



INTEGRATION OF SITE CONDITIONS INFORMATION USING GEOGRAPHIC INFORMATION SYSTEM FOR THE SEISMIC EVALUATION OF BRIDGES

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ABSTRACT

While seismic hazard is generally moderate in eastern Canada, the seismic risk in urban area is increased by the density of the population, the value and the age of the infrastructure and the relative importance of the economic activities. Among the consequences of a seismic event, damages to infrastructures, such as bridges and overpasses, may compromise the safety of users and the free movement of people and goods. According to modern seismic codes and regulations, structures designed for seismic loading should sustain moderate to severe earthquakes with minimal and repairable damages and without collapse. However, older structures build prior to the introduction of seismic requirements in codes and standards, are more vulnerable and exposed to a high seismic risk. Geotechnical and geological site conditions may result in severe damages to the structures and contribute to their seismic vulnerability. This project proposes to extract these information using geographical information system (GIS) tools at the bridge sites and integrate this information in the seismic evaluation procedures. Local soil amplification and induced effects are integrated into scoring evaluation procedures and seismic risk studies. In this paper, the amplification phenomenon will be investigated by the compilation of existing data for the Saint-Lawrence valley and ambient noise measurements on soil and bridges. The aim of this study is to develop a susceptibility scale to the amplification effect based on GIS information. The results will contribute to a better estimation of the seismic vulnerability of bridges and overpasses to prioritize mitigation as well as post-earthquake interventions.

Keywords: site effect, amplification, ambient noise, bridge, vulnerability

1. INTRODUCTION

Study of damages from past seismic events gives valuable information on the behaviour of infrastructure or bridges under seismic loads and provides a better understanding of their weaknesses. Most bridges structural deficiencies were identified following the 1995 Kobe earthquake (Chen and Duan, 2003) in Japan, and the 1994 Northridge earthquake (Mitchell et al., 1995) in USA. Lessons learned from these events led to improvements in seismic design provisions. More recently, the 2009 L'Aquila and the 2010 Haiti earthquakes revealed the necessity to better understand the propagation of seismic waves and their induced effects known to increase the probability of damages to buildings and infrastructures (Akinci et al., 2010; Hisada et al., 2005; Theilen-Willige, 2010).

While seismic hazard is generally moderate in Eastern Canada, local site effects are known to increase the seismic risk (Cassidy et al., 2010; Lamontagne, 2002; Lamontagne et al., 2003). In the last ten years, three seismic events with magnitude 5 or more were felt in the Lowlands of the Saint-Lawrence Valley in the province of Quebec (Government of Canada, 2015), leading to landslides such as in Val-des-Bois (2010) or dike damages in south of Bowman. Furthermore, damages to chimneys and houses were related to local soil amplification. The 1988 Saguenay earthquake ($M_w=5.9$) caused damages up to a distance of 340 km, most of which related to site

amplification effect (Paultre et al., 1993). This is partly due to the presence of marine clay deposits (Parent and Rivard, 2015), a sediment known to be very sensitive to local amplification.

Knowledge on seismic hazard, site effects and infrastructures structural vulnerabilities is key to developing more effective mitigation measures and improving emergency planning to face seismic risk. This risk increased drastically over the last century due to massive urbanisation. The province of Quebec counts nearly 9600 bridges and overpasses, of which 5300 are part of the provincial network and 4300 are part of the municipal network (MTQ, 2014). Out of this total number, 70% of bridge structures were built between 1960 and 1980 (MTQ, 2014), when seismic design provisions were not as stringent as today. The challenge in managing such a large number of structures is to maintain the operability and to limit severe damages after an earthquake. To achieve this goal, bridges are usually classified using a seismic vulnerability index that considers their structural deficiencies. A recent study on scoring procedures to assess the seismic vulnerability of bridges (Lemaire, 2013) revealed that when confronted to the lack of data on site conditions, managers often choose the most conservative hypothesis, leading to an overestimation of the seismic risk for a large number of bridges. Although the best evaluation of site effects is obtained from site specific geological and geotechnical characterisation and measurements, it is also possible to define a susceptibility to site effects from geological, geomorphological or hydrological information. The aim of this study is to use Geographic Information System (GIS) to extract geological information for the evaluation of the susceptibility to amplification for the specific region of the Lowlands of the Saint-Lawrence Valley in the province of Quebec. The proposed susceptibility scale is calibrated to site specific measurements. Geographic information system softwares are powerful tools for modeling large scale phenomenon such as earthquake impact (FEMA, 2003; Theilen-Willige, 2010). Moreover, such tools allow visualisation of a large variety of information such as geological phenomenon combined to structural data specific to bridges. This paper presents a methodology to produce susceptibility map for amplification. The susceptibility maps are used with scoring seismic evaluation procedures to evaluate the seismic risk for bridges located within the Lowlands of the Saint-Lawrence Valley in the province of Quebec.

