A TOOL FOR SEISMIC IMPACT ASSESSMENT ON MUNICIPAL HIGHWAY BRIDGES NETWORK

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Abstract

In moderate seismic activity regions of Eastern Canada, tools for prediction of potential negative impacts are critical to mitigation, emergency and recovery planning for transportation facilities. The post-earthquake capacity of a highway bridge network to carry traffic flow depends on the expected degree of damage and the corresponding repair costs and downtime. This paper presents the development and implementation of a rapid tool for assessment of earthquake induced damage to municipal highway bridge networks. It consists of four consecutive models: hazard, exposure, damage and impact. The seismic hazard model generates spatial distribution of the shaking intensity for the selected earthquake scenario including local site amplification and epistemic uncertainties. The existing bridges are categorized into broad classes with respect to their structural, geometric and material properties. Respective fragility functions are assigned to each bridge class as a probability of reaching a given damage state in terms of the peak ground acceleration as shaking intensity measure (IM). The damage model evaluates the seismic performance of bridge classes applying respective fragility functions, whereas the impact model evaluates the post-earthquake traffic carrying capacity of the bridge network based on the predicted damage including repair costs of bridges, road closures and inspection priority. To demonstrate the capacity of the tool, a case study of damage assessment of a bridge network in Quebec City is presented at the end for multiple earthquake scenarios.

Keywords: Seismic risk; Bridges; Fragility; Earthquake scenarios; Assessment.

1. Introduction

In moderate seismic regions such as Eastern Canada with a few earthquakes induced damage observations [1], assessment of potential negative impacts to bridge networks is critical to mitigation, emergency and recovery planning for transportation infrastructures [2, 3]. 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 [4]. 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 generation of potential damage scenarios to identify the most vulnerable sections of the network where resources should be put to achieve cost-effective seismic retrofit.

This paper describes the development and implementation of a software tool for rapid seismic impact assessment to bridge networks. The successive steps to run seismic risk scenarios include hazard, exposure, damage and impact models and are integrated into an Excel spreadsheet with a simple user interface. Results are computed considering shaking intensity at each bridge site and include mean damage factor, damage state, relative priority rank for inspection and economic losses. They are presented in tabular form as well as on a geographic information system platform. To demonstrate the capacities of the proposed framework, a case study is presented for impact assessment of a bridge network in Quebec City consisting of 76reinforced concrete and steel bridges and 31 other types of bridges.

2. Methodology

The proposed analytical methodology consists of consecutive steps including hazard, exposure, damage and impact models. The seismic hazard model generates spatial distribution of the shaking intensity (shakemap) for selected earthquake scenario in terms of ground motion intensity measure (IM). Exposure consists of a database of bridge classes determined according to the construction material, structural system and the design code level based on year of construction. The damage model evaluates the seismic performance of the bridges in the network applying respective fragility functions represented as probabilistic relationships between the IM at the location of the bridge and the degree of expected damage. The impact model evaluates the post-earthquake traffic-carrying capacity of the bridge network based on the predicted damage including repair cost, traffic-closure and post-earthquake inspection priority. Epistemic uncertainties could be estimated through the consideration of different models at each step of the risk analysis: three hazard confidence levels (lower, median and upper), three sets of fragility functions, and two repair-cost models.

2.1 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) with user-specified magnitude, epicentre and simple fault geometry. The AA13 GMPE for Eastern Canada [5], currently recommended by the National Building Code of Canada NBCC 2015 [6], is applied for reference peak ground acceleration (PGA) and spectral accelerations (SA) at rock level. The epistemic uncertainty can be captured with the provided upper and lower confidence levels. At each site, the rock IM is automatically corrected for the local site conditions with amplitude and frequency dependent site amplification factors as functions of the average V_{S30} as defined by NBCC 2015: hard rock (A; Vs30>1500m/s), rock (B; 760<Vs30<1500m/s), very dense soil and soft rock (C; 360<Vs30<760m/s), and stiff soil (D; 180<Vs30<360m/s) [7]. The AA13 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.

