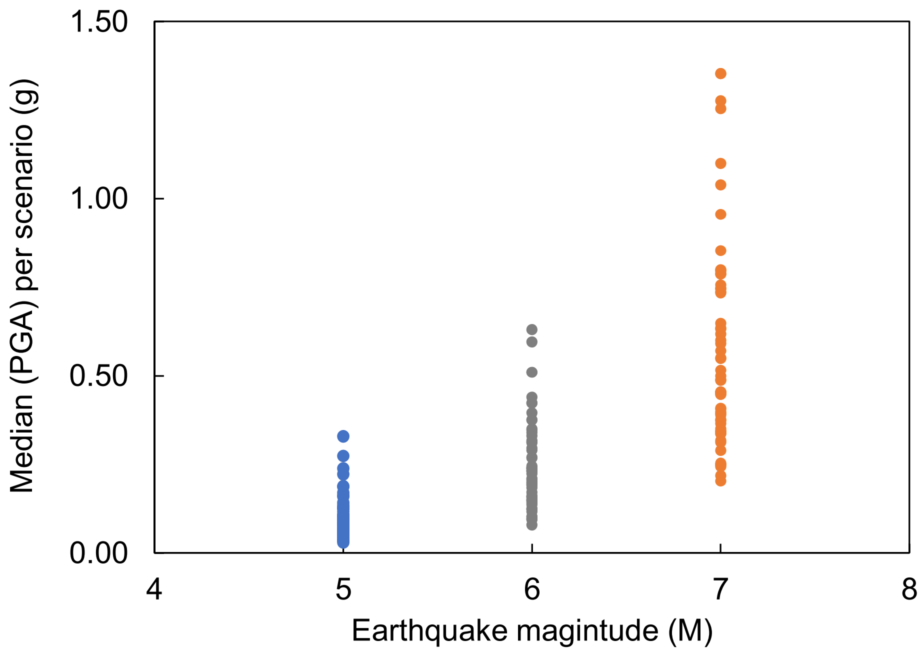

Fig. 2 Variability in the median PGA per scenario for M5, M6 and M7 events

$$PGA_{lower} = e^{\left[(0,0618\times M^2-0,3642\times M-1,0189)+((-0,0066\times M^2+0,115\times \mathrm{M}-0,5168)\times R_{epi})\right]}, 6.5 \le M < 7 \quad (2)$$

$$PGA_{lower} = e^{\left[(-1,693\times \mathrm{M}+13,129)+((0,8873\times M-7,0945)\times \ln(R_{epi}))\right]}, 7 \le M < 7.25 \quad (3)$$

$$PGA_{median} = e^{\left[(-0,0523\times M^2+1,2429\times M-6,1598)+((0,0003\times M^2+0,0142\times M-0,1546)\times R_{epi})\right]}, 5 \le M < 6.5 \quad (4)$$

$$PGA_{median} = e^{\left[(0,0853\times M^2-0,7475\times M+1,0734)+((-0,0097\times M^2+0,1611\times M-0,6912)\times R_{epi})\right]}, 6.5 \le M < 7 \quad (5)$$

$$PGA_{median} = e^{\left[(-1,5911\times M+13,085)+((0,8578\times M-6,9448)\times \ln(R_{epi}))\right]}, 7 \le M < 7.25 \quad (6)$$

$$PGA_{upper} = e^{\left[(0,024\times \mathrm{M}^2+0,392\times \mathrm{M}-3,3028)+((-0,0051\times M^2+0,0724\times M-0,3026)\times R_{epi})\right]}, 5 \le M < 6.5 \quad (7)$$

$$PGA_{upper} = e^{\left[(0,1181\times M^2-1,2651\times M+3,6513)+((-0,0144\times M^2+0,2296\times M-0,9485)\times R_{epi})\right]}, 6.5 \le M < 7 \quad (8)$$

$$PGA_{upper} = e^{\left[(-1,4856\times M+13,028)+((0,8281\times M-6,7977)\times \ln(R_{epi}))\right]}, 7 \le M < 7.25 \quad (9)$$

As noted earlier, the GMPEs are based on a B/C boundary with Vs30 = 760 m/s. Therefore, the values of PGA were multiplied by a modification factor of 1.208 to estimate the ground motion for the reference site class (in this case site class C: very dense soil and soft rock) as proposed by Halchuk et al. (2014). To account for variation of ground motion intensity for different site classes (A, B, C, D and E), the (CSA 2014) requires that the value of the PGA_{ref} (i.e., the PGA for site class C) be modified by a site factor F(PGA). Table 1 summarizes the values of F(PGA) as a function of the soil classes and the reference maximum horizontal acceleration (PGA_{ref}).

