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INTEGRATION OF SEISMICALLY INDUCED SITE EFFECTS TO THE EVALUATION OF THE SEISMIC VULNERABILITY OF BRIDGES THROUGH A GIS PLATFORM

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Abstract: This paper proposes an approach to integrate seismically induced site effects to the evaluation of the seismic vulnerability of bridges through a GIS platform. The evaluation of the seismic vulnerability of bridges aims to assess the potential damage to structures in order to prioritize the interventions following an earthquake or to plan mitigation strategies. Evaluation procedures are generally index-based, and consider structural vulnerability and seismic hazard, which is usually defined in terms of the probable acceleration that could integrate the amplification effect of seismic waves by the site. A few index-based procedures take into account induced site effects, such as landslides, rock falls or soil liquefaction. Quantification of amplification and induced site effects requires site-specific geotechnical information. However, seismic risk assessment studies are usually performed on a regional scale for a large number of infrastructures scattered on a large territory. The lack of site-specific geotechnical information makes the evaluation of the seismic vulnerability of these infrastructures less representative. This study is based on the development of susceptibility scales to amplification effect, landslides, rock falls and soil liquefaction using geographical information systems (GIS). These susceptibility scales are defined documenting and characterizing the general context of geomorphology, geology and hydrography. The resulting susceptibility maps are then used to integrate susceptibility levels to seismically induced site effects into an index-based procedure for a better evaluation of the seismic risk of bridge networks.

Keywords: amplification, landslide, rock falls, seismic vulnerability, risk assessment, scoring procedure, bridge

1 INTRODUCTION

Southeastern Canada experiences about 600 earthquakes every year (Government of Canada, 2011). While seismic hazard is generally moderate in eastern Canada, the density of the population in urban areas makes it the second-largest seismic hazard area in Canada. In the southeastern Canada, two seismic events with magnitude 5 (on a Richter scale) or more were felt in the last ten years (Government of Canada, 2018b). These events induced landslides such as in Val-des-Bois (2010), or dike damages in south of Bowman and damages to chimneys and houses due to local soil amplification (Gouvernement du Canada, 2010). During the 1988 Saguenay earthquake (Mw=5.9), rock falls, landslides and liquefaction, were observed along the Lowlands as far as 200 km from the epicentre (Lamontagne, 2002). More than 20 landslides occurred due to the presence of marine clay (Lefebvre et al., 1992; Locat, 2008). Moreover, damages, due to local amplification, were triggered up to a distance of 340 km on Montreal Island (Paultre et al., 1993).

Seismic risk assessment is an essential step towards effective mitigation measures and emergency planning. As the number of infrastructures and installations exposed to seismic hazard increase, interventions must prioritize the most vulnerable structures. In the province of Quebec, the total number of bridges and overpasses under the jurisdiction of the province is approximately 9600 (MTMDET, 2017); out of this total number, 70% were built between 1960 and 1980, when seismic design provisions were not as stringent as today (MTMDET, 2017). Bridges and overpasses of municipal networks experience similar situation. The province of Quebec counts approximately 10600 bridges and overpasses among which 48% are located in the region of study (Government of Canada, 2018a).

The first multi-criterion procedure for prioritization of bridges was developed by the California Department of Transportation following the San Fernando earthquake in 1971 (Basöz et Kiremidjian, 1995; Small, 1999). This method was the inspiration for several other procedures in the US (Kim, 1993; NYSDOT, 2002), Canada (Liu, 2001) and in the province of Quebec (Tinawi et al., 1993). In Quebec, the most recent procedure applied by the *Ministère des Transports, de la Mobilité durable et de l'Électrification des transports* (MTMDET) is based on the scoring procedure developed for the Quebec City bridges (Hida, 2009). It has been since modified and revised for a better identification of the most vulnerable bridges by considering the socioeconomic index to quantify value at risk (Lemaire, 2013). As in similar procedures, it considers the seismic hazard, the structural vulnerabilities of the bridges and the amplification effect. The potential of liquefaction of soil is sometimes taken into consideration when information is available. However, the contribution of those site effects to the seismic risk is frequently approximated due to the lack of site-specific information. Ground mass movements such as landslides or rock falls are rarely taken into consideration (Davi et al., 2011).