2. AMPLIFICATION

2.1 Quantification of the amplification effect

There are three main phenomena responsible for the amplification. The most current one appears when an unconsolidated layer is overlaying a more consolidated one. The phenomenon is triggered by the impedance contrast between the shallow soft layer, and the more rigid layer, such as bedrock. Seismic waves are trapped in the soft layer and are amplified by the resonance phenomenon (Finn and Wightman, 2003; Ghofrani and Atkinson, 2014). The impedance contrast κ , at the origin of this case of amplification, can be calculated by Eq. 1 (Finn and Wightman, 2003):

$$[1] \quad \kappa = \frac{(\rho_1 \times V_{s1})}{(\rho_2 \times V_{s2})}$$

where ρ_1 and V_{s1} are, respectively, the density and the shear wave velocity of the soft layer and ρ_2 and V_{s2} , are the density and shear wave velocity of the rigid layer, respectively. The amplification (A) is then given by Eq. 2:

$$[2] \quad A = \frac{1}{\left(\kappa + \beta \cdot \frac{\pi}{2} \right)}$$

where β is the damping ratio.

The lower the shear wave velocity of the soft layer, the higher the amplification. The shear wave velocity (V_s) of a shallow layer of thickness h can be related to the resonance frequency (f_0) of the maximum amplitude using Eq. 3. It is therefore possible to estimate the local amplification from the measurement of the fundamental resonance frequency.

$$[3] \quad f_0 = \frac{V_s}{4 \times h}$$

The second case of amplification, also called topographical site effect, is happening on cliff edges (Hartzell et al., 2014). The last case is produced by surface waves resulting from the impedance contrast between two layers at the surface, in a valley.

In most building codes, amplification is usually considered through amplification factors associated to different seismic site classes defined from the mean shear-wave velocity to 30 m, V_{s30} (m/s) (Finn and Wightman, 2003; NRCC, 2015). The mean shear-wave velocity V_{s30} is given by:

$$[4] \quad V_{s30} = \frac{30}{\sum_{i=1}^n (h_i / V_i)}$$

In Eq. 4, h_i and V_i are respectively, the thickness and the shear wave velocity of the different layers on the top 30 meters of a 1D soil column.

The National Building Code of Canada (NRCC, 2015) defines six seismic site classes (A to F). The first five (A to E), from hard rock to soft soil, could be assigned from direct measurement of shear wave velocities by reflection or refraction techniques, or in boreholes and in-situ measurements methods, such as the energy corrected average standard penetration resistance tests values (N), or piezocone point resistance (q_c), both related to the soil rigidity and to V_s , or from soil average undrained shear strength (s_u) (Hunter et al., 2012). It can also be investigated by indirect techniques such as measurement of the resonance frequency using ambient vibration technique and horizontal to vertical spectral ratio (HVSr). The sixth class (F), attributed to other soils (i.e.: liquefiable soils, peat and organic clays, etc.), requires a site-specific evaluation.

2.2 Microzonation

While building codes usually require that the seismic site class, and related amplification factors, be determined from specific geotechnical properties measured at the site, seismic risk studies or seismic vulnerability evaluation of buildings and infrastructures often rely on microzonation information. Seismic microzonation is the process of subdividing a seismic prone area into zones with respect to amplification characteristics defined from code's seismic site classes, or by amplification factors. The attribution of the seismic site class or amplification factor to each zone is usually carried out by geostatistical data interpolation techniques between points of measurements of the mean shear-wave velocity to 30 m (NRCC, 2015) or the resonance frequency (Ghofrani and Atkinson, 2014). These can be obtained from a combination of the techniques presented in the previous section. In the province of Quebec, such regional microzonation maps are only available for Montreal (Chouinard and Rosset, 2012), Quebec City (Leboeuf et al., 2013) and Gatineau-Ottawa (Motazedian et al., 2011).