Nine (9) closed form equations were developed, one for each confidence level (upper, median and lower) for distances up to 40 km and for three ranges of magnitudes: from M5 to M6.5, from M6.5 to M7 and from M7to M7.25.. Equation (1) represents an example for median GMPE from 5M to 6.5M and equation (2) an example of closed form solution for M6.

$$PGA = e^{[(-0.0516\times M^2+1.2089\times M+0.8738)+((-0.0004\times M^2+0.024\times M-0.1852)\times R_{epi})]} \quad (1)$$

$$PGA\,[g] = 526 \times e^{-0{,}05\times \boldsymbol{Repi}\ (\boldsymbol{km})} \quad (2)$$

where: PGA is the peak ground acceleration and Repi represents the epicentral distance in kilometers.

2.2 Exposure model

The inventory of bridges in the study area was conducted by interpreting data available for the Quebec City area according to Quebec Ministry of Transportation (MTQ) bridge classification system [8]. To simplify the damage analyses, the individual bridge structures were grouped into broad classes according to their expected behaviour under seismic loading [9, 10]. The following structural parameters were inventoried: year of construction, number of spans (single span or multiple span), super-structure type (reinforced concrete, steel, or wood), pier type (single column bent, multiple column bents, or pier wall), abutment type (monolithic or non-monolithic), bearing type (high rocker bearings, low steel bearings or elastomeric bearings), isolation bearings (with or without), span continuity (continuous, discontinuous, in-span hinges or simply supported). A total of 110 bridges were considered with the majority (66%) built with reinforced concrete girders and piers and 50% identified as single-span bridges. The original MTQ bridge classification were converted to equivalent Hazus classes since the majority of the fragility functions available in the literature correspond to the Hazus classification scheme [10]. For example, pre-stressed precast concrete girder bridges and overpasses were converted in Hazus in single-span or in multi-span simply supported concrete bridges. Details on the assumed bridge classes are given in Table 1.

Table 1. Classification of the identified bridges in Quebec City according to the Hazus classification scheme.

Bridge type	Quantity	Percent
SS (Single span) - Concrete	33	30,00%
SS (Single span) - Steel	2	1,82%
MSC (Multi-span continuous) - Concrete	23	20,91%
MSSS (Multi-span simply supported) - Steel	1	0,91%
MSC (Multi-span continuous) - Slab	3	2,73%
MSSS (Multi-span simply supported) - Concrete	17	15,45%
Other *	31	28,18%
Total	110	100,00%

*bridges which could not be categorized into one of the six major classes, such as wood-steel girder, triangulate Pony Warren steel girder, triangulate girder with steel low deck, steel girder with concrete coating, culvert with reinforced concrete slab, reinforced concrete overpass and reinforced concrete culvert overpass.

2.3 Damage model

Fragility functions are central to estimate the damage to bridge structures. A set of fragility functions quantifies the conditional probability representing the likelihood that a given bridge structure will meet or exceed a specified damage state for a given intensity measure (IM) of the seismic hazard scenario. Here the selected IM is the peak ground acceleration (PGA) as defined by equation 1. Four bridge damage states (DS) are defined: slight, moderate, extensive and complete [10]. The following equation is used to derive the fragility functions:

$$PE[(DS|PGA)] = \Phi\left[\frac{\ln(PGA) - \ln(PGA\_median)}{St.Dev}\right] \quad (3)$$

where, DSi denotes the damage state, PGA is the intensity measure, PGA_median is the median PGA threshold for the considered damage state DSi., and St.Dev is the logarithmic standard deviation. Figure 1 shows an example of fragility functions for a multi-span continuous concrete bridge class in Hazus.

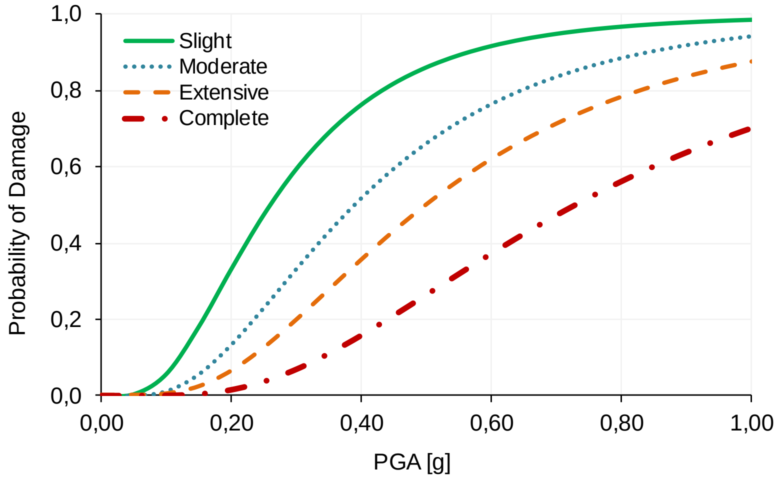

Fig. 1 – Fragility curves for a multi-span continuous concrete bridge as defined in Hazus.

