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FRAMEWORK FOR SEISMIC VULNERABILITY 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 of the bridge determined by its capacity to carry traffic flow. The various losses of bridge functionality induce reduction or disruption of the transportation network, increase costs due to detour or reduced traffic flow and, what is most important, restrict access to emergency routes. This paper presents a framework for development and implementation of seismic vulnerability of highway networks. The proposed framework 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 ground motion intensity measure (IM); the exposure model provides a database of bridge classes broadly defined with respect to their static and dynamic properties; the damage model assesses seismic performance of bridge classes in the network applying respective fragility functions represented as probabilistic relationships between the IMs 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 costs of bridges, road-closures and inspection priority. A case study of application of the proposed framework is presented for damage assessment of a hypothetical bridge network in Quebec City subjected to a magnitude M6 seismic scenario.

1 INTRODUCTION

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 of the bridge determined by its capacity to carry traffic flow (Werner et al. 2006, Padgett and DesRoches 2007). The various levels of bridge functionality losses typically induce reduction or disruption to the transportation network, increase costs due to detour or reduced traffic flow and, what is most important, potentially restrict access to emergency routes. Following a strong earthquake event, the transportation emergency managers have insufficient time to carry on detailed bridge-by-bridge inspections; yet decisions to keep the traffic flowing or close a given bridge have to be made. The rapid assessment of bridge condition, therefore, is essential for informed decision on the post-earthquake functionality (Lin et al. 2004, Wald et al. 2006). Furthermore, pre-earthquake mitigation planning relies heavily on generation of potential damage scenarios to identify the most vulnerable sections of the transportation system where resources should be put first to achieve maximum cost-benefit of the seismic retrofit (Werner et al. 2006).

This paper describes the methodological development and implementation of seismic vulnerability of highway networks. The successive models for running damage scenarios are described including hazard, exposure, damage and impact models. To demonstrate the capacities of the proposed framework, a case-example is presented for damage assessment of a hypothetical bridge network in Quebec City subjected to a M6 earthquake scenario.

2 FRAMEWORK

The proposed framework for seismic vulnerability of highway bridge networks is presented in Figure 1. The seismic hazard model generates spatial distribution of the shaking intensity for earthquake scenarios in terms of ground motion intensity measure (IM); the exposure model provides a database of bridge classes defined according to construction material, structural system 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.

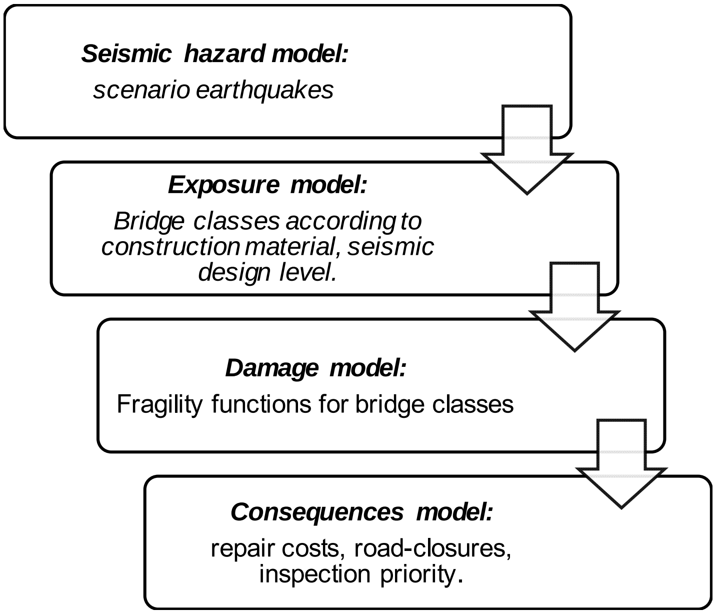

Figure 1: Framework for seismic vulnerability of highway bridges network.

