

Susceptibility modelling of seismically induced effects (landslides and rock falls) integrated to rapid scoring procedures for bridges using GIS tools for the Lowlands of the Saint-Lawrence Valley

Azarm Farzam, Marie-José Nollet and Amar Khaled

Génie De La construction, École de Technologie Supérieure, Montréal, Québec, Canada

ABSTRACT

Assessment of the seismic vulnerability of a bridge structure relies on its structural characteristics and site data. However, seismically induced effects, such as landslides or rock falls, are often unknown at a bridge site, making seismic risk assessment difficult. The objective of this paper is to develop a methodology to produce susceptibility map for landslides and rock falls for the Lowlands of the Saint-Lawrence Valley based on geological and slope models, groundwater table and proximity to watercourses. The methodology is inspired by the concepts of the methodology of Hazus and adapted to the specificity of the region of study. The final map of susceptibility to landslides shows a predominance of high level of susceptibility. The digital inventory of landslides is compared to the landslides susceptibility levels. Sixty-eight percentage (68%) of landslides from the inventory are located on areas evaluated as highly or very highly susceptible. Therefore, the method of attribution of susceptibility level is well correlated to the inventory of landslides. This map is used within scoring procedures for a rapid assessment of the seismic vulnerability of bridges giving a better classification of the most vulnerable installations, improving the effectiveness of mitigation measures and the efficiency of emergency planning.

ARTICLE HISTORY

Received 5 May 2017
Accepted 26 March 2018

KEYWORDS

Site effects; geographic information systems; earthquakes; landslides

1. Introduction

Although seismic hazard is recognized as moderate in eastern Canada, population density in urban areas, such as Montreal or Quebec City, makes it the second largest zone at risk in Canada (Adams et al. 2002). In the province of Quebec, the Lowlands of the Saint-Lawrence Valley is characterized by marine clay deposits and is thereby highly sensitive to landslides (Quinn et al. 2011). During the 1988 Saguenay earthquake ($M_w = 5.9$), 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).

Induced site effects, such as landslides and rock falls, can cause severe damages to bridges and structures. Landslides can cause translation or rotation of bridge abutments used as retaining walls for the embankments, leading to bridge deck collapse (Mitchell et al. 2012). Falling rocks can seriously damage structural elements such as piers and abutments. Although the initiation of those two site effects may be governed by similar factors (i.e. geology, slope, groundwater table), external factors that may decrease rock falls or landslides hazard are different. As a consequence, structural

vulnerabilities of bridges and their external protections are different depending on the induced site effect. A clear distinction between landslides and rock falls must therefore be considered.

The province of Quebec counts nearly 9600 bridges and overpasses (MTQ 2016). Forty-eight percentage (48%) of these structures are located in the Lowlands of the Saint-Lawrence Valley, while 70% were built between 1960 and 1980, when seismic design provisions were not as stringent as today. Seismic risk assessment of a large number of aged infrastructures is an essential step towards effective mitigation measures and emergency planning.

The conventional knowledge of the seismic hazard information alone such as type of ground shaking information, intensity and frequency is not sufficient for informed decision-making. Seismic risk assessment presumes not only knowledge of earthquake hazards that might impact a region but also knowledge of vulnerability of existing infrastructures such as bridges or buildings. While the assessment of the seismic vulnerability of a bridge structure relies generally on easily accessible data, seismically induced site effects, such as landslides or rock falls, are often undefined or unknown at a bridge site, making seismic risk assessment difficult, especially when dealing with a large number of structures located on an extended area.

Seismic evaluation by scoring procedures is a widely used seismic risk management approach (Kim 1993; Basöz and Kiremidjian 1995; NYSDOT 2002; Davi et al. 2011). It allows the classification of structures using a relative seismic risk index (SRI) that considers seismic hazard combined to the structural vulnerability of the bridges through structural characteristics and identification of seismic deficiencies. In the context of this simplified approach to seismic risk assessment at regional scale, structural vulnerability of bridges is typically conditioned on a single seismic hazard parameter such as the peak ground acceleration (PGA) or the spectral acceleration (Basöz and Kiremidjian 1995; Coburn and Spence 2002; Kiremidjian et al. 2007).

Combining geographical information system tools to seismic evaluation procedures increases the efficiency of the procedure while improving management of mitigation measures and emergency planning (Kiremidjian et al. 2007). This could be achieved through Geographic Information System (GIS) tools which allow visualization of information related to geology or geomorphology that may usually govern susceptibility to seismically induced effects from ground mass movements.

In the United States, Hazus software (FEMA 2012) is one of the most effective and used GIS technical tool to evaluate the seismic risk. The Hazus procedure consists of a two steps methodology to evaluate the ground mass movement hazard using expert judgment approach: a scoring procedure is first used to evaluate the ground mass susceptibility with 10 levels considering geology, slope and dryness of soil. These levels are then related to a probability of occurrence depending on PGA. It has been pointed out that site specific acceleration should be combined with a probability of occurrence of the effect in order to quantify the risk of seismically induced effects (Davi et al. 2011; FEMA 2012). In the absence of specific site geotechnical data, susceptibility to landslides and rock falls could be defined from relevant parameters such as geology, topography, groundwater table, proximity to rivers and lakes, land use and pluviometry (Pourghasemi et al. 2013; Theilen-Willige 2010; Quinn 2009). The concepts of the Hazus scoring procedure (FEMA 2012) is used in this study to evaluate the ground mass susceptibility for the Lowlands of the Saint-Lawrence Valley.

This paper presents the development of landslide and rock fall susceptibility maps for the Lowlands of the Saint-Lawrence Valley in the Province of Quebec. The method used to develop the susceptibility maps is based mainly on expert judgements and is intended to be used within existing seismic scoring procedures for bridges. Definitions of susceptibility scales are based on Hazus scales for gravitational mass movements and modified to consider proximity to watercourses. A clear distinction is also made between rock falls and landslides since bridge structures are differently impacted by landslides and rock falls. Furthermore, the protective measures against landslides and rock falls differ considerably. Geological, geomorphological and hydrological information are used to produce landslide and rock fall susceptibility maps. New geological databases are used with recent surficial geological model (Parent et al. 2018). The model defines 12 lithologies compared to 8 in

previous studies (Quinn 2009). In order to validate the landslides susceptibility map, results are compared to a digital landslides inventory of the region of study.

2. Geological context and seismically induced site effects in the Lowlands of the Saint-Lawrence Valley

2.1. Geological context

The region of study shown in Figure 1 covers an area of about 32,000 km² in the Lowlands of the Saint-Lawrence Valley. Bedrock outcrops in few regions but predominant geology is composed of glacial and post-glacial unconsolidated deposits. It is mainly dominated in the north-west by metamorphic and igneous rocks dated from Precambrian, in the centre by sedimentary rocks from the Iapetus ocean (Ordovician-Silurian) and in the south-east by the metamorphic rocks of Appalachians orogeny (Cambrian-High Ordovician) (Nastev et al. 2016). Till deposits (identified by T in Figure 1), which are predominant at the bottom of the quaternary deposits, are very heterogeneous with a large variety of grain size cemented by a compacted silty or sandy silt matrix (Russell et al. 2011; Nastev et al. 2016). During the last deglaciation (between 18,000 and 12,000 years BP), the moraine was eroded by the eskers and replaced by glaciofluvial (GF) or glaciolacustrine (GL) deposits (Parent and Occhietti 1999; Russell et al. 2011; Savard 2013). GF deposits are mainly composed of sands and gravels (Nastev et al. 2016) while GL are mostly composed of clays (Parent and Occhietti 1988). During the interglacial stage, glacial deposits were covered by up to 30 m of marine clays (M) (Lefebvre 1986; Nastev et al. 2016). For the region of study, the source of these deposits is mainly the Champlain sea dated between 12,000 and 10,000 years BP (Parent and Occhietti 1999; Savard 2013). This period of deposition was followed by alluvial deposits (A) or lacustrine deposits (L) from the Proto-Saint-Laurent or the Lampsilis lake. They are composed by tills, gravels, sands, clays and silts reworked (Savard 2013). Organic deposits (O) mostly composed of peats and plant residues are also found close to lakes or mixed with eolian deposits (E-sands) (Fransham and Gadd 1977; Filion 1987). In some areas, colluvium deposits (C) were also deposited on top of the stratigraphic column (Savard 2013).