2.2 Inventory model

The inventory of bridges potentially exposed to ground shaking is the second major input dataset. It can be conducted at a local (bridge) scale by sidewalk and virtual desktop surveys, or at regional scale by interpreting data from municipal bridges or databases from the department of transportation. For the case study area, bridge information was obtained from the inventory and inspection of structure database available online at the Quebec Ministry of Transportation website (MTQ 2020). The database provides a description of the condition of all bridges, culverts, retaining walls and tunnels under the management of the ministry of transportation. The following bridge information was available: geolocation, MTQ bridge type based on the ministry of transportation classification system (MTQ 2017), year of construction, dimensions (e.g., length, width, clearance height, superstructure surface area). The MTQ bridge types are classified according to the construction material and structural system of the superstructure including: (1) slab bridges (solid, hollow, rigid frame) made of reinforced concrete or pre-stressed concrete; (2) girder bridges (cast-in place concrete beams, precast concrete beams, steel beams, timber beams, steel or concrete rigid frame); (3) box girder bridges (steel, concrete, pre-stressed concrete); (4) truss bridges; (5) arch bridges and (6) cable bridges. This information was used along with a visual survey using Google Street view imagery to assign for each bridge the corresponding fragility-based class. This approach of grouping bridges with similar parameters into fragility classes is widely used in regional-scale bridge seismic risk assessment to simplify the damage analysis process (Nielson 2005; Tavares et al. 2012; FEMA 2020). Based on available fragility functions in the literature, bridges were grouped into classes (Table 2) according to the number of spans (single span, multiple span), span continuity (simply supported, continuous), material of construction of the bridge superstructure (steel, concrete) and type of bridge superstructure (girder, slab). The following fragility-based classes were adopted: (1) Single Span Concrete Girder (SS-Concrete); (2) Single Span Steel Girder (SS-Steel), (3) Single Span Monolithic Abutment (SS-MA-Concrete), (4) Multi-Span Continuous Steel Girder (MSC-Steel); (5) Multi-Span Continuous Concrete Girder (MSC-Concrete); (6) Multi-Span Continuous Concrete Slab (MSC-Slab); (7) Multi-Span Simply Supported Concrete Girder (MSSS-Concrete), (8) Multi-Span Simply Supported Truss (MSSS-Truss). Once the bridge classes are determined, fragility functions corresponding to each state

Table 1 Values of the F(PGA) as a function of site classes and PGA_{ref} according to the (CSA 2014)

PGAref	F(PGA) (A)	F(PGA) (B)	F(PGA) (C)	F(PGA) (D)	F(PGA) (E)
≤0.1	0.62	0.71	1	1.29	1.81
0.2	0.66	0.75	1	1.10	1.23
0.3	0.68	0.78	1	0.99	0.98
0,.4	0.7	0.8	1	0.93	0.83
≥0.5	0.71	0.81	1	0.88	0.74

Table 2 Identified bridge classes for the case study area in Quebec City

Bridge class	Number of bridges	Percentage of total	Average year of construction
MSC-Concrete	24	21%	1972
MSC-Slab	3	3%	1957
MSC-Steel	3	3%	1991
MSSS-Concrete	21	18%	1970
MSSS-Truss	2	2%	1922
SS-concrete	31	26%	1979
SS-MA-Concrete	20	17%	1972
SS-Steel	13	11%	1973
Total	117	100%	

of damage for this bridge class is used to determine the probability of being in each damage state. The inventory revealed that 55% of bridges are single span compared to 45% of multi-span bridges and 85% of bridges were built with reinforced concrete superstructure compared to 15% with steel.

2.3 Damage model

The damage model consists of a dataset of fragility functions related to the bridge classes in the inventory model. A set of fragility functions quantifies the conditional probability representing the likelihood that a given bridge structure will meet or exceed specified level of damage for a given IM. There are three main approaches for creating seismic fragility functions: (1) experts' opinion methods estimate the probable damage distribution of bridges when subjected to different earthquake intensities based on a questionnaire completed by experts (ATC 1985); (2) empirical methods using damage data from post-earthquake field observations (Basöz et al. 1999, Shinozuka et al. 2000); and (3) analytical methods that rely on numerical structural models to simulate the seismic response of bridges (Nielson 2005; FEMA 2020, Tavares et al. 2012) which is typically applied in regions with limited historical earthquake damage data. The assessment of bridge fragilities represents a major recurring challenge for seismic risk modelers in terms of judgment to select fragility functions from available literature with the constraint of lacking sufficient resources or data to develop site-specific functions. Developing specific fragility functions considering the regional construction practice for the types of bridges in Quebec would provide more representative results. However, such task warrants an independent study which is outside the scope of this article. On order to demonstrate the methodology and the developed web-application, the damage model is established by attributing the most appropriate fragility data to each class of bridges in the inventory model based on searching existing literature. Only one study was found in the literature that provided fragility functions for multi-span bridge classes representative of construction practice in Quebec (i.e., MSC-Steel; MSC-Concrete; MSC-Slab; MSSS-Steel and MSSS-Concrete) based on the study of (Tavares et al. 2012) and therefore were retained since they were generated using representative Quebec bridges characteristics subjected to ground motion time histories compatible with Eastern Canada seismicity.

It should be noted that complete damage state median was not reported in the study of (Tavares et al. 2012) for two classes, the MSC-Concrete and MSC-Steel. Therefore, it was assumed that their complete damage state median PGA equals 1.95 times the value of the corresponding extensive damage median PGA. This ratio (i.e., 1.95) represents that average ratio of the complete to extensive median PGA from the reported classes. For other bridge classes (i.e., MSSS-Truss bridges, SS-Concrete, SS-Steel, SS-MA-Concrete), no comprehensive fragility datasets were found in the literature representative for Quebec bridges. Therefore, existing literature was used for comparable bridge classes in North America in order to establish the damage model for inventoried bridges. For MSSS-Truss bridges, Acar (2009) model was selected. This model is based on expert judgement on fragility functions for truss bridges in Central and Eastern United States (CEUS). For single-span bridges, fragility functions developed by Nielson (2005) was retained which were based on seismic response of bridges regions in CEUS. This model is based on nonlinear dynamic analyses of representative bridge models. Finally, for SS-MA-Concrete class, the fragility model proposed by Basoz and Mander (1999) was selected which is based on nonlinear static analytical modelling of typical bridges in the United States. Table 3 summarizes the median PGA and the lognormal standard deviation values of the bridge classes fragility functions selected and applied in this study. The lognormal standard deviations of the fragility functions were assumed constant for all damage states to simplify implementation process in the web application. This approach has also been applied by Nielson (2005) to simplify the dissemination of information given the small differences in the lognormal standard deviation values for different damage states based on dynamic analyses.