2.1 Seismic Hazard Model

A simple algorithm has been developed with a shake map generation capacity for earthquake events with specified magnitude, distance and simple fault geometry (Nastev et al. 2015). It applies the new generation of ground-motion prediction models for reference response spectral accelerations on rock including PGA and PGV: AA13 for Eastern Canada (Atkinson and Adams 2013) applied in the National Building Code of Canada NBCC 2015 (NRC 2016). The epistemic and aleatory uncertainty can be captured with the provided upper and lower confidence levels. The ground motion intensity is then corrected for the local soil conditions with the amplitude and frequency dependent site amplification factors as functions of the average VS_{30} at each site as defined by NBCC 2015. In Eastern Canada, microzonation have been completed on a regional scale for three cities: Quebec City (Leboeuf et al., 2013), Montreal (Rosset et al. 2015) and Ottawa-Gatineau (Motazedian et al., 2011). It is also available as a 3D-Model for the Lowlands of the Saint-Lawrence Valley (Nastev et al. 2016).

2.2 Exposure Model

The inventory of bridges potentially exposed to ground shaking is the second major input parameter. It can be conducted at a local (bridge) scale by sidewalk and virtual desktop surveys, or at urban or regional scale by interpreting data from municipal bridges or databases from the department of transportation. To simplify the structural analyses, the individual bridge structures are grouped into relative broad classes according to their expected behaviour under seismic loading (Basoz and Mander 1997, FEMA 2012). The following structural parameters are 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). Figure 2 shows an example of bridge categorisation according to the classification scheme proposed in Hazus (FEMA 2012). This classification scheme is specifically intended for seismic assessment.

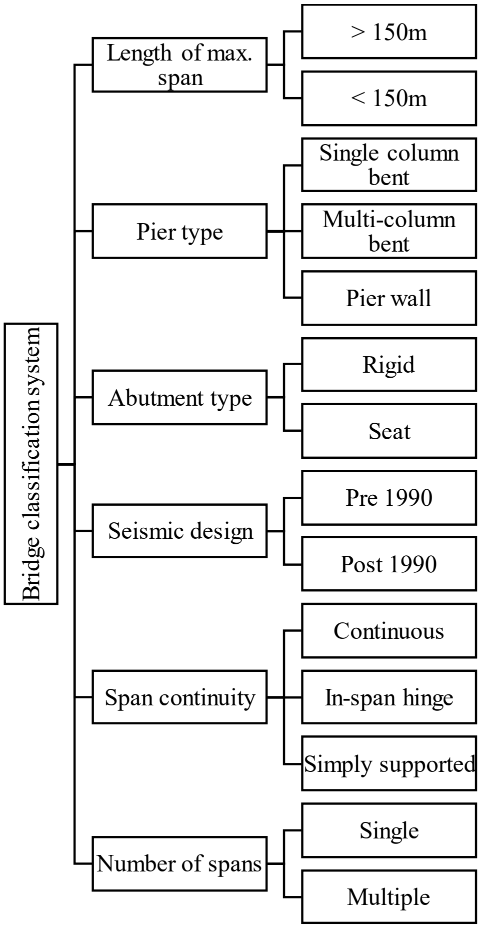

Figure 2: Bridge classification scheme according to Hazus (FEMA 2012).

2.3 Damage Model

The damage model consists of a dataset of fragility functions related to the bridge classes in the exposure 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 intensity measure (IM) of the seismic hazard. 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 standardised questionnaire completed by experts (ATC 1985); (2)

empirical methods using damage data from post-earthquake field observations (Basoz and Kiremidjian 1999, Shinozuka et al. 2000, Yamazaki et al. 2000); and (3) analytical methods that rely on mechanical or numerical structural models to simulate the seismic response of bridges (FEMA 2012, Tavares et al. 2012). Figure 3 shows an example of a set of fragility function for pre-1990 multi-span continuous concrete bridge classes in Hazus (FEMA 2012) representing the thresholds of attaining or exceeding four limit states (slight, moderate, extensive and complete). The damage state probabilities corresponding to Sa(1.0s)=0.2g is shown as an example on the left side of the figure. On the right, the distribution of five post-earthquake damage level probabilities is shown, and is calculated by the difference between two consecutive limit state curves for Sa(1.0s)=0.2g.