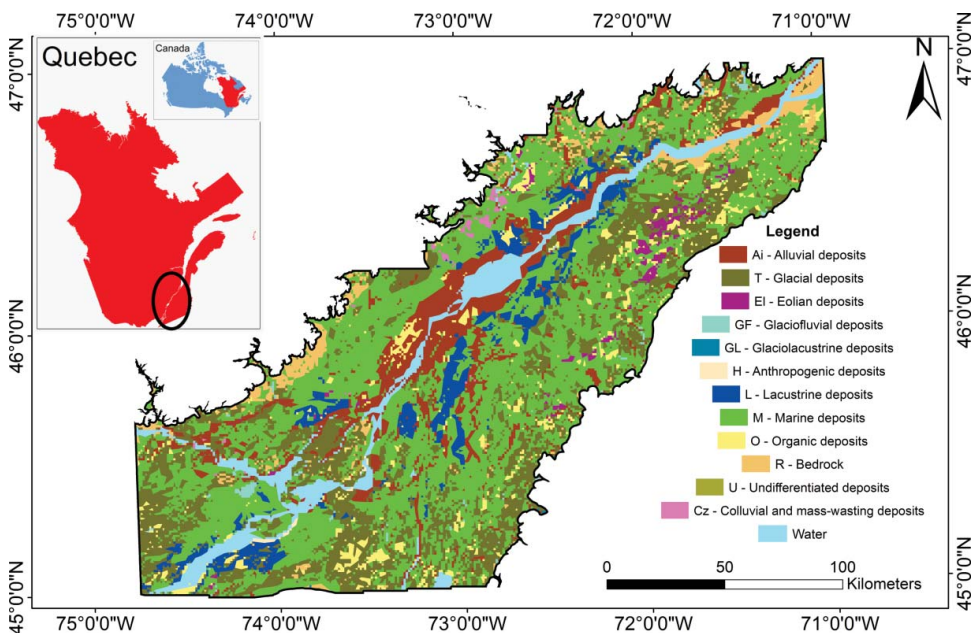


Figure 1. Surficial geological map of Lowlands of Saint-Lawrence Valley (produced from data taken from Parent et al. (2018)).

Clays of the Champlain Sea (Leda clay) are extremely sensitive to landslides, particularly in the presence of water (Lefebvre 1986; Quinn Peter 2009), thereby, increasing the risk of landslides or lateral spread at bridge sites. Local geology and predominance of marine clay should be taken into account to develop a methodology adapted to the area of study.

2.2. Seismically induced site effects from past earthquakes

Seismicity of eastern Canada is mainly due to the extension of the medio-oceanic ridges which causes north-east compression and the uplift of the North American Plate after the glacier melting 10,000 years ago (Government of Canada 2011).

During the last 10 years, 3 earthquakes of magnitude 5 or more were felt in the Lowlands of the Saint-Lawrence Valley (Government of Canada 2011). During the 1663 Charlevoix-Kamouraska earthquake (Locat 2008), landslides were observed on the shores of the rivers Betsiamites, Rivière du Gouffre (Charlevoix), St-Maurice (LaBissonnière and Saint-Boniface), Shipshaw (Saguenay, Saint-Jean Vianney), Pentecôte, Batiscan and St-Lawrence (Desjardins 1980; Fillion et al. 1991; Gouin 2001; Locat 2008). Locat (2008) estimated that a total of 1.7 km³ mass movements, including sub-aqueous landslides, were triggered. The 1860 earthquake in La Malbaie (Charlevoix-Kamouraska, Mw~6), induced landslides in the region of Pointe-aux-Alouettes (60 km away), where part of the forest slid into the river (Lamontagne 2008).

The 1870 earthquake (Mw~6.5) located near Baie St-Paul (Charlevoix-Kamouraska), resulted in landscape changes due to mass movement. Rock falls were reported in the cliff of Saint-Anne de Beupré 60 km from the epicentre and three people were reported dead in Batiscan, 175 km from the epicentre (Lamontagne 2008).

The strongest earthquake of the twentieth century (Mw = 6.2) occurred in Charlevoix-Kamouraska in 1925 (Government of Canada 2016). Damages due to site effects were reported in Quebec City as well as in Shawinigan, about 230 km away (Lamontagne 2008).

3. Methodology and dataset

Seismically induced site effects such as rock falls or landslides are governed by intrinsic factors such as geological, topographical and hydrological conditions but they are also correlated to causative seismic factors such as seismic intensity, PGA, distance to the seismogenic fault and distance along the fault. In general, the most influencing seismic factors are the distance from the fault and the PGA (Xu et al. 2012; Xu et al. 2013). In the context of risk assessment for seismically induced site effects, seismic hazard generally evaluated from PGA, is combined to the susceptibility information and structural vulnerability assessment to obtain a global evaluation of the seismic risk (Van Westen et al. 2008). In this study, landslides and rock falls susceptibility are therefore assessed from geological or topographical conditions while PGA is selected, as the main seismic factor, to evaluate seismic hazard since it also correlates well to seismic damage to structures and bridges (Basöz and Kiremidjian 1995; Coburn and Spence 2002; Kiremidjian et al. 2007).

Seismically induced 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 induced site hazards is obtained from site specific prospection, the information from the general context allow mapping large scale phenomenon influencing induced effect at smaller scale. Geographic information system methods are powerful tools for modelling large scale phenomenon such as earthquake impact. In the specific domain of mapping site effect including landslides, Theilen-Willige (2010) used topographic data of LANDSAT (USGS 2015) to detect local site conditions influencing earthquake shaking and secondary effects in south-west Haiti. More recently, Karimzadeh et al. (2017) used hybrid

site condition mapping to create local amplification mapping. This approach consists in using data from remote sensing such as LANDSAT with geological data. New technologies, such as remote sensing, are also available and allow quantifying the relation between earthquake magnitude and surfaces affected by landslides and rock falls (Van Westen et al. 2008). Quinn Pete and Zaleski (2015) studied the threshold of PGA inducing landslides in sensitive clays in eastern Canadian regions but no clear results were inferred from the available data.

Multicriteria decision analyses and weights of evidence approach are today well established methods for site effects mapping and seismic risk evaluation (Theilen-Willige 2010; Feizizadeh et al. 2014; Feizizadeh and Kienberger 2017; Karimzadeh et al. 2017). A regional-scale landslide susceptibility map for the region of study was developed by Quinn (2009) using the weights of evidence method (Pourghasemi et al. 2013; Feizizadeh et al. 2017; Gheshlaghi and Feizizadeh 2017). The method consists in assigning coefficients to each factor influencing landslides based on an existing inventory of landslide features. The weight of evidence method is then used to produce a susceptibility map to landslide with three susceptibility scales: low, low to moderate and moderate to high. A multicriteria decision analyses was selected for this work in which landslides and rock falls susceptibility are evaluated based on expert judgement considering the geotechnical context of the region of study.

In this paper, the methodology used to develop landslides and rock falls susceptibility map were developed following four steps:

- Development of dataset and construction of a spatial database related to ground mass movement factors.
- Definition of susceptibility levels, following expert judgments from FEMA (2012), with respect to geology, slope and groundwater table.
- Addition of a specific factor related to watercourses effects on Champlain clay.
- Validation of the results with an inventory.

3.1. Development of datasets

The collected data consists of four parameters required to develop the susceptibility map. They are extracted from the following sources:

- a. Geology is extracted from a surface geology model with 12 main lithologies for the Lowlands of Saint-Lawrence Valley (Parent et al. 2018).
- b. Slopes are calculated from the digital elevation model (DEM) provided by the United States Geological Survey (USGS 2015) with a resolution of 1.0 arc-sec equivalent to about 30 m (Farr et al. 2007).
- c. The level of the groundwater table is determined from 78,792 boreholes available on the website of hydrogeological information system (SIH) of the *Ministère du Développement Durable Environnement et Lutte contre les Changements Climatiques* (MDDELCC 2014).
- d. The proximity to watercourse model for the studied area is derived from a compilation of five hydrographic digital databases from different data sources (Québec. Ministère de l'Énergie et des Ressources naturelles 2000; Land Information Ontario 2011, 2015; Quebec. Ministry Natural Resources 2016; Statistics Canada 2016).

3.2. Mapping of ground mass movements susceptibility

The considered parameters are then mapped in GIS dataset form as input for the susceptibility evaluation model (Figure 2). The mapping was produced according to (a) geology, (b) slope, (c) groundwater table and (d) watercourse proximity.

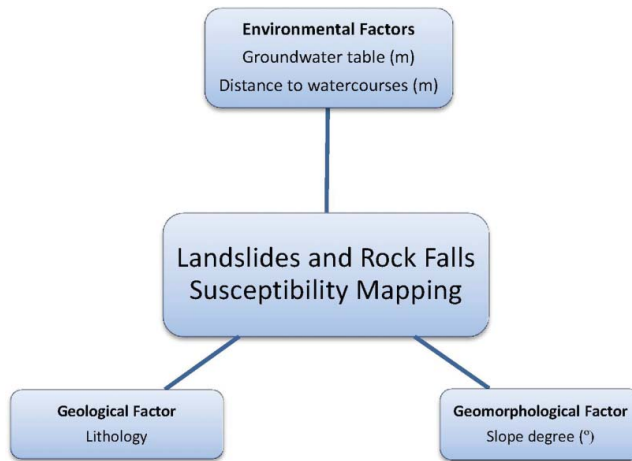


Figure 2. Factors used for landslides and rock falls susceptibility mapping.

a. Geology

Geological factor related to the lithologies and their state of consolidation at a site gives information on the cohesion and angle of internal friction, both controlling shear strength, which is one of the main forces influencing landslide. A high degree of consolidation is related to a high cohesion. As a consequence, the risk of instability increases as the state of consolidation decreases. To relate the susceptibility to mass ground movements, the 12 lithologies of the studied area (Figure 1) are classified in 3 geological groups (A, B, C) depending on the effective cohesion c' and the effective angle of internal friction ϕ' . The three groups are similar to those proposed in Hazus (FEMA) in terms of susceptibility to mass movements. It is worth noting that Hazus considers landslides and rock falls as the same induced effect even though rock falls susceptibility can be increased or decreased by the quality of a rock. In this study, distinction is made between landslides and rock falls according to the geology since rock falls are triggered only for strongly cemented rocks. Group A is defined by strongly cemented rocks (crystalline rocks and well-cemented sandstone, $c' = 14.4$ kPa, $\phi' = 35^\circ$). Group A includes all bedrocks (R-Bedrocks outcrop in Figure 1). Group A is not susceptible to landslides but is the only geological group susceptible to rock falls. Various types of bedrocks are included in this group (Table 1). Consequently, susceptibility to rock falls differs from susceptibility to landslide by the presence of bedrock at the surface.