To explain the adopted damage assessment procedure, a simple example of MSSS-Concrete bridge class subjected to ground motion intensity of PGA = 0.4 g (Fig. 3) is presented here. The corresponding damage state probabilities at the performance point are computed with the following set of lognormal probability as shown in Eq. 10.

Table 3 Lognormal parameters for the considered fragility functions of bridge classes

Bridge class	Median PGA [g]				Lognormal Standard	Reference
	Slight	**deviationModerate**	**Extensive**	**Complete**		
MSC-Concrete	0.64	1.00	1.42	2.77	0.8	**Tavares et al. (2012)**
MSC-Slab	0.6	0.90	1.21	2.48	0.6	**Tavares et al. (2012)**
MSC-Steel	0.77	1.16	1.62	3.16	0.7	**Tavares et al. (2012)**
MSSS-Concrete	0.81	1.12	1.48	2.76	0.8	**Tavares et al. (2012)**
MSSS-Truss	0.2	0.33	0.47	0.61	0.6	Acar (2009)
SS-concrete	0.35	1.33	1.83	2.5	0.9	**Nielson (2005)**
SS-MA-Concrete	1.2	1.5	2.1	2.43	0.6	Basoz and Mander (1999)
SS-Steel	0.64	1.19	1.59	2.59	0.6	**Nielson (2005)**

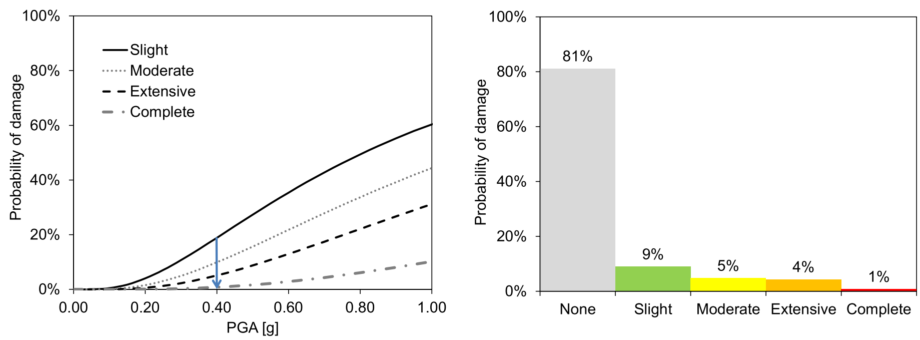

Fig. 3 Fragility functions for the MSSS-Concrete bridge class (left) and the corresponding probabilities of damage states for PGA = 0.4 g (right)

$$PDSi\ (PGA = x) = 1 - \phi\left(\frac{\ln\left(x/\lambda_{DS1}\right)}{\beta_1}\right)\ i = 0$$
$$PDSi\ (PGA = x) = \phi\left(\frac{\ln\left(x/\lambda_{DSi}\right)}{\beta_{DSi}}\right) - \phi\left(\frac{\ln\left(x/\lambda_{DSi+1}\right)}{\beta_{DSi+1}}\right)\ 1 \le i \le 3 \tag{10}$$
$$PDSi\ (PGA = x) = \phi\left(\frac{\ln\left(x/\lambda_{DS4}\right)}{\beta_{DS4}}\right)\ i = 4$$

where, PDSi (PGA = x) denotes the probability of a damage state DSi given PGA equals x; the index i is 0 for no damage, 1 for slight damage, 2 for moderate damage, 3 for extensive damage and 4 for complete damage); Φ is the cumulative standard normal distribution; λ_{DS} is the median value of the fragility function in terms of PGA, as given in Table 3; and β_{DS} is the lognormal standard deviation. For the MSSS-Concrete bridge class the median PGA values are 0.81 g, 1.12 g, 1.48 g and 2.76 g for damage states 1 to 4, respectively, whereas the corresponding β_{DS} is 0.8. The respective discrete structural damage state probabilities obtained for this seismic scenario are 81% no damage, 9% slight damage, 5% moderate damage, 4% extensive damage and 1% complete damage (Fig. 3).

2.4 Impact model

Based on the damage assessment results using fragility functions, the expected impacts of the generated damage to bridges are quantified. These include the expected damage state, mean damage ratio (MDR) defined as the mean repair to the replacement cost ratio (Werner et al. 2006), inspection priority, and the likely immediate post traffic state given the expected damage state (Dukes 2013) as presented in Table 4. The MDR is computed as the weighted sum of the best estimate of damage ratios (Di) for each damage state multiplied by the probability of being in each damage state PDSi (eq. 11). The MDR can then be used to identify the expected damage state and the priority rank for inspection. For example, if the MDR is estimated to be 20%, therefore the expected damage state of the bridge is moderate (Table 4). To estimate the uncertainty in the damage ratio estimates, the standard deviation is estimated using eq. 12 according to (Padgett et al. 2010).