On a larger scale, some researchers have proposed to use statistical relation between V_s and thickness to bedrock for the microzonation. They first create a 3D geological model, by compiling all the data available for the area, and then produce a microzonation map and a resonance frequency map based on all the data collected (Nastev M. et al., 2015). In the absence of specific data on site effect or regional microzonation, the most widespread approach to include seismic amplification effect in seismic risk studies or scoring procedures to assess the seismic vulnerability of bridges, is to consider a default seismic site class D (FEMA, 2003). This process triggers an overestimation of the seismic risk associated to the bridge and can induce a disqualification of the evaluation.

The next sections present the methodology used to develop the susceptibility index from geological information available through GIS and that could be used with seismic vulnerability scoring procedures for bridges in the absence of site specific amplification information.

3. DEFINITION OF SUSCEPTIBILITY TO AMPLIFICATION USING GIS INFORMATION

The methodology to define a susceptibility index to amplification effect includes two main steps: (1) Analysis of the relation between quaternary deposits, thickness of quaternary deposits and probable seismic site class from a statistical analysis, and (2) Validation of the proposed relations from measurement of the resonance frequency at bridges sites. The resulting relation between quaternary deposits, their thickness and the probable seismic site class is converted into a susceptibility index. GIS tool is then used to extract deposits and depth of bedrock information and assign susceptibility index to produce a susceptibility to amplification map for the Lowlands of the Saint-Lawrence valley.

3.1 Analysis of quaternary deposits and seismic site classes

The first step is to evaluate the relation between quaternary deposits present in the region of study (Parent and Rivard, 2015), thickness of quaternary deposits (NRCAN et al., 2004), and seismic site classes available for the following cities: Montreal, Québec and Ottawa-Gatineau. The purpose is to estimate the probability of belonging to a seismic site class based on thickness of quaternary deposit and surficial geology (Ghofrani and Atkinson, 2014). Two spatial information files (shapefile) of the surficial geology gives points every 500 m (Figure 1), and the thickness of quaternary deposit giving polygons with an approximate resolution of 275 m, while the three microzonation maps give seismic site class zonation information in both formats. The total number of surficial data used for this study is 118 672 points.