Group B includes weakly cemented rocks and soils (sandy soils and poorly cemented sandstone, $c' = 0$, $\phi' = 35^\circ$), such as sand, silt and gravels including alluvial (A) (Nastev et al. 2016), eolian (E)

Table 1. Correspondence between geological groups and lithologies of the studied area.

Lithology/geological group	Group A $c' = 14.4$ kPa, $\phi' = 35^\circ$	Group B $c' = 0$, $\phi' = 35^\circ$	Group C $c' = 0$, $\phi' = 20^\circ$
A – Alluvial deposits (tills, gravels, sands, clays and silts reworked)	–	×	–
C – Colluvial and mass-wasting deposits (clays and silts reworked)	–	–	×
E – Eolian deposits (sands)	–	×	–
GF – Glaciofluvial deposits (sands and gravels)	–	×	–
GL – Glaciolacustrine deposits (clays)	–	–	×
H – Anthropogenic deposits	–	–	×
L – Lacustrine deposits (silts)	–	×	–
M – Marine deposits (mostly clays)	–	–	×
O – Organic deposits (mostly peats and plant residues)	–	–	×
R – Bedrock	×	–	–
T – Till-glacial deposits	–	×	–
U – Undifferentiated deposits	–	–	×

(Filion 1987), lacustrine (L) (Savard 2013), glaciofluvial (GF) (Nastev et al. 2016) and till (T) deposits (Nastev et al. 2016).

Group C includes argillaceous rocks (shales, clayey soil, existing landslides, poorly compacted fills $c' = 0$, $\phi' = 20^\circ$). It includes all unconsolidated deposits such as the very sensitive marine clays (M) of Champlain Sea (Lefebvre 1986), clay from glaciolacustrine (GL) deposits (Parent and Occhietti 1988), organic (O) deposits (Fransham and Gadd 1977; Robertson 1990), colluvial and mass-wasting (C) (Savard 2013). When assigning a group to a site, the most susceptible category is chosen for anthropic (H) and undifferentiated (U) deposits (Table 1).

b. Slopes

Slopes have an impact on normal and shear stress values acting on the sliding plan: the higher the slope gradient, the higher the instability. The slope criterion proposed by Hazus is based on expert judgment and is adopted in this study. To estimate the influence of slope angle on the susceptibility to landslides and rock falls, six ranges of values for the slope gradient model are considered (Figure 3): 0° – 10° , 10° – 15° , 15° – 20° , 20° – 30° , 30° – 40° and $>40^\circ$. The slope gradient is computed as the first derivative of the value given by the DEM. Figure 3 shows the slope gradient model of the studied area. While slope is a major factor to characterize rock falls and landslides susceptibility, the Lowlands of Saint-Lawrence have very few sites with high slopes. The most recognizable sites are the Monteregian hills from the cretaceous close to the City of Montreal but there are also few other regions in the west and north part of the area.

c. Groundwater table

The presence of groundwater table on a potential failure plan will highly increase the susceptibility to ground mass movement. Youd and Perkins (1978) have established a threshold of 10 m as the limit for the level of groundwater table to distinguish dry soil from wet soil. This threshold is used in this study to identify wet and dry soil.

The groundwater table was measured at the end of the work on the boreholes using available data. Since boreholes are not uniformly distributed in the area of study, ‘natural neighbour’ tool

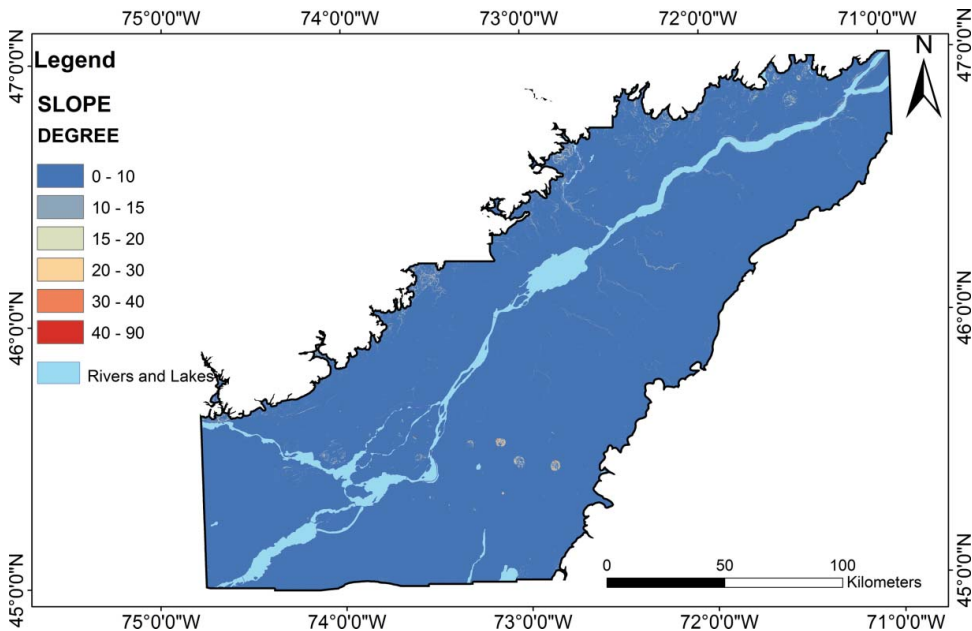


Figure 3. Slope gradient model.

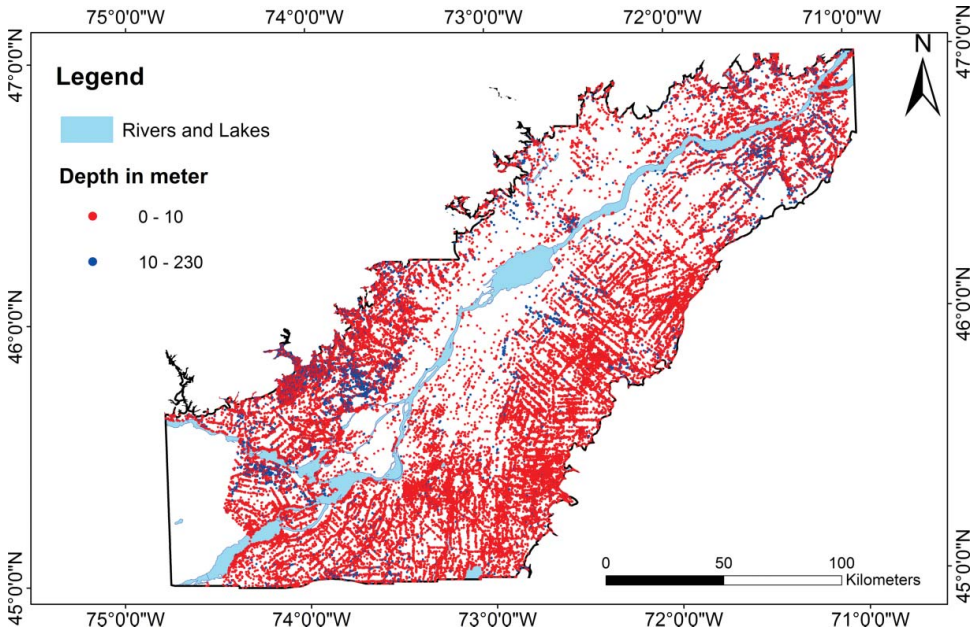


Figure 4. Groundwater table depth map from SIH boreholes.

defined by two steps of Voronoi (Thiessen) polygons (Sibson 1981) is used to interpolate the groundwater table level for the whole region.

Figure 4 presents the groundwater table depth map from SIH boreholes.

The final groundwater table model showing wet soil (0–10 m) from dry soil (10–230 m) is presented in Figure 5. Wet soils cover 87% of the area whereas dry soils cover only 13%.