Table 4 Bridge damage states and the corresponding inspection priority and likely post-event traffic states and repair cost ratios

Damage state	Slight	Moderate	Extensive	Complete
Range of damage ratio (Werner et al. 2006)	1%–5%	5%–50%	50%–80%	80%–100%
Best estimate of damage ratio (Di) (Werner et al. 2006)	3%	25%	75%	100%
Inspection priority (Dukes 2013)	Low	Medium	Medium-high	High
Likely post-event traffic state (Dukes 2013)	Open to normal traffic- no restrictions	Open to limited traffic- speed/weight/lane restrictions	Emergency vehicles only- speed/weight/lane restrictions	Closed until shored/braced- potential for collapse

$$MDR = \sum_{i=1}^{4} D_i \times PDS_i \tag{11}$$

$$\sigma_D = \sqrt{\sum_{i=1}^{4} (D_i - MDR)^2 \times PDS_i} \tag{12}$$

2.5 Uncertainty quantification

Equations 11 and 12 presented in the impact model section provides a simplified estimate of the uncertainty in the damage assessment process given the realization of a ground motion intensity of a given earthquake scenario with a specific magnitude. Important sources of uncertainties are combined including the variability in the damage ratio given the attainment of a specific damage state with the variability in the prediction of damage state through probabilities from fragility functions. Fragility functions probabilities integrate the uncertainty in the dynamic seismic response and the capacity of the population of bridges within a given class through the lognormal standard deviation (β_{DS}). To estimate the uncertainty of the shaking intensity itself at a given bridge site for a specific earthquake scenario, the methodology applies three sets of the GMPE including the median, lower, and upper-bound estimates of the PGA intensity as explained in section 2.1. The uncertainty in the location of future earthquake events is considered by developing a database of precalculated earthquake damage scenarios with varies magnitude (M5, M6 and M7) based on the 10 km grid spacing (Fig. 4). This allows for a direct communication of the inherent uncertainty in seismic damage assessment and understanding of their significance on the results to end users.

2.6 Web-application

The generation of an interactive web application for earthquake damage scenarios was conducted in three distinct steps: (i) development of the computational algorithm to associate damage state probabilities to PGA, as presented in the previous sections; (ii) generation of a database with values of expected damage state, MDF, inspection priority tabulated in increasing order associated to different earthquake scenarios; and (iii)

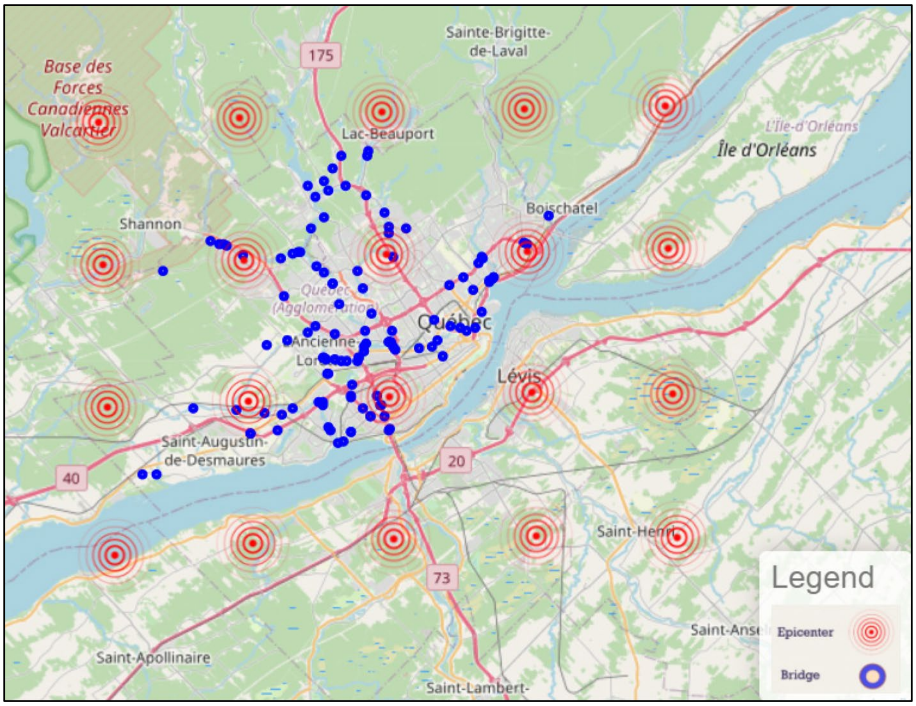

Fig. 4 Earthquake scenarios epicenters with 10 km grid spacing for the bridge network in Quebec City

development of a visual web interface which employs the database to provide risk assessment results of the precalculated scenarios.

The proof-of-concept web application allows rapid evaluations of potential earthquake induced damage and inspection priority for a user-specified earthquake scenario. The interface was developed on python language using Dash-Leaflet and Plotly (PyPI 2020) and is designed to be user-friendly and easy to use. it consists of background map layers, a navigation bar, and a variety of dialog boxes. The user does not need to prepare and provide any data inputs; all the required inputs are preconfigured and stored on a dedicated server PostgreSQL database (PostgreSQL 2020). Default parameters are offered to the user, including the bridge inventory and information at each bridge location and automatic damage maps. Data retrieval process is accompanied by intuitive on-screen prompts that guide the user through different output results as presented in the software flow diagram (Fig. 5). The web-application starts with opening of the scenarios and bridge locations map and dialog box. It provides a quick and easy way to navigate the map and convenient means to prepare the planned scenario. The user can select the epicentre location and the respective value of the magnitude from the drop-down menu (Fig. 5A). Once the epicentre and magnitude are selected, the software automatically retrieve the corresponding data from the PostgreSQL database including the site class, bridge class, estimated PGA, MDR and standard deviation, expected damage state, inspection priority and ranking (Fig. 5B). The results are then visualized on the map along with a summary table for the overall bridge damage states for the specified scenario (Fig. 5C). The user can also display for each bridge the aforementioned information by simple clicking on the bridge location. Figure 6 illustrates an example of the web-application running an earthquake scenario of M6 at a distance 10 km from downtown