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 standardized questionnaire completed by experts;

(2) empirical methods using damage data from post-earthquake field observations, and;

(3) analytical methods that rely on mechanical or numerical structural models to simulate the seismic response of bridges.

In this study, three sets of fragility functions were used to provide the capacity to test the sensitivity of the risk assessment results with respect to the selection of the fragility functions. The first set was based on the results of dynamic analyses of Quebec multi-span bridge models [9]. The second set was based on the dynamic analyses of single and multi-span bridge models compatible with the construction practice in Central and Eastern United States[11]. The third set was based on the standard Hazus method for single and multi-span bridge classes in Eastern United States [10]. It applies the nonlinear static method for fragility development. Aleatory uncertainty is included in each of these models.

2.4 Impact model

Based on the damage assessment results, the negative effects of the simulated damage to bridges are quantified using the impact model. This model includes: inspection priority, likely immediate post-event traffic state the bridges can be assigned in terms of inspection priority, likely immediate post-event traffic state of the bridge and repair cost ratios. In order to estimate the incurred economic losses, the mean damage factor (MDF) is computed as the weighted sum of the average damage ratios (Di) multiplied by the probability of being in each damage state P(DSi) according to the following equation,

$$MDF = \sum_{i=1}^{4} \mathrm{Di} \, . \, \mathrm{P(DSi)} \tag{4}$$

The MDF can then be used to identify the priority rank for inspection. Two repair-cost models were implemented in the tool: Basöz and Mander [12] and REDARS[13], as given in Table 2. It should be noted that REDARS repair-cost model proposes an estimation of the standard deviation for the damage ratio.

Table 2. Damage states and relationship with inspection priority and traffic state [10, 13].

Damage state		None	Slight	Moderate	Extensive	Complete
Range of repair cost ratio	REDARS	0	1%-5%	5%-50%	50%-80%	80%-100%
	Basoz	0	1%-3%	2%-15%	1%-40%	30%-100%
Average damage ratio (D_i)	REDARS	0	3%	25%	75%	100%
	Basoz	0	3%	8%	25%	* 100% if $n \leq 2$ $2/n$ if $n > 2$
Inspection priority		None	Low	Medium	Medium-high	High
Likely post-event traffic state		Open to normal traffic- no restrictions	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

*n: number of spans.

3. Software implementation and user interface

The four models described in the previous section, and their respective variants, were integrated in an Excel spreadsheet. A relatively simple user interface was then created to evaluate the seismic impact of an earthquake scenario to the exposed bridge network (Figure 2). The user is first prompted to provide magnitude and epicenter for the considered earthquake scenario, and select the confidence level of the AA13 GMPE (lower, median or upper), the source of the applied set of fragility functions according, e.g., Hazus [10] , Tavares [9] and Nielson [11], as well as the source of the repair-cost model, e.g., REDARS [13] or Basöz and Mander [12]. It is therefore possible to assess the variation in damage estimation, and priority ranking, according to the set of hazard, fragility and impact models considered. This contributes to the decision process in emergency and recovery planning for transportation infrastructures.