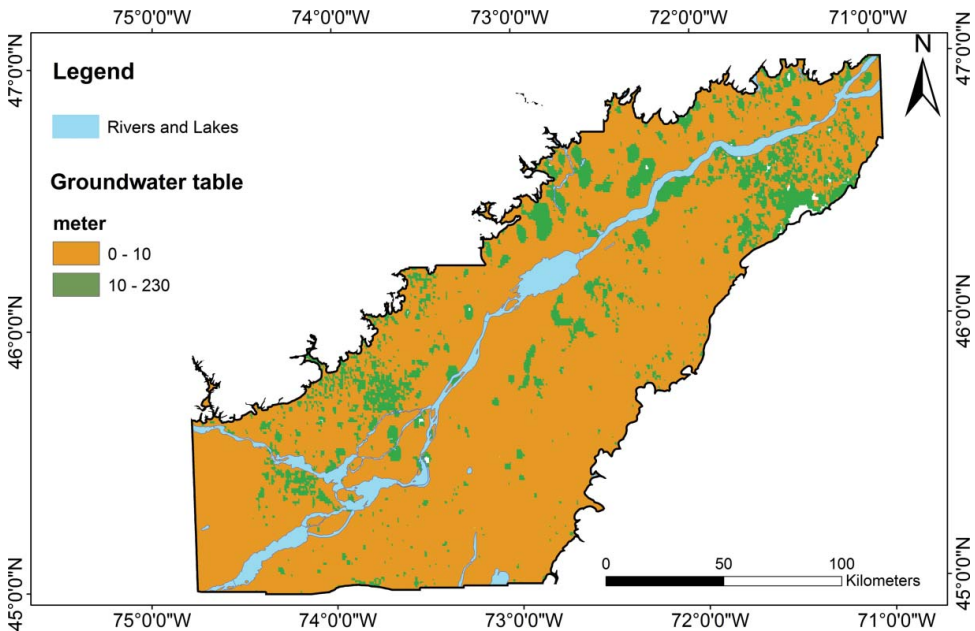


Figure 5. Groundwater table model.

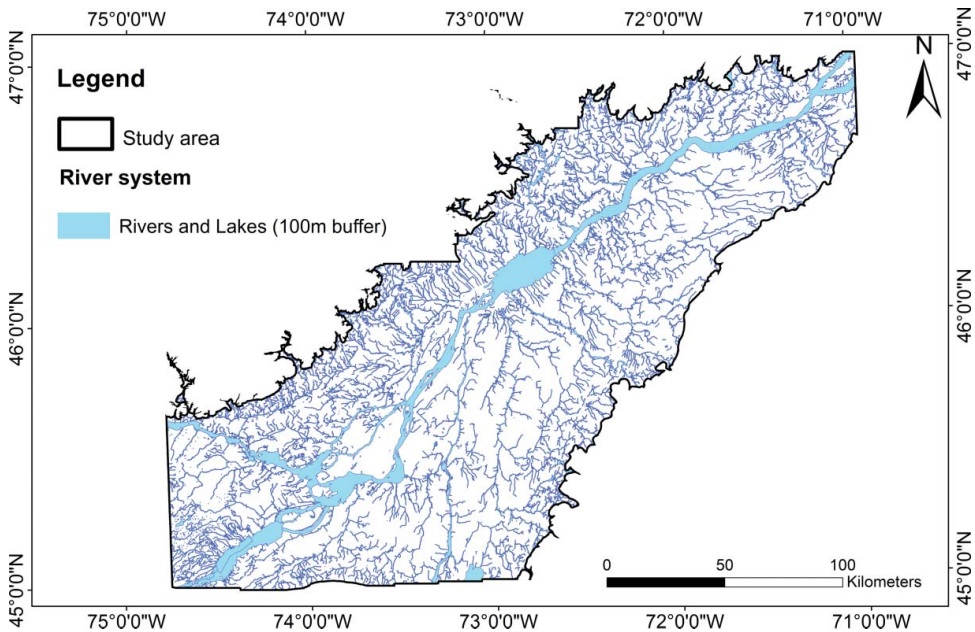


Figure 6. Proximity to watercourses model.

d. Watercourses

Because of the high potential of Champlain clay to be eroded, the proximity to watercourses is taken into consideration in this project as a parameter for landslides and rock falls susceptibility, as suggested by recent studies (Quinn 2009). The watercourse model is derived from a compilation of 105,046 entities which have been merged. A buffer of 100 m was applied to consider the proximity to watercourses (Figure 6). All sites within 100 m of these 105,046 entities had an increased susceptibility level to landslides and rock falls. A distance of 100 m was chosen after observation of multiple landslides hazard maps available on the websites of regional county municipalities (MTQ 2012, 2013b, 2013a).

4. Landslides and rock falls susceptibility maps: Results and validation

4.1. Definition of a susceptibility scale

Table 2 presents the susceptibility level (from None to Very High) of a site depending on its geological group (A, B or C), the slope angle and the level of the groundwater table (below or over 10 m). The proximity to rivers and lakes (<100 m) is upgrading the susceptibility levels by 1°. For example, the susceptibility to landslide of a wet site on alluvial sediment (group B) with a slope angle of 11° is high (H), and becomes very high (VH) when located near a watercourse.

4.2. Susceptibility map for landslides and rock falls

The final map of susceptibility to rock falls and landslides, established from the criteria defined in the previous section and Figure 2, is presented in Figure 7. Six levels of susceptibility (None, Very Low, Low, Moderate, High and Very High) are assigned. Surface covered by geological group B and C (95% of the area studied) can be susceptible to landslides and surface covered by geological group A related to rocks (5% of the area studied) can be susceptible to rock falls (Table 1 and 2).

Table 2. Rock falls and landslides susceptibility scale of geologic groups, adapted from FEMA (2012) and Youd and Perkins (1978).

Rock falls and landslides susceptibility scale												
Slope angle (degrees)	0–10		10–15		15–20		20–30		30–40		>40	
Proximity to watercourses	>100	≤100	>100	≤100	>100	≤100	>100	≤100	>100	≤100	>100	≤100
<i>Geological group</i>						<i>Dry lithologies (groundwater >10 m)</i>						
Group A Rock falls	None		None		VL	L	VL	L	L	M	M	H
Group B Landslides	None		L	M	L	M	M	H	M	H	H	VH
Group C Landslides	M	H	M	H	H	VH	VH	VH	VH	VH	VH	VH
						<i>Wet lithologies (groundwater <10 m)</i>						
Group A Rock falls	None		L	M	M	H	H	VH	H	VH	H	VH
Group B Landslides	M	H	H	VH	VH	VH	VH	VH	VH	VH	VH	VH
Group C Landslides	H	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH	VH

Note: VL = Very Low.
 L = Low.
 M = Moderate.
 H = High.
 VH = Very High.

4.3. Analysis and validation of susceptibility to landslides

Figure 8 shows the distribution of different levels of susceptibility to landslides for group B and C (95% of the area studied). Most of the area is either moderately (37%, in yellow in Figure 7) to highly susceptible (47%, in orange in Figure 7). Champlain marine clay is particularly sensitive and covers almost the entire area. Very high susceptibility level sites correspond mostly to sites with sensitive geology and lakes and rivers erosion. Sites with very high level of susceptibility are attributed to 10% of the area. It should be recalled that these results represent a qualitative distribution of the levels of susceptibility and does not provide a probability of occurrence to landslides.

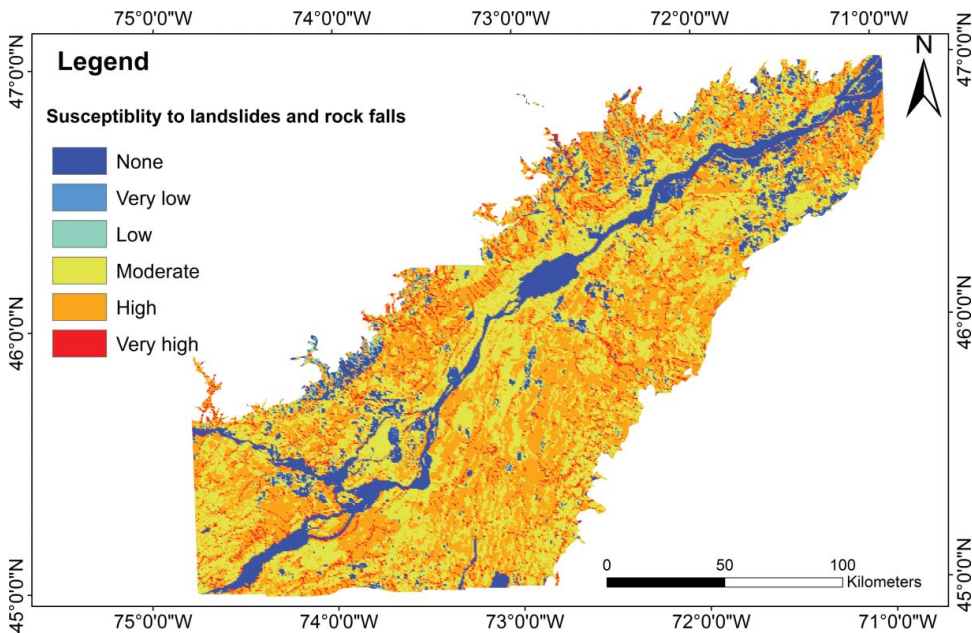


Figure 7. Susceptibility to rock falls and landslides map: red = high, blue = low.