Seismic risk is composed of three main parameters: hazard, vulnerability and value at risk (UNDRO, 1991). This study focuses on the hazard aspects of the seismic risk in rapid screening procedures for bridges considering induced site effects. The proposed methodology is based on the development of maps characterizing susceptibility scales to amplification effect, landslides, rock falls and soil liquefaction using geographical information systems (GIS) based on hydrological, topographic and geological cartographic data (Farzam et al., 2016; Farzam et al., 2018). To validate the susceptibility scale to amplification effect, ambient noise measurements have been performed at the site of bridges and on the structures. The landslide susceptibility scale was validated using a landslide inventory in the St. Lawrence Valley (Quinn et al., 2008). The objective of this paper is to demonstrate how induced site effects could be integrated into seismic assessment scoring procedures for bridges using a GIS platform. An application to the seismic procedure developed by Lemaire (2013) for the bridges in the province of Quebec illustrates the impact of considering seismically induced site effects on the prioritization of bridges.

2 METHODOLOGY FOR SUSCEPTIBILITY MAPPING OF SITE EFFECTS

Seismically site effects are governed by geotechnical factors taking place in a geological context. There are many ways to characterize the susceptibility to seismic site effects including prospecting site by site with in situ geotechnical measurements and laboratory testing, and documenting and characterizing the general context of geomorphology, geology, hydrography and even climate factors (Theilen-Willige, 2010). Although a best estimate of seismically site effects hazards is obtained from site-specific prospecting, the information from the general context allow mapping large scale phenomena influencing site effect at smaller scale.

2.1 Susceptibility Mapping to Amplification

Seismic amplification is usually characterized by the attribution of a seismic site class as defined by codes and regulations. This process also called microzonation is mainly based on the calculation of the time-averaged shear-wave velocity V_{s30} over 30 metres (NRCC, 2015). However at a local scale, in the absence of specific shear wave velocities data, information about thickness of quaternary deposits and surficial geology can be correlated to seismic site classes using geostatistical relations obtained from existing microzonation maps for other regions with similar geological characteristics. This methodology is based on the hypothesis that soil column is similar for a same region depending on the surficial geology and the thickness of quaternary deposits (Braganza et al., 2016). Consequently, all sites with same surficial geology and same thickness of quaternary deposits should have equal V_{s30} and thereby the same seismic site class. For the region of study and its vicinity, microzonation have been completed for three cities: Quebec city (Leboeuf et al., 2013), Montreal (Rosset et al., 2015) and Ottawa-Gatineau (Motazedian et al., 2011). The geostatistics conducted for these three cities provide the probabilities to belong to a seismic site class for a specific surficial geology and thickness of quaternary deposits. However, in some cases, probabilities are not strictly defining one seismic class and intermediate levels are introduced. Seven levels of susceptibility to amplification ranging from very very low (VVL) to very high (VH) are introduced in this study as presented in Table 1.

Table 1: Susceptibility scale for amplification depending on attributed seismic site class

Attributed seismic site class from surficial geology and thickness deposits	Susceptibility scale
A and B	Very very low (VVL)
B - C	Very low (VL)
C	Low (L)
C - D	Low to moderate (LM)
D	Moderate (M)
D - E	High (H)
E	Very high (VH)

To validate the approach by geostatistical relations ambient vibration measurements were conducted on 50 different sites. Knowing the thickness of quaternary deposits and the average shear wave velocity of bedrock at the sites, resonance frequencies of soil were extracted and V_{s30} were computed. The results were then compared with the seismic site class attributed to the sites from the information on the surficial geology and thickness deposits. The final susceptibility scale is presented in Table 2 for the surficial geology and thickness of deposits in the region.