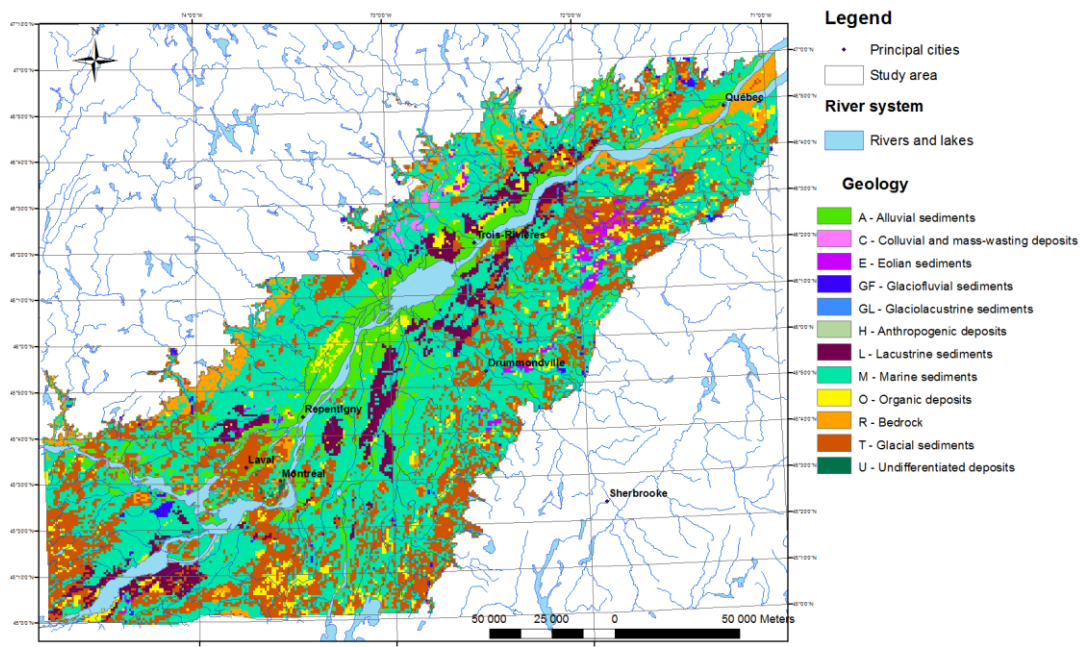


Figure 1: Surficial geological map of Lowlands of Saint-Lawrence Valley, (Produced from data taken from (Parent and Rivard, 2015))

During the last 1 800 000 years, glaciers follow each other on the continent and mould the landscape with rivers and valleys. Consequently, predominant quaternary deposits are composed of glacial and post-glacial unconsolidated deposits from 18 000 to 6 000 yr B.P. In the Province of Quebec, and particularly in the Lowlands of the Saint-Lawrence valley, sediments are mostly till, clays and sands. The most outcropping sediments are clays from the Champlain Sea (marine deposits). Till are also among the most common, when other sediments have been eroded. Alluvial is the third common surficial deposits.

To analyse the recurrence of surficial deposits as a function of depth of bedrock, within the Lowlands of Saint-Lawrence River, the thickness deposits were subdivided in five depths from 0 to 5 m, 5 to 10 m, 10 to 20 m, 20 to 30 m and 30 m and up. The results, presented in Table 1, give distribution of the different surficial deposits as a

function of the thickness of the quaternary deposits in the region of study. These results emphasize the predominance of marine and till surficial deposits.

Table 1: Recovering percentage of surficial deposits in the region of study in function of their thickness

Surficial deposits	0 to 5 [m]	5 to 10 [m]	10 to 20 [m]	20 to 30 [m]	>30 [m]
A-Alluvial	1.19%	1.40%	2.43%	2.24%	4.17%
C-Colluvial	0.04%	0.03%	0.06%	0.12%	0.24%
E-Eolian	0.16%	0.48%	0.39%	0.11%	0.02%
Gf-Glaciofluvial	0.17%	0.13%	0.16%	0.04%	0.13%
Gl-Glaciolacustrine	0.01%	0.02%	0.01%	0.01%	0.02%
H-Anthropogenic	0.02%	0.04%	0.06%	0.01%	0.00%
L-Lacustrine	0.24%	0.59%	1.47%	1.76%	1.70%
M-Marine	7.39%	10.52%	16.20%	7.81%	4.70%
O-Organic	0.94%	1.50%	1.49%	0.46%	0.64%
T-Till	8.03%	7.75%	6.45%	1.23%	0.35%
U-Undifferentiated	0.02%	0.04%	0.02%	0.01%	0.00%

To obtain relation between quaternary deposits, their thickness and the probable seismic site class, geological and microzonation information was extracted at 11674 points for Montreal, Québec and Ottawa-Gatineau. Table 2 presents the results for marine surficial deposits as a function of thickness of quaternary deposit. Similar tables were produced for alluvial, colluvial, glaciofluvial, anthropogenic, organic, till and undifferentiated deposits. No or few outcrop of eolian, glaciolacustrine or lacustrine deposits was identified in the three cities, and no relation with probable seismic site class could be defined for these surficial deposits. This lack of information will be counterbalanced by ambient noise measurements as will be shown in the next section.

As expected, the thicker the quaternary deposits the higher is the probability of the site to be in seismic site class D or E, associated to higher amplification. In general, for thin layer of all surficial deposits (less than 5 m), the seismic class A or B are predominant. For marine deposits (Table 2) there is almost a sixty percent probability to be in class A or B when the thickness of layer ranges between 0 and 5 m; about 25 % to be in soil class C, and nearly 10% to be in D. On the other hand, there is 81% of probability to be in seismic class E, with the highest amplification, if quaternary deposits are thicker than 30 m, and the nature of surficial geology is marine deposits.