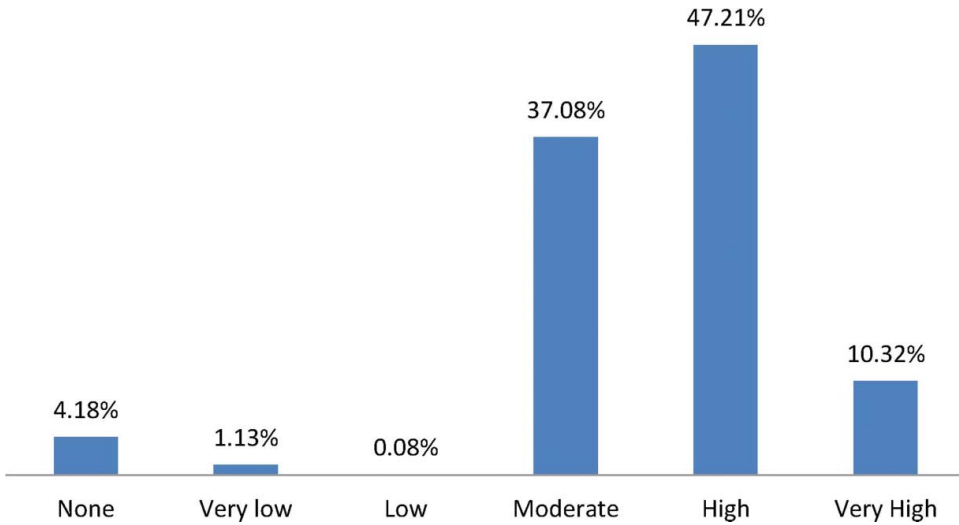


Figure 8. Distribution of different levels of susceptibility for landslides (95% of the studied area).

To validate the approach used to create a susceptibility scale to landslide for the Lowlands of the Saint-Lawrence Valley, the map created in Figure 8 is compared to a detailed georeferenced digital landslides inventory produced by Quinn (2009). This inventory is reproduced in Figure 9. It was created from aerial photos (National Air Photo Library in Ottawa) at various scales (typically 1:50,000) and several other sources (Wilson and MacKay 1919; Clark 1947; Morin 1947; Eden 1956; Karrow 1959, 1972; Lajoie 1974; Desjardins 1980; Carson and Lajoie 1981; Grondin and Demers 1996; Leroueil and Locat 1998; Demers et al. 1999). These landslides were not systematically induced by earthquakes. However, they can be used as tools to measure the predictive capability of the landslide susceptibility map. Quinn (2009) reported that the inventory is limited by the size and diversity of

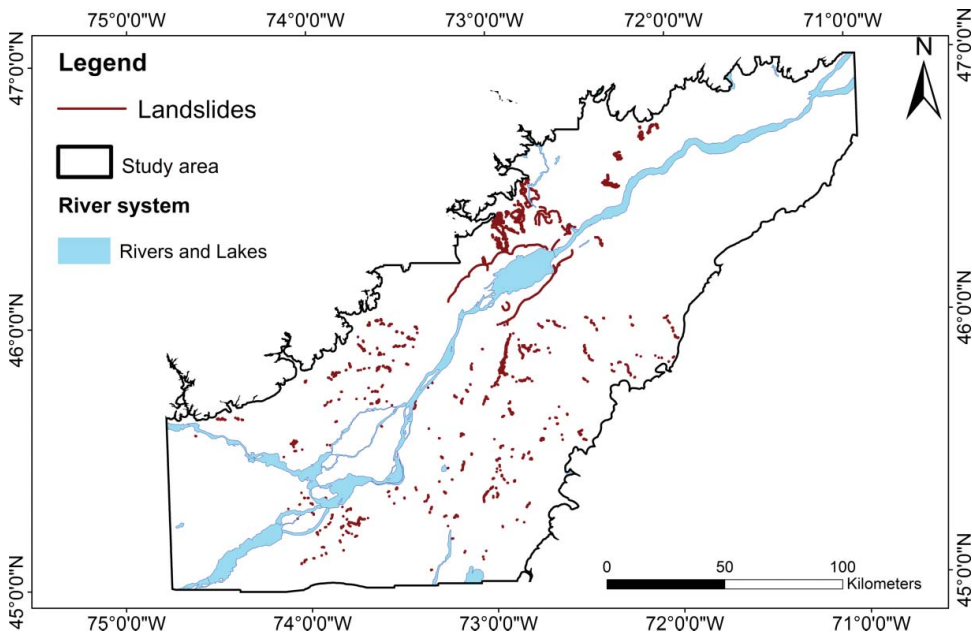


Figure 9. Landslides inventory map created from data provided by Quinn (2009).

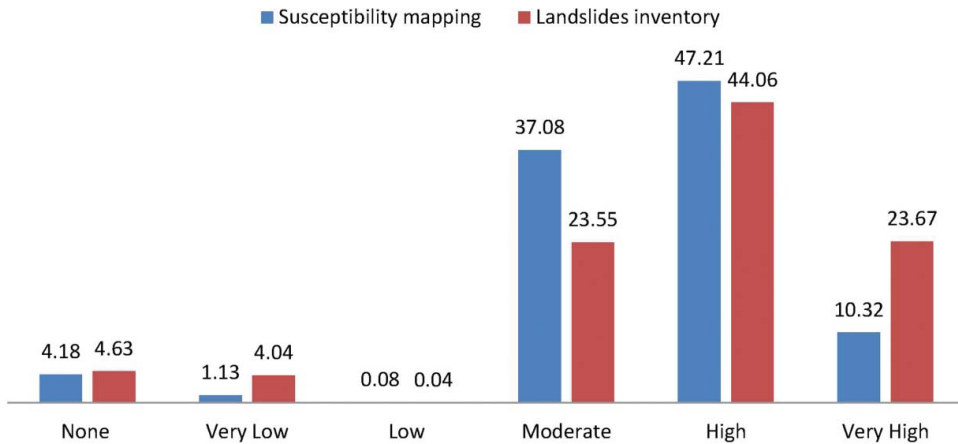


Figure 10. Histogram of the distribution of susceptibility level to landslides corresponding to landslides inventory.

geology and physiography, availability of appropriate data, resolution of available visual data and consistency of available data.

The digital inventory of landslides is compared to the landslides susceptibility levels over the complete area of study. Susceptibility map to landslides is composed of points at every 500 m. As a consequence, the distance of 250 m, corresponding to half of the distance between each point (500 m), is defined as the maximum distance between a point of susceptibility level and a line from the landslide inventory.

Figure 10 presents the distribution of the landslide inventory (in red) according to their location on the susceptibility map to landslides (see Figure 7). This distribution is compared to the random probability of sites in the region of study (in blue) to be evaluated in any of the six levels of susceptibility to landslides. The overall results indicate that the method of attribution of susceptibility levels is relatively well correlated to the inventory of landslides.

Most of inventoried landslides are located on sites with a susceptibility to landslides (in red) evaluated as moderate (24%), high (44%) and very high (24%), for a total of 92%. In comparison, the random probabilities (in blue) for a site to have a moderate, high or very high susceptibility to landslides are 37%, 47% and 10%, respectively, for a total of 94%. The larger number of landslides occurred on sites evaluated to have a high susceptibility (44% in red) while the prediction for this same level of susceptibility is 47%.

4.4. Analysis of susceptibility to rock falls

Susceptibility to rock falls is very low in the region of study: only 5% of the area is more or less susceptible to rock falls due to the outcropped bedrock. The results reveal that 73% of the 1530 km² have no susceptibility (level none), 15% are exposed to very low susceptibility and only 13% are distributed in descending order between low to very high susceptibility (Figure 11).

The territory affected by rock falls being relatively small, it makes it difficult to obtain an inventory on rock falls for validation. Unfortunately, no inventory for rock falls is available at this time. However, Promontory of Quebec known as a very sensitive site is identified as highly susceptible to rock falls by our approach.

5. Application to seismic vulnerability index for bridges

The choice of a relative qualitative scale, rather than a numerical scale for the susceptibility levels, offers the advantage and flexibility to be converted into indices and to be adapted into several available rapid scoring procedures for other sensitive infrastructures and lifelines.

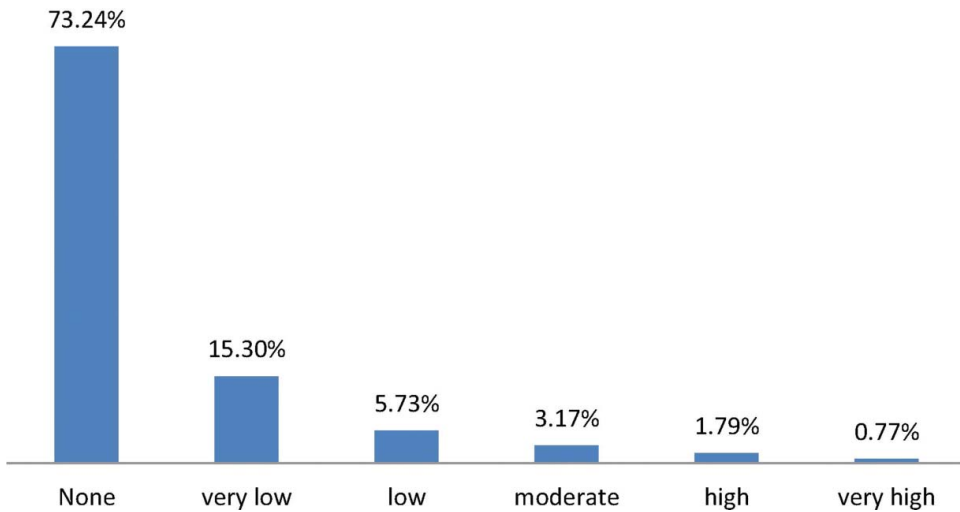


Figure 11. Distribution of different levels of susceptibility for rock falls (5% of the studied area).