Table 2: Susceptibility scale for amplification depending on surficial geology and thickness of deposits

Surficial geology\Thickness of deposits	0 to 5 [m]	5 to 10 [m]	10 to 20 [m]	20 to 30 [m]	>30 [m]
Alluvial deposits	LM	LM	LM	H	H
Colluvial and mass-wasting deposits	H	H	H	VH	VH
Eolian deposits	LM	L	L	LM	LM
Glaciofluvial and glaciolacustrine deposits	VVL	L	L	L	L
Anthropogenic deposits	L	L	L	L	N/A
Lacustrine deposits	VVL	LM	LM	M	M
Marine deposits	VL	L	LM	H	VH
Organic deposits	VVL	VL	VL	H	VH
Till-Glacial deposits	VVL	VL	VL	LM	LM
Undifferentiated deposits	VVL	L	L	LM	N/A

The map presented in Figure 1 shows the distribution of the susceptibility to amplification for the Lowlands of the Saint-Lawrence Valley. Very high levels of susceptibility of amplification are mostly found in the centre of the region of study where thicknesses of quaternary deposits are particularly high. The susceptibility map for amplification has a resolution of about 405 m, calculated from the root mean square of surficial geology layer with a resolution of 500 m (Parent et al., 2018) and thickness of quaternary deposits with a resolution of 275 m (Gouvernement du Canada, 2004).

To validate this susceptibility map for amplification, a comparison was done with the regional microzonation maps of Montreal and Quebec City: seismic site classes assigned from geostatistical relations were similar to the regional microzonation for 75% of the area covered by the two cities.

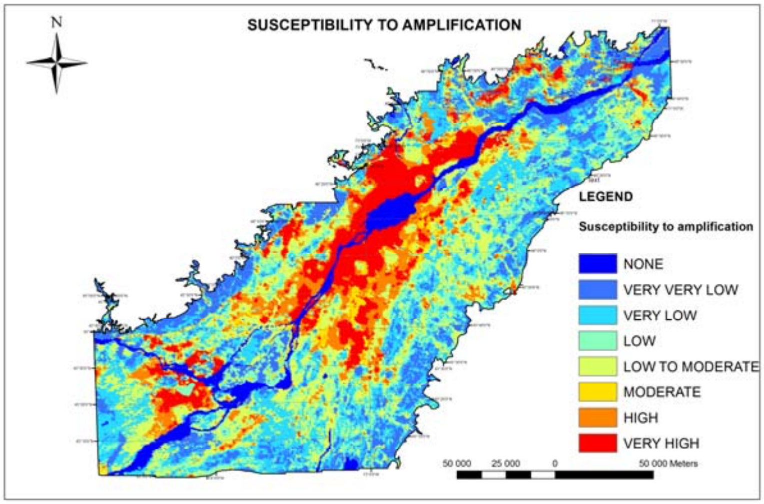

Figure 1: Susceptibility to amplification map (red = high, blue = low)