Table 2: Percentage area of marine deposits belonging to each seismic class in function of thickness of quaternary deposit

Site class	0 to 5 [m]	5 to 10 [m]	10 to 20 [m]	20 to 30 [m]	>30 [m]
A or B	59.53%	37.87%	24.25%	4.42%	1.27%
C	25.97%	36.98%	33.15%	18.58%	2.96%
D	10.80%	19.59%	33.74%	38.69%	14.38%
E	3.70%	5.57%	8.86%	38.31%	81.40%

3.2 Ambient noise measurements

Horizontal to vertical spectral ratio (HVSr) of ambient noise measurements is a technique developed in Japan and spread by Nakamura (1989). The method using a microtremor three-component sensor (Tromino®, 2011), allows identifying resonance frequency of soil (Ghofrani and Atkinson, 2014) or structures such as bridges (Stabile et al., 2013). Fifty single measurements were taken at sites selected according to their geological settings. Bridges were selected on the secondary road network to avoid important perturbations due to heavy traffic. Treatment of the 20 minutes recording involves dividing signal in windows of 20 seconds, detrended and tapered with Bartlett window.

The signal is then fast Fourier transformed and the amplitude spectrum obtained is smoothed by triangular window. The Nakamura technique consists in dividing the two horizontal components by the vertical component of the signal. Geometric average is computed using Eq. 5.

$$[5] \quad \frac{\sqrt{H_{NS} \times H_{EW}}}{V}$$

In Eq. 5, H_{NS} and H_{EW} are the smoothed spectra, in terms of amplitude, of the horizontal components and V is the smoothed spectrum of the vertical component. The final HVSR is the average amplitude of the calculated values for each window as function of frequency. The point of maximum amplitude ratio is identified as the resonance frequency of the site (SESAME, 2004).

The fifty sites were selected from the characteristics of the surficial geology and thickness of the sediment. Three conditions were defined: First, as mentioned previously, some geological deposits of the Lowlands (Figure 1 and Table 1) are not identified in any of the three cities for which an analysis of the probable seismic site class was achieved. Therefore, to complete the relation between surficial deposits and probable seismic site class, 14 sites of lacustrine deposits or eolian sediments were selected. Second, some geological deposits are more common than others, such as marine sediments (Table 1). Furthermore the marine deposits are particularly more sensitive to amplification. Then, 14 sites on marine outcrop were selected. Third, other selected sites had geological characteristics corresponding to the case where probabilities are not strictly defining one seismic site class, such as for marine deposits between five to ten meters of thickness in Table 2

A total of 96 ambient noise measurements were carried out on fifty different sites. One measurement on soil and one on bridge were taken at each site, except for four bridges that could not be reached. Data from each site were recorded, extracted and analysed as described in the previous paragraphs. Twenty-seven sites show site resonance frequency close to bridge resonance frequency. Interaction between soil and structures is maximal at resonance frequency (Finn and Wightman, 2003; Ghotbi, 2014). This means that amplification effect will be the highest at this frequency. Figure 2 shows a perfect case of resonance between soil and bridge at 1.25 Hz. This site is characterized by marine deposits with a thickness of 17 meters.

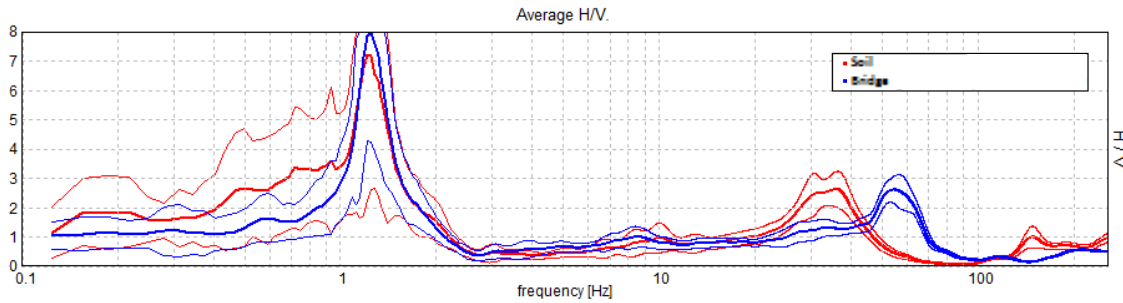


Figure 2: HVSR for a bridge on marine deposits in Saint-Elisabeth (Soil in red; Bridge in blue).