SRI is generally expressed by the multiplication of a global index for the vulnerability of the structure by a seismic hazard index, as follows:

$$\text{SRI} = \text{Index}_{\text{seismic hazard}} \times \text{Index}_{\text{structure vulnerability}} \quad (1)$$

The seismic hazard index is defined from the seismic hazard according to a seismic factor, such as PGA, and generally takes into account the site amplification effect while landslide, rock falls or liquefaction hazards are not always considered. An additional index, corresponding to the value of the elements at risk, is sometimes included in the SRI computation. This value index can be related to the importance of the bridge on the road network (highway, municipal road, etc.) or on public services (connecting electricity or water supply).

The first multicriteria procedure for prioritization of bridges was developed by the California Department of Transportation, following the 1971 San Fernando earthquake (Basöz and Kiremidjian 1995; Small 1999). This procedure was the inspiration for the development of several others in the US (Kim 1993; NYSDOT 2002), Canada (Liu 2001) and in the province of Québec (Tinawi et al. 1993). The Caltrans procedure (Caltrans 1992) considered landslides as collateral hazards but neglected rock falls (Basöz and Kiremidjian 1995).

The New York State Department of Transportation (NYSDOT 2002) classifies the New York's regular bridges from 0 to 100 according to the seismic hazard and their seismic structural vulnerabilities which includes the vulnerability to abutment failures. Seismic hazard was related to the seismic zone defined according to spectral acceleration values. Kim (1993) developed a GIS-based regional risk analysis approach for bridges against seismic hazards, defined from the PGA, considering liquefaction but not landslides as site condition effects induced by earthquake. Moreover, no other ground failure is included in the final application due to the lack of data. In France, the *Direction des Routes et le Service d'Études Techniques des Routes et Autoroutes* uses the SISMOA method as a preliminary evaluation procedure of seismic risk of bridges (Davi et al. 2011). It is one of the few methods that include liquefaction, landslides and rock falls hazards. Each of these induced effects is computed independently depending on the structural characteristic of the bridge (vulnerability to the induced effect) and its hazard. The latter is a relationship between the critical ground acceleration necessary to induce landslides, rock falls or liquefactions. SISMOA approach can be used as reference for the attribution of vulnerability indices to bridge structures towards different induced effects.

Methods developed in Canada only consider the ground shaking hazard, defined from spectral acceleration values, without taking into account induced effects such as landslides or rock falls (Tinawi et al. 1993; Liu 2001). In Québec, the procedure applied by the *Ministère des Transports du Québec (MTQ)* considers the amplification effect by adjusting the seismic hazard index (Tinawi et al. 1993). However, the contribution of site amplification is frequently approximated or too conservative due to the lack of site specific information. An adapted GIS approach to the susceptibility modelling of seismically induced site effect could significantly improve the capability of seismic scoring procedures to identify the most vulnerable bridges. Susceptibility ground mass movements can be merged with structural parameters characterizing the vulnerability of bridges to assess a global SRI.

In the procedure developed in the Province of Quebec, the SRI (calculated from the Equation (1)) combines a seismic hazard index ($Index_{\text{seismic hazard}}$) and a structure vulnerability index ($Index_{\text{structure vulnerability}}$). The SRI ranges from 0 to 100. A score of 50 and higher identifies bridges that should be considered as vulnerable to earthquakes (Lemaire 2013).

The structure vulnerability index is established for structural and geometrical data on the bridge and ranges from 0 to 32. The weight of this index has been carefully established from simulation scenarios of damage to the bridges of the inventory (Lemaire 2013). It takes into account the quality of the foundations which influence significantly the vulnerability of bridges to landslides. It considers also the quality of piers and decks, which plays a major role in the vulnerability of bridges to rock falls.

The seismic hazard index, combining the acceleration and amplification hazards, ranges from 0 to 3.125. To include the landslides or rock falls hazard, a new seismic hazard index is defined as

$$Index_{\text{Seismic hazard}} = F_{\text{Acceleration hazard}} \times F_{\text{Amplification}} \times F_{\text{(Landslides or Rock falls)}} \tag{2}$$

The factor relative to the seismic acceleration hazards is correlated to the PGA, one of the most widely used seismic hazard parameter for the evaluation of the seismic risk of bridges in regional studies (Kim 1993; Basöz and Kiremidjian 1995; Kiremidjian et al. 2007; Davi et al. 2011). Its value

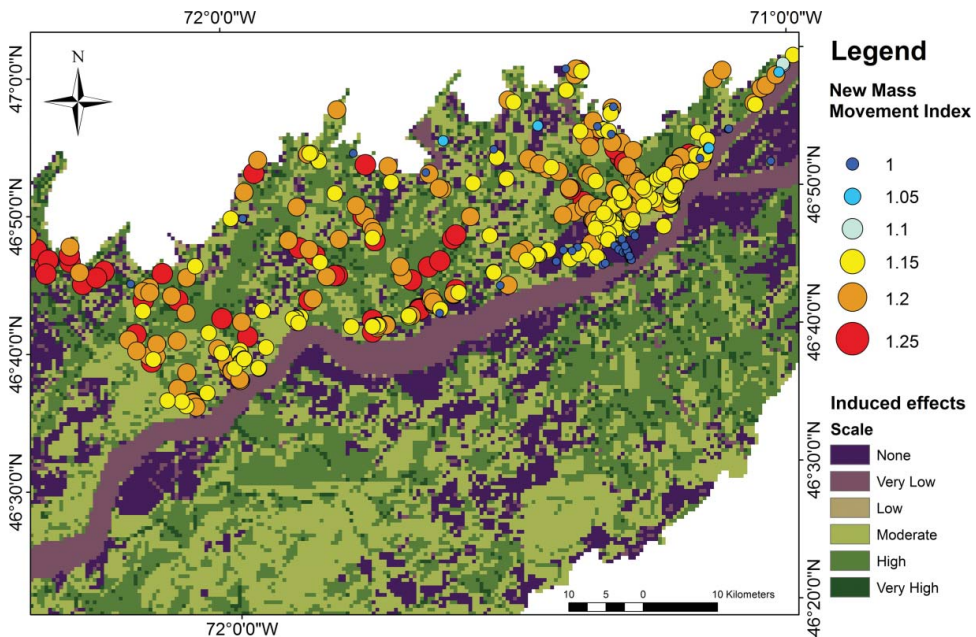


Figure 12. Map of the susceptibility to induced effects with bridges database.

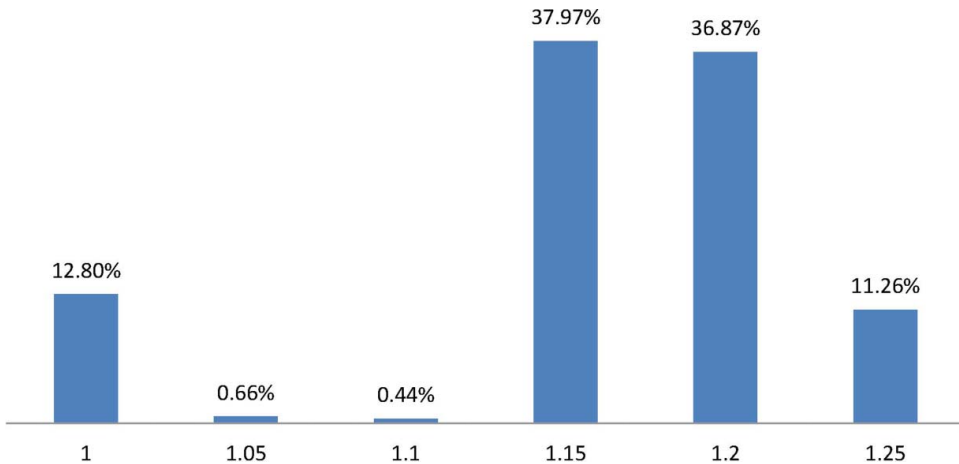


Figure 13. Distribution of landslides and rock falls susceptibility index for the 450 bridges of the Ministère des Transports database.

varies linearly between 1.0 for $PGA \leq 0.1$ g and 2.0 for $PGA \geq 0.4$ g whereas the factor relative to the amplification varies between 1.0 and 1.25.

Susceptibility scale to ground mass movements (landslides and rock falls) is converted 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) compatible with the scoring procedure to modify the seismic hazard index. This latter vary from 1 to 3.125, preserving the weight attributed to the structure vulnerability index.

Database provided by *MTQ* counts 450 bridges on the region of study on an area of 2750 km². (Figure 12)

These bridges have a new score representing the susceptibility to landslides or rock falls. This score is combined with their structural characteristics and the acceleration hazard to assign a new SRI. Figure 13 shows the distribution of landslides and rock falls susceptibility index for the 450 bridges of the *MTQ* database.

Most of the bridges have new susceptibility to ground mass movements' index between 1.15 (38%) and 1.2 (37%). The maximum value of 1.25 is attributed to 11% of the bridges from the database.

6. Discussions

Geology, slope, groundwater table and proximity to watercourses are used for ground mass movements susceptibility mapping. The results presented show landslides susceptibility mapping level high and very high corresponding mostly to regions where landslides were triggered in the past with the inventory (68%). These results are close to those find by the weight of evidence method applied for linear structure (67%) by Quinn (2009). However, qualitative scales are difficult to compare to each other because criteria are more related to the future application of the method.