2.2 Susceptibility Mapping to Ground Mass Movements

The methodology used in this study to characterize ground mass movements (landslides and rock falls) hazard is highly inspired by susceptibility scale developed from experts judgments in the context of seismic hazard loss estimation (HAZUS) of the Federal Emergency Management Agency of US (FEMA, 2012). However, the particular sensitivity to fracture and erosion of Leda clay in the region of study is taken into account by introducing a new parameter that characterizes the proximity to watercourses. Six susceptibility levels to ground mass movement, ranging from none to very high, are developed based on: (a) the 12 types of surficial geology present in the Lowlands of the Saint-Lawrence Valley, in terms of their composition and state of consolidation divided in three groups (Group A: strongly cemented rocks, Group B: weakly cemented rocks and soils and Group C: argillaceous rocks) (b) the slope of the ground divided in 6 ranges (0 - 10°, 10° - 15°, 15° - 20°, 20° - 30°, 30° - 40°, > 40°), (c) the groundwater table (below or above 10 m), and (d) proximity to watercourses (< 100 m). For example, a site with till outcrop (Group B), with ground slope of 5°, on wet soil (groundwater table close to the surface (<10 m) and close to watercourse (<100 m) will have a high susceptibility to landslide. Rock falls hazards can be differentiated from landslides hazard by the presence of strongly cemented rock such as bedrock. Since bedrock outcrops is present in only 5% of the region of study, therefore rock falls hazard is only present in this 5%. Landslides and rock falls susceptibilities are mapped together in the Figure 2. The susceptibility map for ground mass movements has a resolution of 355 m, computed from the root mean square of surficial geology layer with a resolution of 500 m (Parent et al., 2018) and the slope derived by the digital elevation model with a resolution of approximately 30m (Farr et al., 2007). Landslide susceptibility map has been validated using an inventory for the region of study provided by Quinn (2009): 68% of landslides from the inventory are located on areas identified as highly or very highly susceptible. The method of attribution of susceptibility level is well correlated to the inventory of landslides.

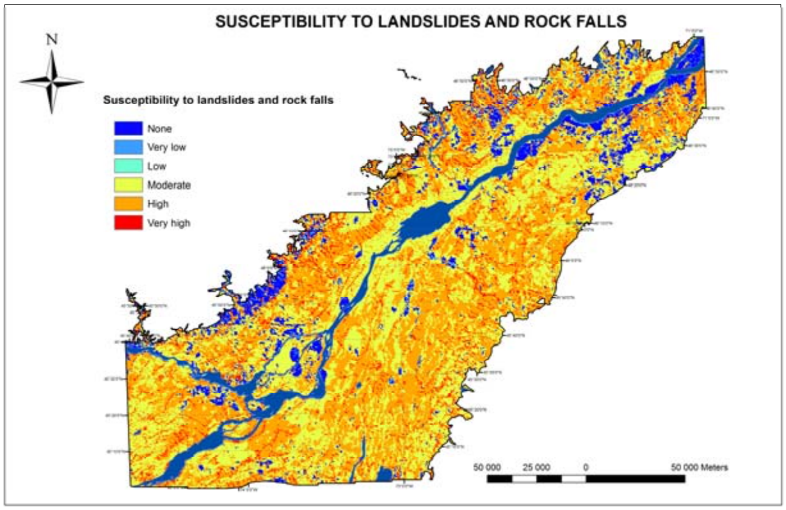

Figure 2: Susceptibility to landslides and rock falls (red = high, blue = low)

2.3 Susceptibility Mapping to Liquefaction

Liquefaction of soil may happen during an earthquake when saturated soils under multiple cycles of loadings lose their shear strength. It is known as a very complex and destructive phenomenon (Priestley, 1996). However, experts from FEMA (2012) classified lithologies in six levels of susceptibility to liquefaction (from none to very high) with respect to their type of deposit and their state of consolidation through their age. The same classification is adopted in this project. If groundwater table is close to the surface (< 10 m), final liquefaction levels of susceptibility are corresponding to those from lithologies classification, i.e. if groundwater table is lower than 10 m from the surface susceptibility level of liquefaction are classified from low to very low. The map in Figure 3 shows the distribution of susceptibility level to liquefaction in the region of study.