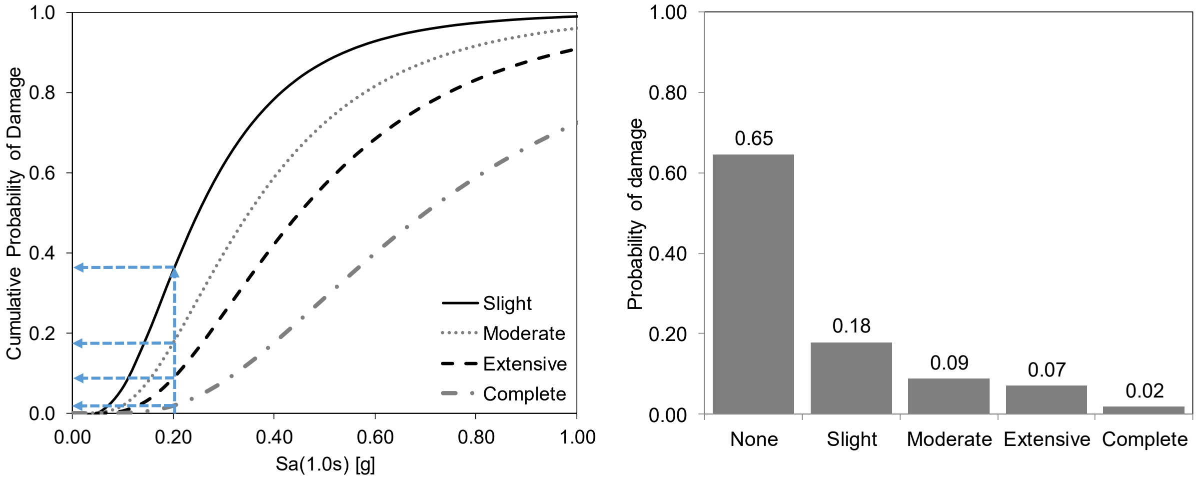

Figure 3: Example fragility functions for pre-1990 multi-span continuous concrete bridge class (left) and the five damage state probability corresponding to Sa(1.0s)=0.2g (right).

2.4 Impact model

Based on the damage assessment results, the negative effects of the generated damage to bridges are quantified using the impact model. It includes: inspection priority, likely immediate post traffic state the bridges can be assigned in terms of inspection priority, likely immediate post event traffic state (Lin et al. 2003) and repair cost ratios (Werner et al. 2006) (Table 1).

Table 1: Bridge damage states and the corresponding, inspection priority and likely post-event traffic states and repair cost ratios.

Damage state	None	Slight	Moderate	Extensive	Complete
Range of repair cost ratio	0	1%-5%	5%-50%	50%-80%	80%-100%
Average damage ratio	0	3%	25%	75%	100%
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

In order to estimate the incurred economic losses, the mean damage ratio (MDR) is computed as the weighted sum of the average damage ratios (Di) multiplied by the probability of being in each damage state P(DSi) (Equation 1). The MDR can then be used to identify the priority rank for inspection.

[1] $$MDR = \sum_{i=1}^{4} \mathrm{Di}\,.\,\mathrm{P(DSi)}$$

3 CASE STUDY

To demonstrate the capacities of the proposed framework, it is applied to assess the inspection priority of for a group of bridges in Quebec City bridges affected by a magnitude 6 hypothetical earthquake event at a distance of about 10km from downtown. A total of 39 bridges were considered for this investigation which represent two classes of simply supported reinforced concrete girder bridges: 20 single span (SSCG) bridges, and 19 multi-span (MSCG) bridges (Figure 4). It should be emphasized that this group of bridges do not represent the complete network in the vicinity of Quebec City. Specific details on the structural systems of the bridges level were not available, and basic information was collected from multiple sources (e.g., Hida 2009, Google Street View, CanVec database https://open.canada.ca) to provide first-order classification of the bridge types for this demonstration study.