HVSR results are then combined with the thickness of quaternary deposits to obtain shear wave velocities (Eq. 3). Average of first 30th meters shear wave velocity and seismic class can be determined by Eq. 4 considering bedrock velocity as 1500 m/s (Adams and Halchuk, 2003). On the fifty different sites, fourteen measurements are investigating marine deposits. The distribution of these sites between the seismic site classes is presented in Table 3. These results for sites with thickness deposits between 0 and 10 m correspond partially to the percentage calculated in Table 2 for marine deposit, the highest proportion of sites being in A, B or C seismic site classes. For sites with thickness between 10 to 20 m, the HVSR data give more amplification than previous statistics, with three sites on soil C and one site on soil E.

Table 3: Number of measurements in seismic site classes calculated from resonance frequencies measured on marine deposit sites

Soil class	0 to 5 [m]	5 to 10 [m]	10 to 20 [m]	20 to 30 [m]	>30 [m]
A and B	1	2	-	-	-
C	2	2	3	-	-
D	-	-	-	3	-
E	-	-	1	-	-

Similar distributions were computed for the remaining sites depending on their surficial geology. The probabilities of belonging to a seismic site class calculated in the first step, were adjusted to consider the results obtained from the resonance frequencies. The final probabilities of belonging to a seismic class depending on thickness of quaternary deposit and surficial geology established for the different surficial geology stated in Table 1, were used to define a susceptibility index to amplification effect.

4. SUSCEPTIBILITY INDEX AND APPLICATION

A susceptibility to amplification index (I_{SA}), varying from 0.5 to 1.0 is attributed to a site depending on the probability of belonging to a given seismic site class in function of geological characteristics. For example, for a site with probabilities clearly identifying one dominant seismic class (greater than 60%), a value of 0.5, 0.6, 0.8 or 1.0 is assigned as indicated in Table 4. When probabilities are not strictly defining one seismic site class, an intermediate index is attributed (Table 4). This amplification susceptibility index should therefore be used only as a relative index rather than an absolute value defined by building codes.

Figure 3 illustrates how Geographic information systems (GIS) allow combining surficial deposits with thickness of quaternary deposit to produce a susceptibility map for amplification. A spatial information file (shapefile) of the surficial geology with points every 500 m is used to extract thickness of quaternary deposits from another shapefile. A new field is then created to provide the susceptibility to amplification index (I_{SA}) owing to the selection by attribute. This latter field is at the end converted to a raster file (Figure 3).

Table 4: Description of susceptibility index for amplification in function of seismic site classes