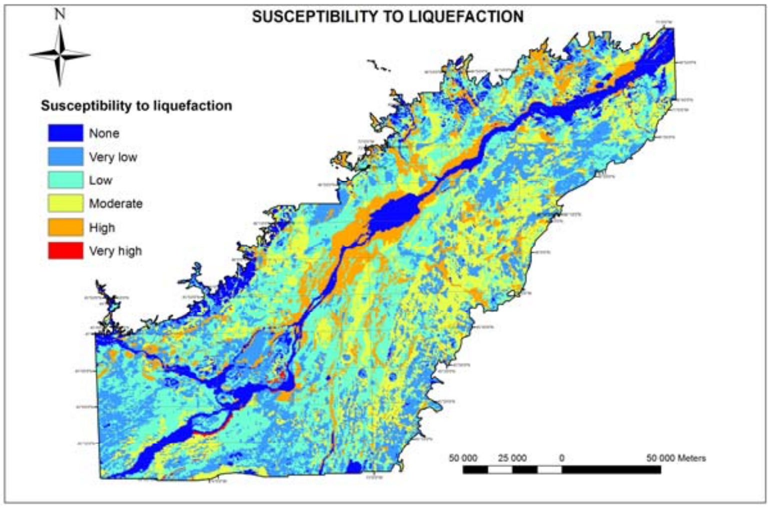

Figure 1: Susceptibility to liquefaction map (red = high, blue = low)

3 INTEGRATION OF SEISMICALLY INDUCED SITE EFFECTS TO SEISMIC RISK ASSESSMENT PROCEDURES FOR BRIDGES

To demonstrate how induced site effects could be integrated into seismic assessment scoring procedures for bridges using a GIS platform, the proposed susceptibility maps are used with the seismic scoring procedure developed by Lemaire (2013). This procedure allows prioritizing bridges in the province of Quebec according to their relative seismic risk. The bridges seismic vulnerability index ($SVI_{MTQ2013}$) proposed by (Lemaire, 2013) evaluates the seismic risk considering the structure vulnerability, the seismic hazard and the amplification effect at the site independently. As a result, the probability of each event intersected with the probability of the others and the resulting probability is given by the product of the respective probability of each independent event. In a rapid scoring procedure, this could be expressed by the product of three independent indices combined to obtain the final seismic risk or vulnerability index (SVI), as in the following equation:

$$[3]\quad SVI_{MTQ2013} = V_{\text{structural vulnerability}} \times F_{\text{hazard}} \times F_{\text{site}}$$

The $SVI_{MTQ2013}$ varies from 0 to 100, with a maximum score for the most vulnerable bridges. The structural vulnerability index, $V_{\text{structural vulnerability}}$, varying from 1 to 32, is defined from structural characteristics and identification of seismic deficiencies of the bridges. The weight of this index has been carefully established from simulation scenarios of damage to the bridges of the inventory. The seismic hazard index, F_{hazard}, is computed from seismic hazard maps in terms of peak ground acceleration (PGA) (Halchuk et al. (2015)). PGA is one of the most widely used seismic hazard parameter for the evaluation of the seismic risk of bridges in regional studies (Basöz et Kiremidjian, 1995; Davi et Schmitt, 2003; Kim, 1993; Kiremidjian et al., 2007). F_{hazard} varies from 1 to 2. Local amplification effect is taken into consideration through the index F_{site}. It is defined from seismic site categorizations (NBC 2010) and varies from 1 to 1.25. Moreover, F_{site} is also taking into account liquefaction susceptibility. A maximum value of 10 is attributed to F_{site} in the case of a very high potential of liquefaction. As a consequence, the final SVI value can increase significantly which reflects the destructive capacity of this particular phenomenon and its impact on structures.

The present study introduces into this procedure susceptibility to ground mass movements including landslides and rock falls. These latter are inconsistent events; meaning that landslides cannot happen at the same time as rock falls. On the contrary, ground mass movements can be triggered during a seismic event at the same time as a local amplification of seismic waves. Therefore, the probability of landslides and rock falls are considered as the union of sets and their indices ($F_{\text{landslides}}$ and $F_{\text{rock falls}}$) are arithmetically added. It is also considered that the probability of ground mass movements intersects with the probability of local amplification (F_{site}) leading to a product of their respective indices, as shown in the revised seismic risk index, SRI (Eq. 4):

$$[4]\quad SRI = V_{\text{structural vulnerability}} \times (F_{\text{hazard}} \times F_{\text{site}} \times (F_{\text{landslides}} + F_{\text{rock falls}}))$$