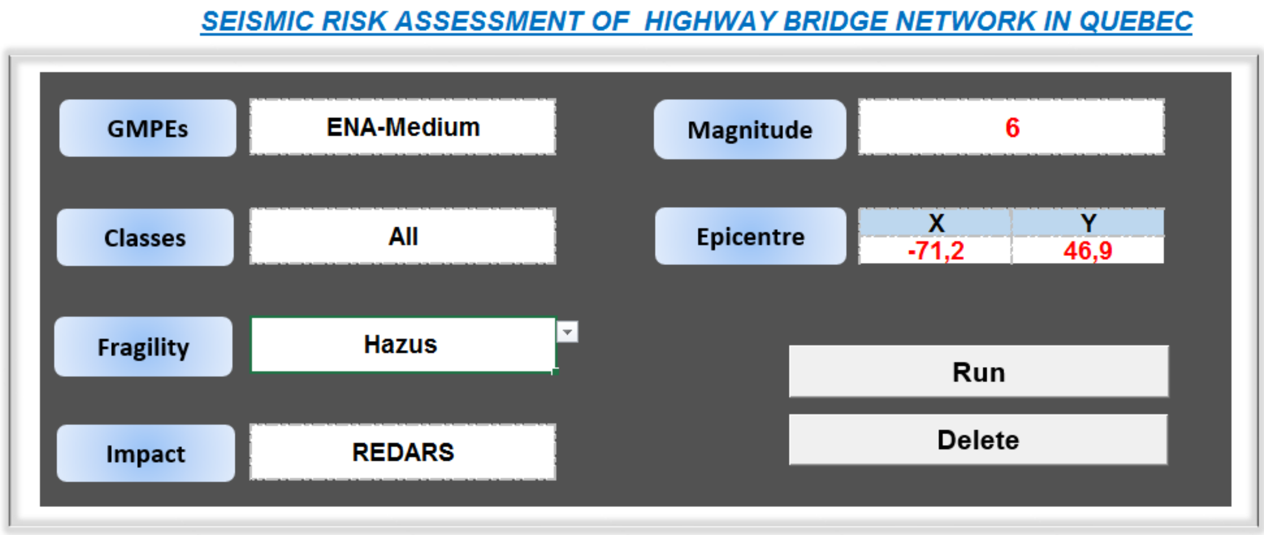

Fig. 2 – User interface of the rapid tool for damage assessment of bridges.

To demonstrate the capacities of the developed tool, it was applied to assess the damage to the 110 bridges in Quebec City. It consists of: 79 bridges involving concrete or steel single-span bridges, multi-span continuous concrete or slab bridges, and simply supported multi-span concrete or steel bridges; and 31 other types of bridges such as wood-steel girder, triangulate Pony Warren steel girder, triangulate girder with steel low deck, steel girder with concrete coating, culvert with reinforced concrete slab, reinforced concrete overpass and reinforced concrete culvert overpass. According to the spatial distribution of the bridges and the available microzonation map [14], Figure 3: 12 are built on hard rock (A); 36 on rock (B), 30 on very dense soil and soft rock (C), and 32 on stiff soil (D).

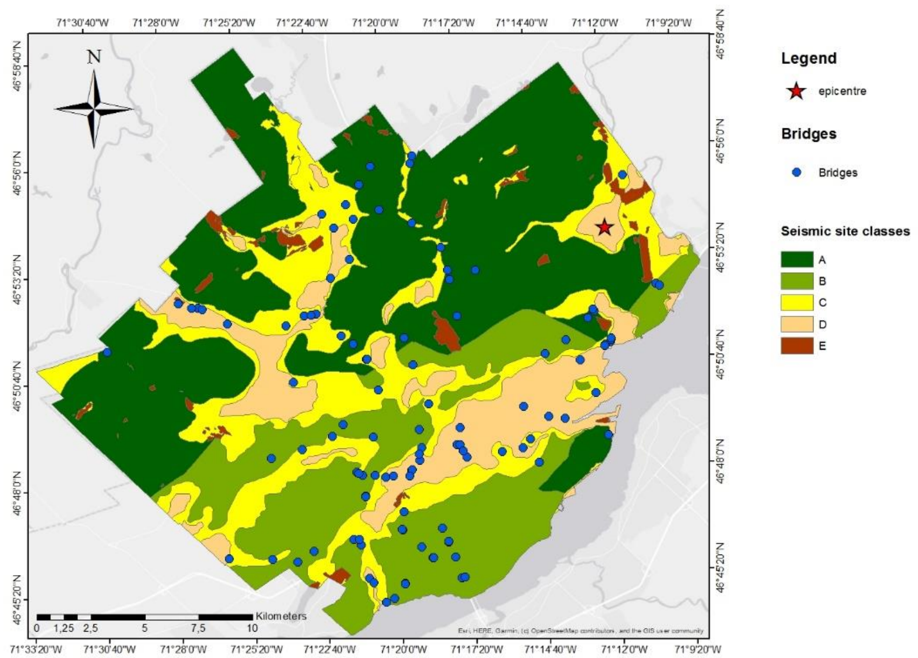

Fig. 3 – Bridge network in Quebec City and microzonation map [14].