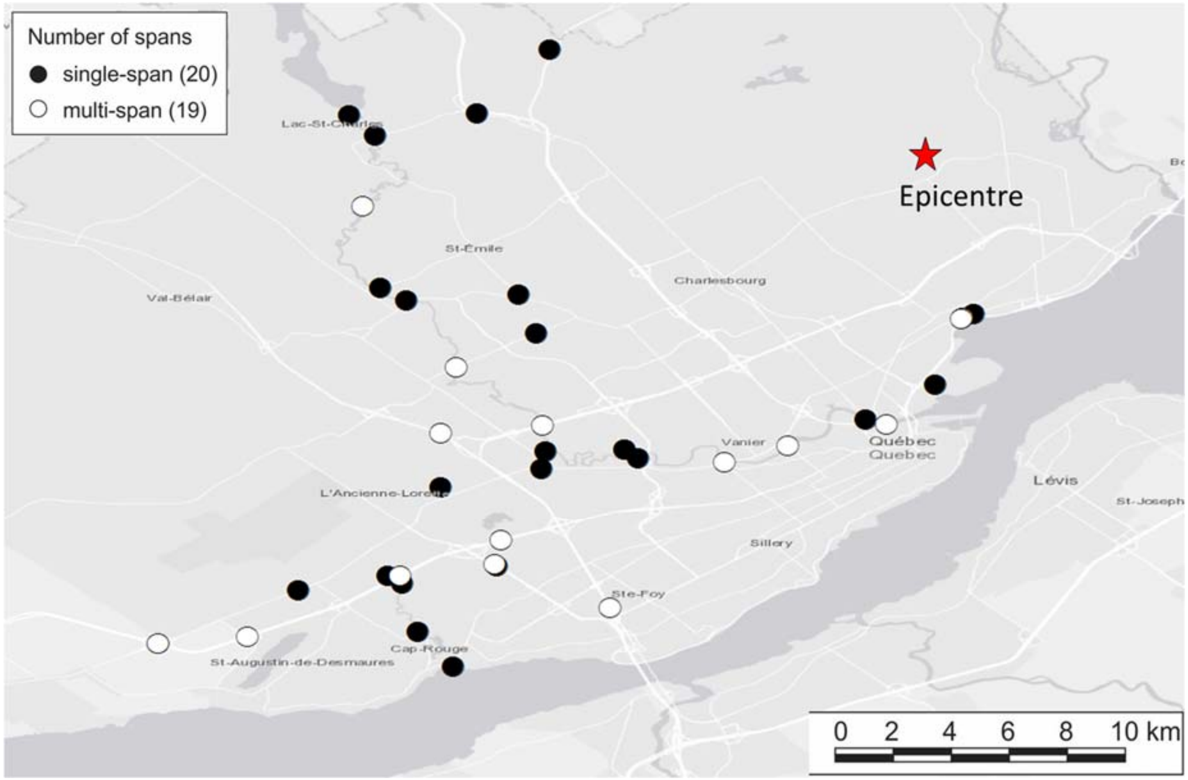

Figure 4: Map showing the location of the 39 simply supported reinforced concrete girder bridges (figure generated by the authors).

The ground motion prediction equation by Atkinson and Adams (2013) was used to estimate the shaking intensity at each bridge location with local site effects computed based on the site classification from the microzonation study for Quebec City (Leboeuf et al., 2013). Currently, there are no available fragility functions developed explicitly for the considered bridges in Quebec City. As a result, Neilson (2005) fragility functions for simply supported SSCG bridges and Tavares et al. (2012) fragility functions for simply supported MSCG bridges were employed.

Figure 5 shows the results of the expected damage states of the bridges and the corresponding inspection priority rank for the M6 scenario, according the computed MDF of each bridge. For example, the values of the MDFs for the 5 bridges with medium inspection priorities are: 16%, 14%, 15%, 8%, and 6%.