In order to preserve a maximum score of 100 and the same weight for hazards and vulnerability, F_{hazard} is set to vary between 1 and 2 instead of 2.5 while the site index F_{site} is kept between 1 and 1.25, depending on local amplification. It is defined from the susceptibility map to amplification (Figure 1) converting the susceptibility scale to scores from 1 to 1.25 (Very Very Low = 1, Very Low = 1.025, Low = 1.05, Low to Moderate = 1.1, Moderate = 1.15, High = 1.2 and Very High = 1.25).

The resulting index, combining landslides ($F_{\text{landslides}}$) and rock falls ($F_{\text{rock falls}}$) hazards, is defined from the susceptibility map to ground mass movements (Figure 3) converting the susceptibility scale to scores from 1 to 1.25 (None = 1, Very Low = 1.05, Low = 1.1, Moderate = 1.15, High = 1.2 and Very High = 1.25). For example a bridge presenting several structural vulnerabilities ($V_{\text{struc}} = 32$), $F_{\text{hazard}} = 2$ and $F_{\text{site}} = 1.25$ located on a site with low level of susceptibility to landslide ($F_{\text{landslides}} = 1$) will have its SRI increased from 80 to 100 if located on a site with very high level of susceptibility to landslide ($F_{\text{landslides}} = 1.25$).

Therefore bridge with no or few structural deficiencies ($V_{\text{structural}} < 16$) but located on a site of maximum seismic hazard should be maintained with a final score under 50, considered to be very low priority.

It should be noted that the modified seismic risk index SRI also takes into account the susceptibility to liquefaction by assigning a score of 2.0 in the case of high susceptibility to liquefaction and a value of 10.0 in the case of very high susceptibility. These relatively high score values are attributed to F_{site} to reflect the destructive capacity of this particular phenomenon and its impact on structures (Priestley, 1996).

4 APPLICATION TO A BRIDGE NETWORK AND DISCUSSION

To illustrate the impact of considering seismically induced site effects on the prioritization of bridges, the modified SRI described in the previous section is computed for 450 bridges in the region of study. Using a GIS platform, susceptibility levels to amplification, ground mass movements (landslides and rock falls) and liquefaction extracted at bridges sites are integrated in the computation of the respective SRI. It should be emphasized that to preserve confidentiality of the network analyzed, bridges from an existing network were relocated. The new geographical locations of the bridges are as shown on Figure 4, in an area where the seismic hazard index, F_{hazard}, is established to vary between 1.52 and 1.73.