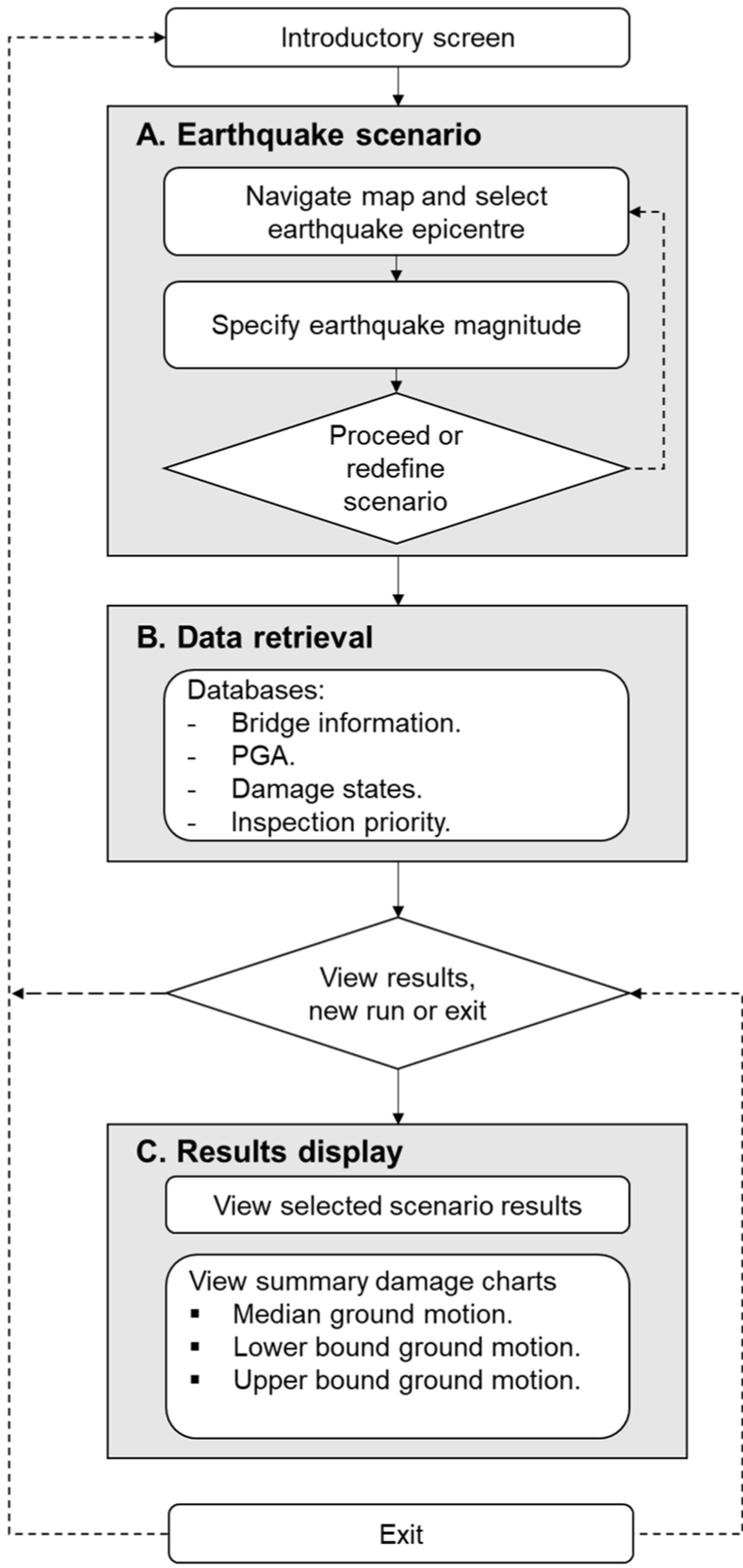

Fig. 5 Flow diagram for the web-based application

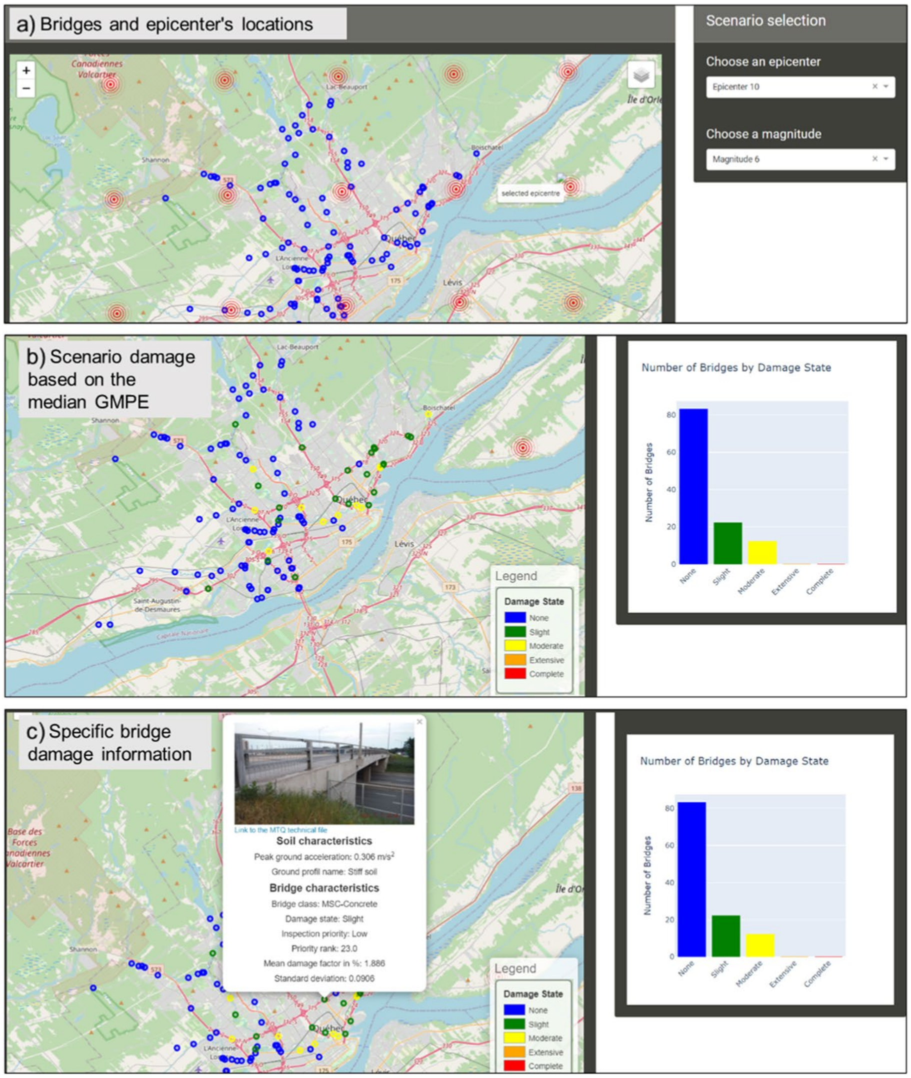

Fig. 6 Example of the web application running an earthquake scenario of M6 at a distance 10 km from downtown Quebec City: (1) the landing screen where the user can select the epicentre and visualize the bridge information; (2) scenario damage results based on the median GMPE with summary statistics of bridges in each damage state and (3) selection of a specific bridge damage information including the estimated PGA, damage state, MDR and inspection priority rank

Quebec City including the landing screen where the user can select the epicentre and visualize the bridge information (Fig. 6a); scenario damage results based on the median GMPE with summary statistics of bridges in each damage state (Fig. 6b) and selection of a specific bridge damage information including the estimated PGA, damage state, MDR and inspection priority rank (Fig. 6c). An important feature of the web-application is the capacity to visualize the spatial distribution of damage for any given scenario considering the interaction between the shaking intensity attenuation with distance from the epicentre, the local geological site effects at each bridge site, and the specific vulnerability of the bridge to seismic loading. The developed framework for interactive spatial damage assessment is of particular interest to the municipal transport planner as well as emergency managers. It provides an order of magnitude estimation of the scale of potential damage given the occurrence of an earthquake with a specific magnitude. This scale of potential damage can be useful for the estimation of the range of resources and funding necessary for post-earthquake inspection, prioritization of expected repair activities, estimate costs associated with detours and