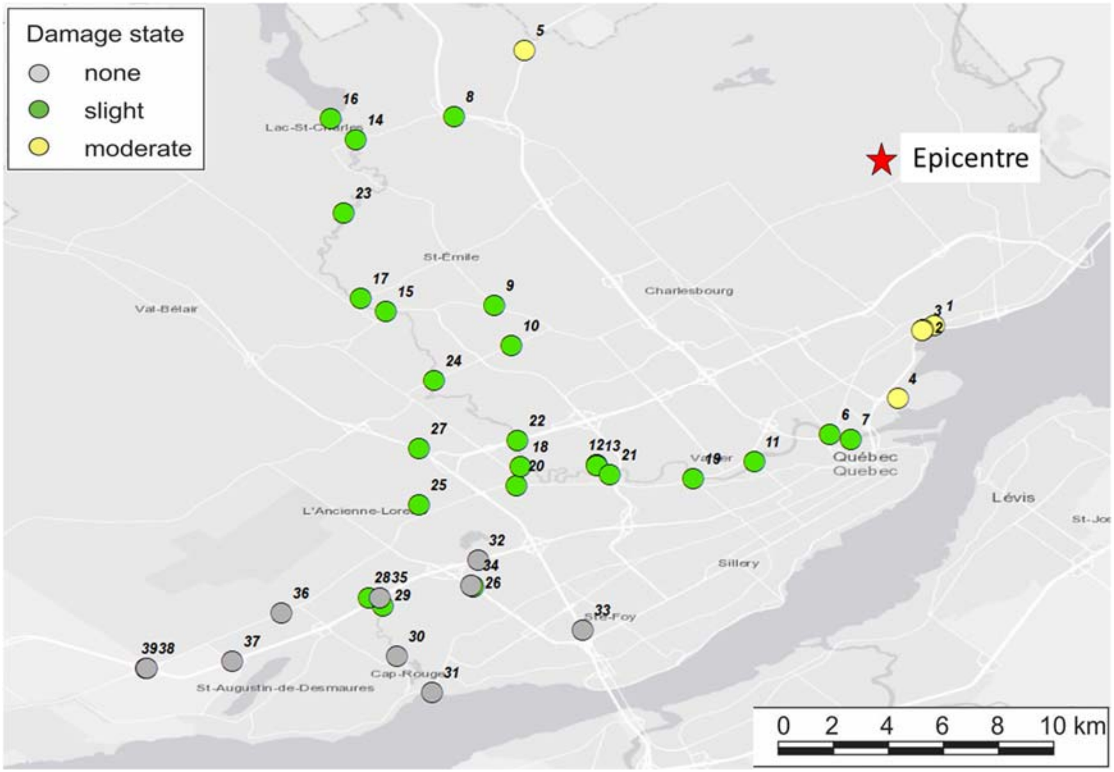

Figure 5: Damage assessment for the M6 earthquake scenario. The numbers indicate inspection priority (figure generated by the authors).

4 CONCLUSIONS

This paper described the methodological development and implementation of seismic vulnerability of highway networks. The successive models for running damage scenarios including hazard, exposure, damage and impact models were discussed. A case study demonstration of the proposed framework was presented for the damage assessment of a hypothetical network of bridges in Quebec City. The network consisted of 39 simply supported reinforced concrete girder bridges with single-span (20) and with multi-span (19). A magnitude M6 earthquake scenario was considered about 10 km from the downtown area. The estimated degree of damage to a given bridge was used to determine the cost and time required for repairs and the level of post-earthquake functionality of the bridge defined by its capacity to carry traffic flow. The results indicate that 5 of the bridges are expected to be moderately damaged. The inspection priority ranking of the bridges based on the MDF could provide highway officials with a risk-informed knowledge for more efficient planning of inspection and repairs activities.

Such rapid assessment of bridge conditions 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. The spatial distribution of damage helps will help identify the most vulnerable sections of the transportation system which will require rapid intervention.

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