Although methodology provides good results, potential improvement can be made by considering land use. Dense vegetation decreases the instability since vegetation allows the evapotranspiration clearing out part of soil humidity because of the cohesive power of the roots. Moreover, various meteorological conditions can affect the susceptibility to ground movements, in particular groundwater table. The melting season is the most adequate moment to measure groundwater table as it reaches its highest level at this period. However, since most of the groundwater table measured by SIH are already close to the surface (< 10 m), this would not affect the results. Earthquakes following an important rainfall can increase the susceptibility to induced rock falls or landslides.

Root mean square has been calculated for geological model and DEM. The result shows a resolution of 355 m. Results are satisfactory when considering surface geology model with a 500-m resolution. These results could be, however, further improved with a higher resolution of the databases.

GIS platforms can deal with easily available data such as DEMs or river system model. These kinds of data are available on the web and therefore susceptibility maps for seismically induced site effects can be cost effective. The new ground mass movement susceptibility index is completing the scoring procedure to estimate seismic risk for bridges. Most of bridges of the database are located on sites with susceptibility between moderate to very high. The new seismic hazard index includes the induced effects such as landslides or rock falls. It should be noted, however, that the structure vulnerability index does not consider the presence of external protection devices against rock falls.

7. Conclusions and Recommendations

In practice, when confronted to the lack of data on site conditions, managers often relies on the most conservative hypothesis, which may lead to an overestimation of the seismic risk for a large number of bridges. To face this challenge, stake holders (provincial government, municipalities, public services) need appropriate tools to evaluate the seismic vulnerabilities of their infrastructures and reliable information related to site sensitivity to seismically induced site effects.

The method for susceptibility mapping considers GIS on geology, slope and depth of groundwater table models. Criteria are inspired by the expert judgement methodology from Hazus but the methodology is adapted to the specific geological context of the Lowlands of Saint-Lawrence where the presence of marine clays (M) increases the susceptibility to landslides (Lefebvre 1986). It also takes into account the proximity to rivers or lakes and makes a distinction between susceptibility to rock falls and landslides. It provides information on the susceptibility to induced effects (landslides and rock falls) when there are no geotechnical field studies at a smaller scale.

Using GIS allows mapping large areas such as the Lowlands of Saint-Lawrence River in eastern Canada. This method provides a qualitative estimation of the seismically induced landslides and rock fall hazards. Landslides inventory validates the approach used to characterize the susceptibility for the area of the study. Producing inventory for rock falls to evaluate the validity of the approach is the next step.

Moreover, GIS allows completing this information with structural data characterizing the vulnerability of a bridge. Therefore, the platform enables to manage and visualize different kinds of data useful to evaluate the seismic risk of bridges to improve the effectiveness of mitigation measures and the efficiency of emergency planning. The susceptibility map to ground movements can be used in the scoring procedures to evaluate the seismic risk of bridges, or with other sensitive infrastructure. This procedure aims to classify installations according to their relative seismic vulnerability and associated risk, and allows identifying the most vulnerable bridges within a large inventory. The new seismic index allows a better classification of the most vulnerable installations. The adapted GIS approach to the susceptibility modelling of seismically induced site effect significantly improves the scoring procedures for a rapid assessment of the seismic vulnerability of bridges and other installations.

The scoring procedure can be improved by taking into consideration the presence of external protection measures such as high strength mesh in the evaluation of the vulnerability index toward rock falls or drainage measures for landslides. Moreover, natural external factors decreasing the effects of velocity of rock falls, such as presence of forest, can be taken into account in order to prioritize the intervention on a bridge.

Acknowledgments

The authors wish to acknowledge the financial support provided by École de Technologie Supérieure and Natural Resources Canada for the scientific contribution to the project. Thanks also to Peter Quinn for giving us the access to his landslides inventory database and to the Ministère des Transports du Québec for information on its bridges.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

École de Technologie Supérieure and Natural Resources Canada.

References

- Adams J, Rogers G, Halchuk S, McCormack D, Cassidy J. 2002. Case for an advanced national earthquake monitoring system for Canada's cities at risk. Proceedings of the 7th US National Conference on Earthquake Engineering, Boston, United States. 42.
- Basöz NI, Kiremidjian AS. 1995. Prioritization of bridges for seismic retrofitting. New York: The National Center for Earthquake Engineering Research State University of New York at Buffalo. Technical Report-95-0007.
- Caltrans. 1992. Seismic hazard components in the Caltrans prioritization algorithm, California: California Department of Transportation - Division of structures.
- Carson MA, Lajoie G. 1981. Some constraints on the severity of landslide penetration in sensitive deposits. *Géographie physique et Quaternaire*. 35(3):301–316.
- Clark TH. 1947. Two recent landslides in Quebec. *T Roy Soc Can*. 41(3):9–18.
- Coburn A, Spence RJS. 2002. Earthquake protection. 2nd ed. Chichester, UK: Wiley.
- Davi D, Kahan M, Légeron F, Marchand P, Portier B, Resplendino J, Schmitt P, Thibault C, Vivier A. 2011. SISMOA: évaluation préliminaire du risque sismique sur les ouvrages d'art existants. Service d'étude sur les transports, les routes et leurs aménagements (S.E.T.R.A.), 29.
- Demers D, Leroueil S, d'Astous J. 1999. Investigation of a landslide in Maskinongé, Québec. *Can Geotech J*. 36(6):1001–1014.
- Desjardins R. 1980. Tremblements de terre et glissements de terrain: Corrélation entre des datations au 14C et des données historiques à Shawinigan, Québec. *Géogr Phys Quat*. 34(3):359–362.
- Eden W. 1956. The Hawkesbury landslide, Canada: Division of Building Research, National Research Council of Canada.
- Farr TG, Rosen PA, Caro E, Crippen R, Duren R, Hensley S, Kobrick M, Paller M, Rodriguez E, Roth L. 2007. The shuttle radar topography mission. *Rev Geophys*. 45(2), 10.1029/2005RG000183.
- Feizizadeh B, Kienberger S. 2017. Spatially explicit sensitivity and uncertainty analysis for multicriteria-based vulnerability assessment. *J Environ Plan Manage*. 60(11), 2013–2035.
- Feizizadeh B, Roodposhti MS, Blaschke T, Aryal J. 2017. Comparing GIS-based support vector machine kernel functions for landslide susceptibility mapping. *Arab J Geosci*. 10(5):122.
- Feizizadeh B, Roodposhti MS, Jankowski P, Blaschke T. 2014. A GIS-based extended fuzzy multi-criteria evaluation for landslide susceptibility mapping. *Comput Geosci*. 73:208–221.
- FEMA. 2012. Hazus-MH: multi-hazard loss estimation methodology earthquake model. Washington (DC): Federal Emergency Management Agency, National Institute of Building Science. Technical manual.
- Filion L, Quinty F, Bégin C. 1991. A chronology of landslide activity in the valley of Rivière du Gouffre, Charlevoix, Québec. *Can J Earth Sci*. 28(2):250–256.
- Filion L. 1987. Holocene development of parabolic dunes in the central St. Lawrence Lowland, Québec. *Quatern Res*. 28(2):196–209.
- Fransham P, Gadd N. 1977. Geological and geomorphological controls of landslides in Ottawa Valley, Ontario. *Can Geotech J*. 14(4):531–539.
- Gheshlaghi HA, Feizizadeh B. 2017. An integrated approach of analytical network process and fuzzy based spatial decision making systems applied to landslide risk mapping. *J Afr Earth Sci*. 133:15–24.
- Gouin P. 2001. Tremblements de terre historiques au Québec (de 1534 à mars 1925), identifiés et interprétés à partir des textes originaux contemporains [Historical earthquakes felt in Quebec: from 1534 to March 1925, as revealed by the local contemporary literature]. In: Montréal Guérin (Ed.), French. p. 1491.
- Government of Canada NRC. 2011. Earthquakes in southeastern Canada. Ottawa, Ontario. ISBN: Paper - Eng: M4-59/4-2010E 978-1-100-12100-0. Natural Resources Canada; [accessed 2017]. http://www.earthquakescanada.nrcan.gc.ca/pprs-pprp/pubs/GF-GI/GEOFACT_earthquakes-SE-Canada_e.pdf.
- Government of Canada NRC. 2016. The 1925 Magnitude 6.2 Charlevoix-Kamouraska earthquake. Ottawa, Ontario. Natural Resources Canada; [accessed 2017]. <http://www.seismescanada.nrcan.gc.ca/historic-historique/events/19250301-en.php>.
- Grondin G, Demers D. 1996. The Saint-Liguori flakeslide: characterisation and remedial works. In: Proceedings of the 7th International Symposium on Landslides. Trondheim, Norway. 1721, 743–748.