The seismic scenario consisted of hypothetical earthquake event with M6 and epicentral distance of about 10km from downtown area. The source of the fragility functions is Hazus and the repair-cost model selected is REDARS. However, two confidence levels of the AA13 GMPE are considered: ENA-median and ENA-upper. Shaking intensity at each bridge site is computed from the closed from GMPE, as in equation (1), using its geographic coordinates, and adjusted for site amplification. Part of the damage results are given in tabular form in Figure 4 for ENA-median confidence level. The distribution of the mean damage factors MDF for the ENA-median confidence level is shown on the microzonation map in Figure 5.

ID	Seismic class	Bridge Class	MDF	Damage State	St.Dev.DR	Inpsection Priority	Priority Rank	Econmic Losses
ID 4	D	SS-Concrete	0,061	Moderate	0,0352	Medium	22	233 188 $
ID 9	C	SS-Concrete	0,059	Moderate	0,0340	Medium	23	150 462 $
ID 14	C	SS-Concrete	0,043	Slight	0,0253	Low	27	22 227 $
ID 40	C	MSC-Concrete	0,049	Slight	0,0250	Low	25	15 547 $
ID 52	B	MSC-Concrete	0,044	Slight	0,0228	Low	26	28 053 $
ID 53	B	MSC-Concrete	0,064	Moderate	0,0327	Medium	20	34 143 $
ID 54	B	MSC-Concrete	0,062	Moderate	0,0317	Medium	21	36 684 $
ID 59	C	MSSS-Steel	0,226	Moderate	0,0973	Medium	11	224 295 $
ID 63	D	MSSS-Concrete	0,332	Moderate	0,1209	Medium	3	3 472 186 $
ID 64	C	MSSS-Concrete	0,232	Moderate	0,0976	Medium	10	263 015 $
ID 65	C	MSSS-Concrete	0,302	Moderate	0,1149	Medium	4	840 758 $
ID 66	B	MSSS-Concrete	0,099	Moderate	0,0489	Medium	15	29 876 $
ID 67	B	MSSS-Concrete	0,066	Moderate	0,0332	Medium	19	4 354 $
ID 68	B	MSSS-Concrete	0,075	Moderate	0,0375	Medium	17	20 654 $
ID 69	D	MSSS-Concrete	0,280	Moderate	0,1101	Medium	5	53 048 $
ID 70	A	MSSS-Concrete	0,197	Moderate	0,0866	Medium	12	224 330 $
ID 71	C	MSSS-Concrete	0,241	Moderate	0,1000	Medium	9	917 605 $
ID 72	C	MSSS-Concrete	0,241	Moderate	0,1001	Medium	8	918 111 $
ID 73	C	MSSS-Concrete	0,272	Moderate	0,1080	Medium	6	1 895 303 $
ID 74	D	MSSS-Concrete	0,252	Moderate	0,1031	Medium	7	633 971 $
ID 75	B	MSSS-Concrete	0,131	Moderate	0,0624	Medium	13	49 004 $
ID 76	C	MSSS-Concrete	0,462	Moderate	0,1359	Medium	1	1 523 965 $
ID 77	C	MSSS-Concrete	0,460	Moderate	0,1359	Medium	2	1 208 767 $
ID 78	B	MSSS-Concrete	0,066	Moderate	0,0336	Medium	18	24 630 $
ID 79	B	MSSS-Concrete	0,049	Slight	0,0250	Low	24	18 326 $
ID 87	C	Other	0,107	Moderate	0,0583	Medium	14	40 250 $
ID 91	C	Other	0,085	Moderate	0,0482	Medium	16	33 034 $
ID 99	D	Other	0,047	Slight	0,0281	Low	27	27 813 $
ID 110	C	Other	0,086	Moderate	0,0486	Medium	16	27 851 $

Figure 4. Part of the results for the M6 seismic scenario with epicentral distance of 10km from downtown for ENA-median confidence level.

Each bridge identified by its ID, its location and its type class is listed. Damage state can be associated to a level post-event traffic state and inspection priority (Table 2), while priority rank is established from the MDF. A standard deviation is provided for damage ratio considering the uncertainties related to the impact model from REDARS. Priority rank is mostly influenced by the proximity of the bridges to the epicenter, with higher PGA, and the bridge class. Multi span simply supported bridges have higher vulnerability and so higher ranking than single span bridge classes.