reduced traffic flow. In addition, such knowledge would provide emergency managers with estimates of potential disruption and loss of functionality of the road network and help plan and anticipate for the expected number of bridges with restricted or reduced access and potential traffic delays. Another potential use of the web application is the evaluation of the performance of bridges for earthquake scenarios corresponding to specific design return period and compare the predicted damage state with the expected performance-based objectives from the bridge design codes (McIntyre et al. 2015). For example, major route bridges would be expected to sustain minimal damage for the 475 year ground motion and repairable damage for 975 year ground motion (McIntyre et al. 2015).

2.7 Damage scenarios statistics

In this section, damage statistics are presented for a total of 180 scenarios: 3 earthquake magnitudes (M5, M6 and M7 earthquakes at 20 epicentre locations), and three ground motion prediction equations considering the uncertainty in the ground shaking at bridge sites for a given scenario. Figure 7 presents a summary of the proportion of bridges in each damage states for all scenarios of the three magnitudes considering the uncertainty in the predictions. The average results statistics show that: (i) for M5, 8% of bridges are expected to sustain some degree of damage: slight (6%) and moderate (2%); (ii) for M6, 46% of bridges are expected to sustain some degree of damage: slight (30%) and moderate (16%); (iii) for M7, 87% of bridges are expected to sustain some degree of damage: slight (25%), moderate (60%), extensive (2%) with very low proportion of complete damaged bridges (0.4%) or only 1 bridge per scenario. The effect of uncertainty in the level of ground shaking intensity per scenario and the location of future epicentres is significant.