- Karimzadeh S, Feizizadeh B, Matsuoka M. 2017. From a GIS-based hybrid site condition map to an earthquake damage assessment in Iran: methods and trends. *Int J Disaster Risk Reduct.* 22:23–36.
- Karrow P, cartographer. 1959. Surficial geology, Grondines, Champlain, Portneuf, Lotbiniere and Nicolet Counties, Quebec. [preliminary series]. Geological Survey of Canada. No 41-1959. Canada,
- Karrow P. 1972. Earthflows in the Grondines and Trois Rivières Areas, Québec. *Can J Earth Sci.* 9(5):561–573.
- Kim SH. 1993. A GIS-based regional risk analysis approach for bridges against natural hazards. Buffalo (NY): State University of New York.
- Kiremidjian A, Moore J, Fan YY, Yazlali O, Basoz N, Williams M. 2007. Seismic risk assessment of transportation network systems. *J Earthq Eng.* 11(3):371–382.
- Lajoie P. 1974. Les coulées d'argile des basses-terrasses de l'Outaouais, du Saint-Laurent et du Saguenay. *Rev Geogr Montreal.* 86(4):419–428.
- Lamontagne M. 2002. An overview of some significant eastern Canadian earthquakes and their impacts on the geological environment, buildings and the public. *Nat Hazards.* 26(1):55–68.
- Lamontagne M. 2008. Les dommages dus aux tremblements de terre dans la région de Québec entre 1608 et 2007. Ottawa, Ontario: Geological Survey of Canada. Open File 5547.
- Land Information Ontario, cartographer. 2011. , OHN - Waterbody: Ontario Ministry of Natural Resources and Forestry - Provincial Mapping Unit. File identifier: 3ebaf6b2-6dd6-4ebb-a6bb-4fc778426709., Ontario: Land Information Ontario
- LandInformation Ontario, cartographer. 2015. , Land Information Ontario. ARA Line Segment: Ministry of Natural Resources and Forestry. File identifier: 233efbfe-281b235-234ab236-949f-dc278b231d237c239cc.
- Lefebvre G, Leboeuf D, Hornych P, Tanguay L. 1992. Slope failures associated with the 1988 Saguenay earthquake, Quebec, Canada. *Can Geotech J.* 29(1):117–130.
- Lefebvre G. 1986. Slope instability and valley formation in Canadian soft clay deposits. *Can Geotech J.* 23(3):261–270.
- Lemaire A. 2013. Étude de sensibilité des paramètres pour l'évaluation de la vulnérabilité sismique des ponts en vue de la calibration de la méthode d'évaluation du Québec. Montréal: École de technologie supérieure.
- Leroueil S., Locat J. 1998. Slope movements: geotechnical characterization, risk assessment and mitigation. In: Proceedings of the 11th Danube-European conference on soil mechanics and geotechnical engineering; Poreč, Croatia, Balkema, pp. 95–106.
- Liu Z. 2001. Seismic prioritization of highway bridges in Canada. Montréal: McGill University.
- Locat J. 2008. Localisation et magnitude du séisme du 5 février 1663 (Québec) revues à l'aide des mouvements de terrain. In: Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management 2008. Québec: Presse de l'Université Laval.
- MDDELCC. Environnement et Lutte contre les changements climatiques. 2014. Système d'information hydrogéologique (SIH). Québec: MDDELCC, Ministère du Développement durable, Environnement et Lutte contre les changements climatiques; [accessed 2014]. <http://www.mddelcc.gouv.qc.ca/eau/souterraines/sih/index.htm>.
- Mitchell D, Huffman S, Tremblay R, Saatcioglu M, Palermo D, Tinawi R, Lau D. 2012. Damage to bridges due to the 27 February 2010 Chile earthquake. *Can J Civ Eng.* 39(12).
- Morin L-G. 1947. La coulée d'argile de Saint-Louis, comté de Richelieu. *Nat Can.* 74(5-6):125–143.
- MTQ. 2012. Zones de contraintes relatives aux glissements de terrain: Feuillet cartographique. la MRC Deux-Montagnes; [accessed]. <http://www.mrc2m.qc.ca/fr/documentation/documentation/#ENV>.
- MTQ. 2013a. Annexe F-3 Zones exposées aux glissements de terrain_Feuillets 1 à 6. MRC des Maskoutains; [accessed]. <http://www.mrcmaskoutains.qc.ca/territoire-cours-eau/amenagement-territoire>.
- MTQ. 2013b. Règlement 353-2013 Annexe "B". Quebec: MRC de Joliette; accessed 2017. http://www.mrcjoliette.qc.ca/upload/File/cartes_annexes.pdf.
- MTQ. 2016. Bibliothèque et Archives nationales du Québec: Gouvernement du Québec: Ministère des transports du Québec. Rapport annuel de gestion 2015-2016.
- Nastev M, Parent M, Ross M, Howlett D, Benoit N. 2016. Geospatial modelling of shear-wave velocity and fundamental site period of Quaternary marine and glacial sediments in the Ottawa and St. Lawrence Valleys, Canada. *Soil Dyn Earthq Eng.* 85:103–116.
- NYS DOT. 2002. Seismic vulnerability manual. Structure design and construction division - bridge safety assurance unit, : New York State Department.
- Parent M, Caron O, Dubé-Loubert H, Rivard J. 2018. Géologie des formations superficielles des Basses-terres centrales du Saint-Laurent et des régions adjacentes (Ottawa à Québec) [Surficial Geology of the Central St. Lawrence Lowlands and adjacent regions (Ottawa-Quebec City)]. Ottawa, Ontario: Geological Survey of Canada. Open File (In Review).
- Parent M, Occhietti S. 1988. Late Wisconsinan deglaciation and Champlain sea invasion in the St. Lawrence valley, Québec. *Géogr Phys Quat.* 42(3):215–246.
- Parent M, Occhietti S. 1999. Late Wisconsinan deglaciation and glacial lake development in the Appalachians of southeastern Québec. *Géogr Phys Quat.* 53(1):117–135.

- Pourghasemi H, Pradhan B, Gokceoglu C, Moezzi KD. 2013. A comparative assessment of prediction capabilities of Dempster-Shafer and weights-of-evidence models in landslide susceptibility mapping using GIS. *Geomat Nat Haz Risk*. 4(2):93–118.
- Quebec. Ministry Natural Resources M, cartographe. 2016. Hydrographie-polygones.
- Quinn P, Hutchinson D, Diederichs M, Rowe R. 2011. Characteristics of large landslides in sensitive clay in relation to susceptibility, hazard, and risk. *Can Geotech J*. 48(8):1212–1232.
- Quinn P, Zaleski M. 2015. Co-seismic large landslides in sensitive clay in eastern Canada, a search for an initiation threshold. Paper presented at the 68th Canadian Geotechnical Conference; Quebec City. Canadian Geotechnical Society
- Quinn P. 2009. Large landslides in sensitive clay in eastern Canada and the associated hazard and risk to linear infrastructure. Kingston, Ontario, Canada: Queen's University.
- Québec. Ministère de l'Énergie et des Ressources naturelles, cartographe. 2000. Couche hypsométrique à l'échelle de 1/20 000 – Warwick Identifiant usuel 21E13-0201.
- Robertson P. 1990. Soil classification using the cone penetration test. *Can Geotech J*. 27(1):151–158.
- Russell H, Brooks G, Cummings D. 2011. Deglacial history of the Champlain Sea basin and implications for urbanization. Geological Survey of Canada. Open File 6947. 86,
- Savard MM. 2013. Inventaire canadien des ressources en eau souterraine: Caractérisation hydrogéologique régionale et intégrée du système aquifère fracturé du sud-ouest du Québec. *Comm Géol Can Bull*. 587, 105.
- Sibson R. 1981. "A brief description of natural neighbour interpolation (Chapter 2)": in *Interpreting multivariate data*, 21-36. John Wiley. Chichester.
- Small EP. 1999. Development of a methodology for the integration of seismic risk mitigation activities in project and network level bridge management systems. New York: State University of New York at Buffalo.
- Statistics Canada, cartographe. 2016. Fichier des limites: Lacs et rivières (polygones) Identifiant: ghy_000c011a_e.
- Theilen-Willige B. 2010. Detection of local site conditions influencing earthquake shaking and secondary effects in Southwest-Haiti using remote sensing and GIS-methods. *Nat Haz Earth Syst Sci*. 10:1183–1196.
- Tinawi R, Tremblay S, Filiatrault A. 1993. Méthode rapide de classement sismique des ponts et viaducs du Québec. Canada: École Polytechnique de Montréal. Coll.«Rapport».
- USGS. 2015. Shuttle radar topography mission (SRTM) 1 Arc-Second Global. USA: USGS; [accessed]. <https://lta.cr.usgs.gov/SRTM1Arc>.
- Van Westen CJ, Castellanos E, Kuriakose SL. 2008. Spatial data for landslide susceptibility, hazard, and vulnerability assessment: an overview. *Eng Geol*. 102(3):112–131.
- Wilson M, MacKay B. 1919. Landslide adjacent to Rivière Blanche, St. Thuribe, Parish of St. Casimir, Portneuf County, PQ. Report on Mining Operations in the Province of Quebec during 1918. Quebec Bureau Min Annu Rep. 1918:152–156.
- Xu C, Xu X, Dai F, Saraf AK. 2012. Comparison of different models for susceptibility mapping of earthquake triggered landslides related with the 2008 Wenchuan earthquake in China. *Comput Geosci*. 46:317–329.
- Xu C, Xu X, Yao Q, Wang Y. 2013. GIS-based bivariate statistical modelling for earthquake-triggered landslides susceptibility mapping related to the 2008 Wenchuan earthquake, China. *Q J Eng Geol Hydrogeol*. 46(2):221–236.
- Youd TL, Perkins DM. 1978. Mapping liquefaction-induced ground failure potential. *J Geotech Eng Div*. 104(4):433–446.