Results for ENA-median indicate that 44 bridges are expected to sustain no damage, 42 are slightly damaged and the remaining 24 are moderately damaged. The mean damage ratios (MDF) vary between 0.01% and 47%

(Figure 5), whereas the total expected economic loss is $13,9M. Results for ENA-upper indicate that 2 bridges are expected to sustain no damage, 34 are slightly damaged, 63 are moderately damaged and the remaining 11 are extensively damaged, while the mean damage ratios (MDF) vary between 0.1% and 78.8%. The total expected economic loss for ENA-upper increases to $32.1M. The uncertainties relative to the two confidence levels of hazard can more than double the amount of expected economic loss.

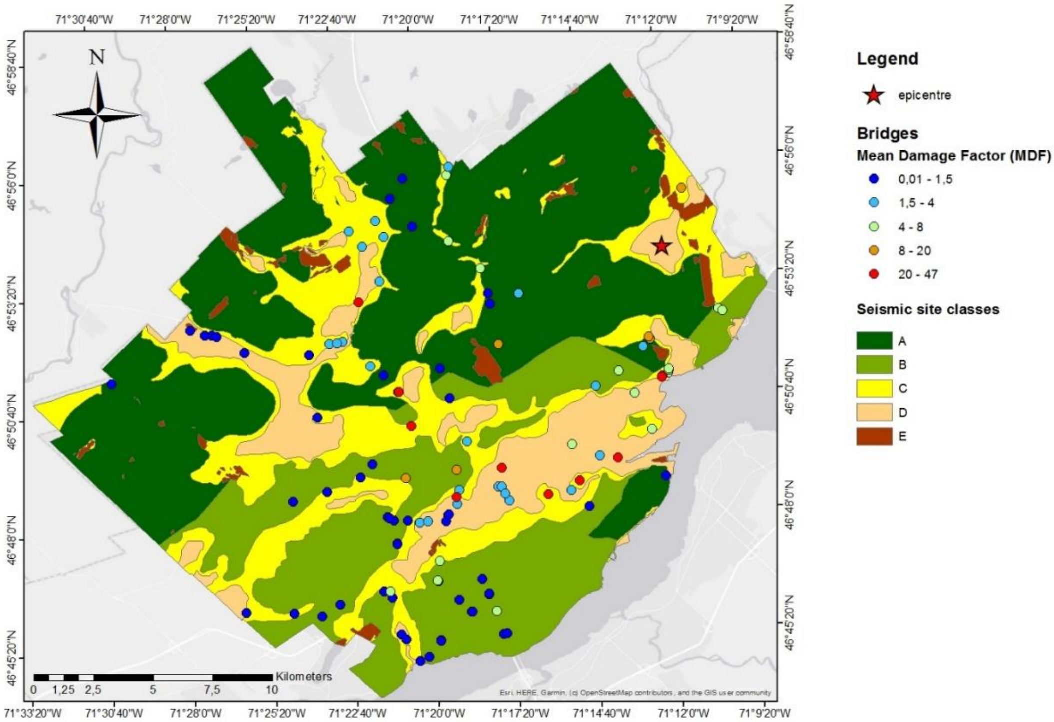

Fig. 5 – Results of expected damage for ENA-median to the bridge network in Quebec City for M6 scenario.

4. Conclusion

This paper describes the development of a methodology and its implementation in a rapid tool for seismic risk assessment of bridge networks. The successive steps to run damage scenarios include hazard, exposure, damage and impact models. Particular attention was paid to include epistemic uncertainty in the selection of the hazard and different damage and impact models.

To demonstrate the capacity of the tool to run seismic risk scenarios, a case study was conducted for the damage assessment of an approximate bridge network in Quebec City, consisting of 110 bridges. The considered scenario was a magnitude M6 earthquake about 10 km from the downtown area. In the given example, two confidence levels of the AA13 GMPE were considered and the degree of damage to a given bridge was estimated using respective sets of fragility curves based on the Hazus methodology. The percentage physical damage was then used to determine the economic loss and priority rank. The spatial distribution of damage will help identify the most vulnerable sections of the highway system which will require rapid intervention. The two confidence levels considered in this paper (ENA-median and ENA-upper) spread the total expected economic loss from simple to more than double ($13.9M to $32.1M).

In the next step of the research, epistemic uncertainties from the fragility and repair-cost models will be estimated. The rapid assessment of bridge conditions following a strong earthquake is essential for informed decision-making on the post-earthquake functionality. It can also be used for pre-earthquake mitigation planning purposes based on potential damage scenarios. Future work will focus on the integration of the methodology into a web application system as well as development and refinement of the fragility functions to better represent local construction practices.

5. Acknowledgements

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