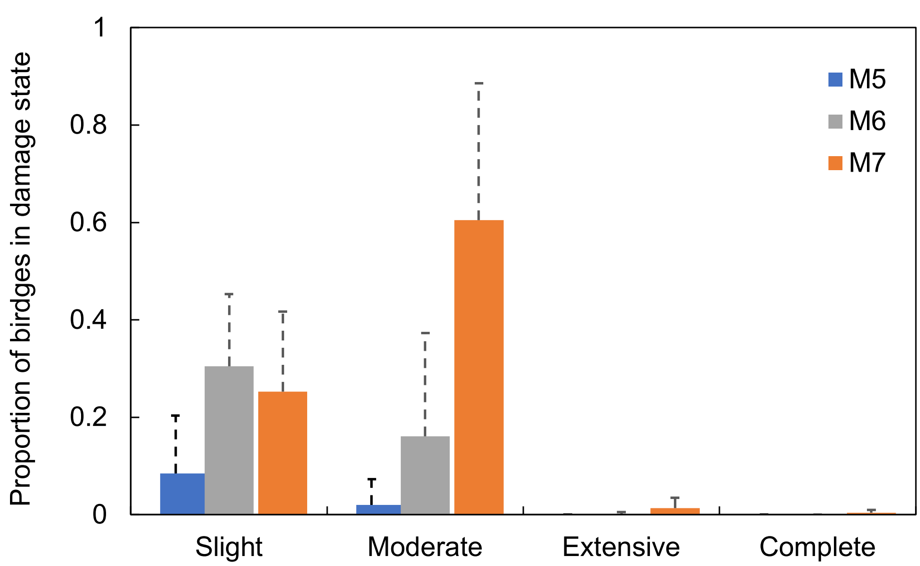

Fig. 7 Predicted proportion of bridges in each damage state for scenarios with M5, M6 and M7

For example, for M6 earthquakes, the upper bounds of the proportion of bridges that would sustain some degree of damage is 83%. The low proportion of extensively damaged bridges is mainly attributed to the applied sets of fragility functions in this study where it can be observed that the median threshold for sustaining extensive damage for all bridge classes varies between 1.2 g to 2.0 g (with the only exception of the two MSSS-Truss bridge with threshold of 0.47 g). On the other hand, the median PGA for M6 and M7 scenarios were 0.24 g and 0.57 g with few scenarios generating PGA exceeding 1.0 g (Fig. 1). These observations highlight the importance of the selection of bridge fragility functions which should be considered for improved reliability of the risk assessment results. Therefore, the presented results are rather to demonstrate the proof-of-concept of the proposed methodology and should not be used directly for decision-making purposes given the limited availability of comprehensive datasets on the seismic fragility of bridges in the province of Quebec.

3 Conclusions

This article presented the development of a framework for rapid geospatial assessment of earthquake damage scenarios of highway bridge networks and its implementation in a proof-of-concept interactive web-application. The proposed methodology intends to facilitate direct communication of potential impacts to emergency managers and city transport officials. The underlying methodology in developing the application is based on the generation of precalculated damage scenarios for multiple-earthquake events compatible with the regional seismicity of Eastern Canada. This includes the development of a computational tool for rapid retrieval and visualisation of the precalculated damage scenario. The article presented the computational framework for earthquake damage assessment of bridges followed by a detailed description of the successive steps in the modelling process including seismic hazard, inventory, damage, and impact models. The seismic hazard model generates spatial distribution of the shaking intensity for earthquake scenarios in terms of ground motion intensity measure; the inventory model provides a database of bridge classes; the damage model assesses seismic performance of bridge classes in the network applying respective fragility functions represented as probabilistic relationships between the intensity measure and the simulated degree of expected damage; whereas the impact model evaluates the post-earthquake traffic-carrying capacity of the highway network based on the predicted damage including repair cost as a percentage of replacement cost of bridges and inspection priority. The various open access input datasets for each model for a case study region in Quebec City, Canada, were presented and discussed to demonstrate the capacity of the proposed modelling methodology. At the end, a comparative analysis of potential earthquake damage for increasing levels of seismic hazard was presented. The case study illustrated an important feature of the proposed methodology, which is the capacity to visualize, in a user-friendly environment, the spatial distribution of damage for any given scenario considering the interaction between the shaking intensity attenuation with distance from the epicentre, the local geological site effects at each bridge site, and the vulnerability of the bridge to seismic loading. The generalized architecture of the web application system allows the framework to analyze other regions with available site classification and bridge inventory data. Future research should consider the following aspects: (1)

development of specific fragility functions for Quebec bridge classes with representative geometrical and material parameters for improved reliability of the risk assessment results, (2) the evaluation of the sensitivity of the damage assessment procedure to the variations of fragility parameters (i.e. median and lognormal standard deviation).

Abbreviations

PSHA	Probabilistic seismic hazard analysis
PGA	Peak ground acceleration
IM	Intensity measure
GMPE	Ground motion prediction equation
Vs30	Average shear wave velocity to a depth of 30 m
MTQ	Quebec Ministry of Transportation
SS-Concrete	Single Span Concrete Girder
SS-Steel	Single Span Steel Girder
SS-MA-Concrete	Single Span Monolithic Abutment
MSC-Steel	Multi-Span Continuous Steel Girder
MSC-Concrete	Multi-Span Continuous Concrete Girder
MSC-Slab	Multi-Span Continuous Concrete Slab
MSSS-Concrete	Multi-Span Simply Supported Concrete Girder
MSSS-Truss	Multi-Span Simply Supported Truss

Acknowledgements
Not applicable.

Authors' contributions
AA: Conceptualization, methodology, analysis, writing - Original Draft Preparation. AF: Analysis, database development, software visualization, writing - review & editing. HF: Analysis, analytical method validation, writing - review & editing. MJN: Funding acquisition, conceptualization, supervision, writing - review & editing. The author(s) read and approved the final manuscript.

Funding
This study was supported through funding by École de Technologie Supérieure.

Availability of data and materials
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

Declarations

Competing interests
The authors declare that they have no competing interests.