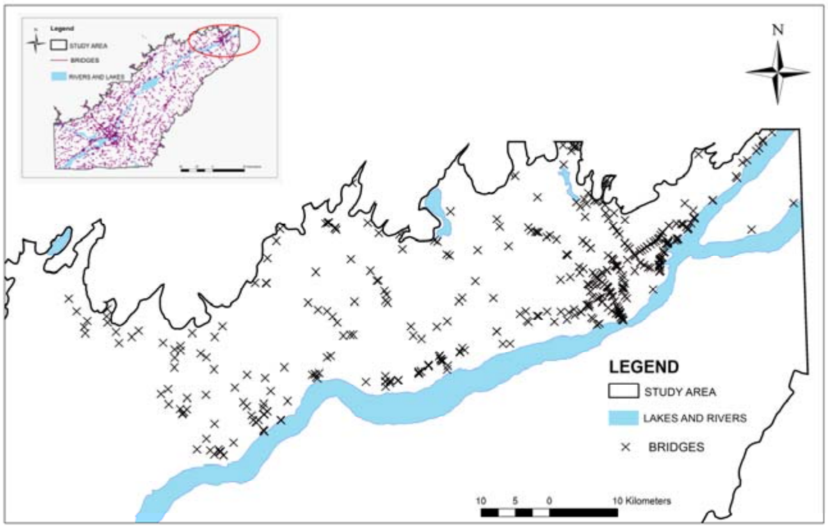

Figure 2: Geographical distribution of database bridges

The seismic risk indices were computed without and with consideration of site effects using susceptibility maps to amplification, ground mass movement and liquefaction (Figures 1 to 3). The SRI varies from 6 to 44 when taking none of the site effects. When considering all site effects, 186 bridges (41.3%) have their SRI increasing above 50, which is considered as higher priority. Furthermore, 11 (2.5%) bridges are located on sites with high susceptibility to liquefaction ($F_{site} = 2$) and their SRI reach the maximum score of 100.

In order to better represent the three aspects of the seismic risk (hazard, vulnerability and socioeconomic value of bridges), a socioeconomic index (SEI) is also assigned to bridges according to their importance on the network. This index varies between 0 and 100 and a value higher than 50 indicates an important bridge for safety and evacuation purposes. Both seismic risk and socioeconomic indices are combined in 4 categories to prioritize bridges for planning emergency measures or to define mitigation interventions (see Table 3).

Table 3: Category of prioritization according to values of seismic risk index and socioeconomic index

Category of prioritization	Seismic Risk Index	Socioeconomic Index (SEI)
I	SRI ≥ 50	SEI ≥ 50
II	SRI ≥ 50	SEI < 50
III	SRI < 50	SEI ≥ 50
IV	SRI < 50	SEI < 50

Figure 5 shows the distribution of bridges within the 4 categories of prioritization when SRI are computed without and with consideration of site effects using susceptibility maps. The results show that 19.3% of the bridges move to category I and 22.0% to category II, when taking into account the susceptibility to the 4 site effects (amplification, landslides, rock falls and liquefaction).

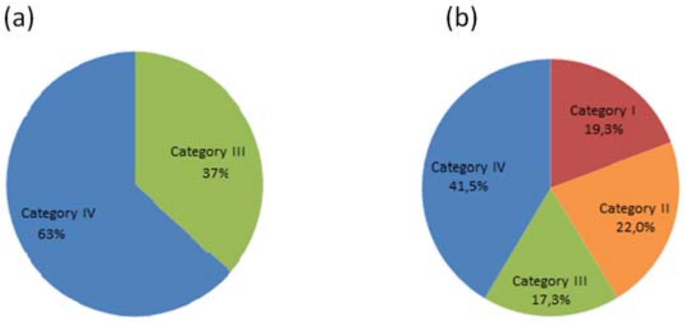

Figure 3: Distribution of the bridges into categories of prioritization: (a) without site effects, (b) with site effects

New indices are well distributed in the 4 categories of prioritization and allow a better classification of bridges taking into account all the components of the seismic hazards for the region of study. The weight of the structural vulnerability in the seismic risk index is preserved, which insure that a bridge with no structural deficiencies will be assigned a maximum SRI of 50 if exposed to a maximum seismic hazard.

5 CONCLUSION

Seismic site effects present in the region of study are amplification, liquefaction, landslides and rock falls. Their susceptibility levels were previously mapped by documenting and characterizing the general context of geomorphology, geology and hydrography. This approach to mapping site effects is conducted on a GIS platform and susceptibility levels can be easily extracted at bridge sites. These maps were then used to illustrate how seismically induced site effects could be integrated into seismic assessment scoring procedures for bridges using a GIS platform. The modified seismic risk index was then applied to a network of 450 bridges in the province of Quebec. Ground mass movements' susceptibilities are included in the new seismic risk index according to set theory. Liquefaction is also taken into consideration by increasing the site index significantly to reflect the destructive capacity of this particular phenomenon and its impact on structures. Results show that integrating susceptibility to seismically induced site effects into a scoring procedure allows a better identification of the most vulnerable structures which lead to improvement of the prioritization process. A GIS approach to susceptibility mapping increases the efficiency of scoring methods in the absence of site-specific information.

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