Soil class	Index (I_{sa})
A and B	0.5
	0.55
C	0.6
	0.7
D	0.8
	0.9
E	1

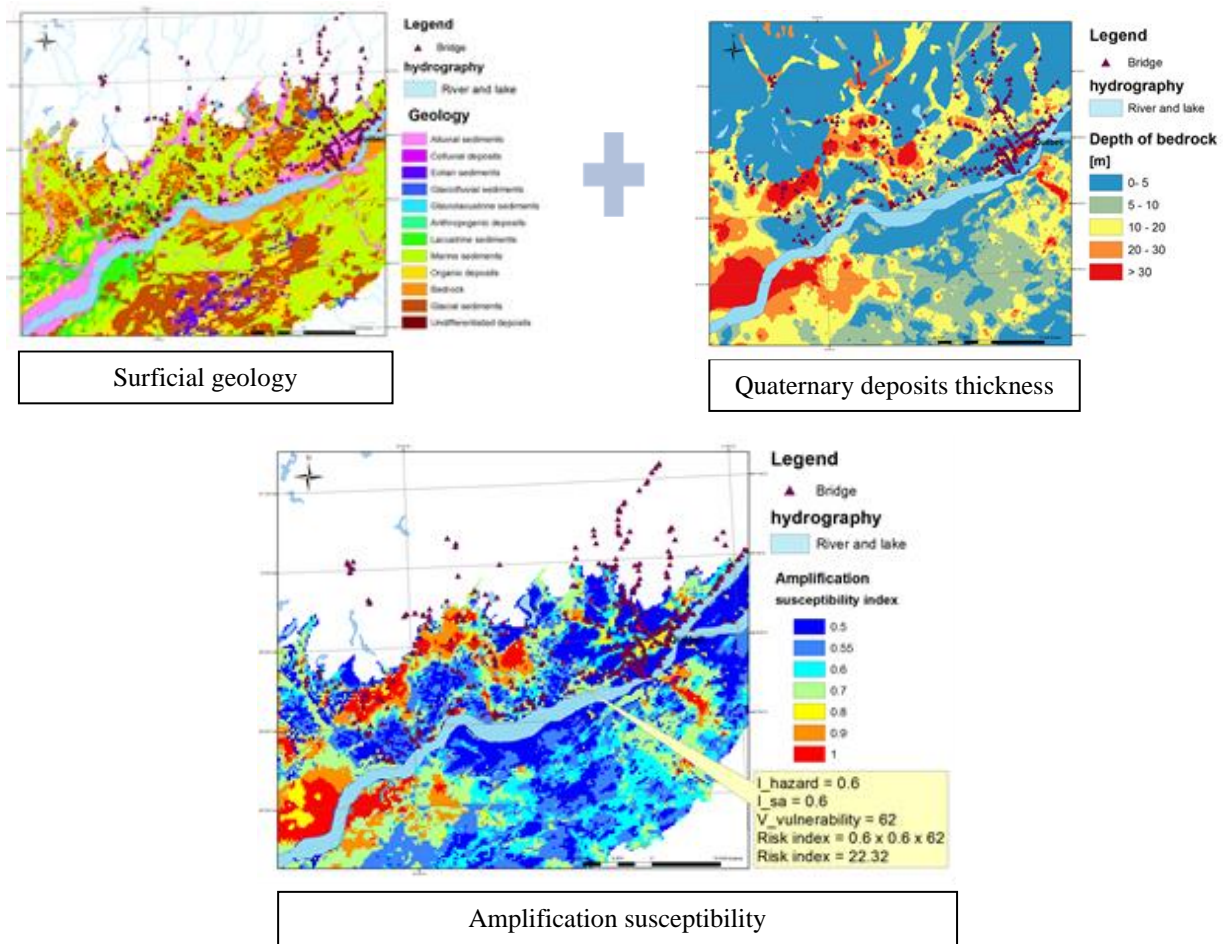


Figure 3: Collecting process to provide seismic risk index for bridges on a GIS platform

In the perspective of using the proposed map to evaluate the potential seismic risk for bridges, this new index, I_{sa} , is used in a typical evaluation of a risk index by combining the hazard index I_{hazard} (established from seismic hazard data) and a structural vulnerability index for bridges $V_{\text{vulnerability}}$, defined from the bridge structural information, as shown in Eq. 6 (Lemaire, 2013). Figure 3 shows how GIS tool can help collecting information on geology and structures to provide a seismic risk index in order to evaluate and manage the seismic risk to bridges for the Lowlands of the Saint-Lawrence Valley in the province of Quebec

$$[6] \quad \text{Risk index} = (I_{\text{hazard}} \times I_{sa}) \times V_{\text{vulnerability}}$$

5. CONCLUSIONS

GIS is a powerful tool to identify geological characteristics at a site. It is here used to extract and combine geological and seismic microzonation information to define a susceptibility index to amplification effect for seismic vulnerability and seismic risk studies. The susceptibility index was defined by analysing the relation between quaternary deposits, thickness of quaternary deposits and probable seismic site class for three cities: Quebec, Montreal, and Ottawa. Results were validated by ambient noise measurements on 50 sites. The susceptibility index to amplification effect is assigned to a site by superposition of geospatial information on the surficial deposit and its thickness using the probabilities to belong to a seismic site class previously established. This index can then be integrated within scoring procedure to obtain the seismic risk index of bridge.

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