Received: 3 January 2023 Accepted: 13 February 2023
Published online: 01 March 2023

References

Abo El Ezz A, Smirnoff A, Nastev M, Nollet MJ, McGrath H (2019) ER2-earthquake: interactive web-application for urban seismic risk assessment. Int J Disaster Risk Reduction 34:326–336

Acar, F. (2009). Rapid damage assessment of infrastructure components in the Central United States. Report no. 09-02. Mid-America earthquake center, University of Illinois at Urbana-Champaign, USA

ATC (1985) ATC-13: earthquake damage evaluation data for California. Applied Technology Council, Redwood City

Atkinson GM, Adams J (2013) Ground motion prediction equations for application to the 2015Canadian national seismic hazard maps. Can J Civ Eng 40(10):988–998

Basoz N, Mander J (1999) Enhancement on the Highway Transportation Lifeline Module in Hazus. National Institute of Building Sciences, Washington

Basöz NI, Kiremidjian AS, King SA, Law KH (1999) Statistical analysis of bridge damage data from the 1994 Northridge, CA, earthquake. Earthquake Spectra 15(1):25–54

CSA (2014) CAN/CSA-S6-14—Canadian highway bridge design code. Canadian Standards Association, Rexdale

Dukes JD (2013) Application of bridge specific fragility analysis in the seismic design process of bridges in California (Doctoral dissertation, Georgia Institute of Technology)

FEMA (2020) Multi-Hazard loss estimation methodology, earthquake model, HAZUS-MH MR1 technical manual. Federal Emergency Management Agency, Washington, D.C

Halchuk S, Allen TI, Adams J, Rogers GC (2014) Fifth generation seismic hazard model input files as proposed to produce values for the 2015 National Building Code of Canada. Geological Survey of Canada, Open File 7576:18

Leboeuf, D., Perret D., Nollet M-J., Lamarche L., Nastev M., and Parent M. (2013). Microzonage sismique des Villes de Québec-Ancienne-Lorette et Réserve indienne de Wendake (Catégories d'emplacement). Commission géologique du Canada, Dossier Public 6875, Échelle 1: 50,000, doi: https://doi.org/10.4095/292640
Lin KW, Turner LL, Wald D (2014) ShakeCast V3: an enhanced tool for post-earthquake response. Caltrans Division of Research, Innovation & System Information, Sacramento
McGuire RK (1995) Probabilistic seismic hazard analysis and design earthquakes: closing the loop. Bull Seismol Soc Am 85:1275–1284
McIntyre J, Gerin M, Leggett C (2015) Seismic design of bridges in British Columbia: ten-year review. 11th Canadian conference of earthquake engineering, Canadian Association of Earthquake Engineering, Victoria
MTQ (2017) Manuel d'inventaire des structures. Ministre de Transport du Québec
MTQ (2020) Inventaire et inspection des structures. Ministre de Transport du Québec https://www.transports.gouv.qc.ca/fr/projets-infrastructures/structures/Pages/inventaires-structures.aspx
Nastev M, Nollet MJ, Abo El Ezz A, Smirnoff A, Ploeger SK, McGrath H, Sawada M, Stefanakis E, Parent M (2017) Methods and tools for natural hazard risk analysis in eastern Canada: using knowledge to understand vulnerability and implement mitigation measures. Natural Hazards Rev 18(1):B4015002
Nielson BG (2005) Analytical fragility curves for highway bridges in moderate seismic zones. Doctoral dissertation, Georgia Institute of Technology, USA
NRCAN (2015). Seismic Hazard tools. Geological Survey of Canada, Natural Resources Canada. Website: https://earthquakescanada.nrcan.gc.ca/hazard-alea/interpolat/calc-en.php
Padgett JE, DesRoches R (2007) Bridge functionality relationships for improved seismic risk assessment of transportation networks. Earthquake Spectra 23(1):115–130
Padgett JE, DesRoches R, Nilsson E (2010) Regional seismic risk assessment of bridge network in Charleston, South Carolina. J Earthq Eng 14(6):918–933
Padgett JE, Nielson BG, DesRoches R (2008) Selection of optimal intensity measures in probabilistic seismic demand models of highway bridge portfolios. Earthquake Eng Structural Dynamics 37(5):711–725
PostgreSQL (2020). PostgreSQL global development group. Website: https://www.postgresql.org
PyPI (2020). The Python package index. Website: https://pypi.org/
Robinson TR, Rosser NJ, Densmore AL, Oven KJ, Shrestha SN, Guragain R (2018) Use of scenario ensembles for deriving seismic risk. Proc Natl Acad Sci 115(41):E9532–E9541
Shinozuka M, Feng MQ, Lee J, Naganuma T (2000) Statistical analysis of fragility curves. J Eng Mech 126(12):1224–1231
Tavares DH, Padgett JE, Paultre P (2012) Fragility curves of typical as-built highway bridges in eastern Canada. Eng Struct 31(40):107–118
Tsionis G, Fardis MN (2014) Fragility functions of road and railway bridges. Dans SYNER-G: typology definition and fragility functions for physical elements at seismic risk. Springer, pp 259–297
Wald DJ, Lin KW, Worden B, Turner L (2006) ShakeCast: facilitating the use of ShakeMap for post-earthquake decision-making and response within Caltrans and other critical lifeline communities. Fifth National Seismic Conference on bridges & highways, San Francisco
Werner S, Taylor C, Cho S, Lavoie JP, Huyck C, Eitzel C, Chung H, Eguchi R (2006) REDARS 2 methodology and software for seismic risk analysis of highway systems (technical manual). Multidisciplinary Center for Earthquake Engineering Research (MCEER), Oakland
Wotherspoon L, Bradshaw A, Green R, Wood C, Palermo A, Cubrinovski M, Bradley B (2011) Performance of bridges during the 2010 Darfield and 2011 Christchurch earthquakes. Seismol Res Lett 82(6):950–964

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