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Earthquake mitigation in the Greater Montreal, from the soil behavior to structural damage

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Abstract: Performing seismic hazard analysis for a major urban area requires a significant effort for characterizing seismic hazards, estimating site effects, obtain a data base on the built environment, assessing vulnerability functions and perform analyses for a range of credible scenarios. The various steps of this process are described in the case of a seismic hazard analysis performed for the Greater Montreal area.

1 Earthquake risk around the metropolitan area of Montreal

The Greater Montreal is the second largest metropolitan area in Canada with more than 3.8 millions inhabitants where Montreal is the cultural and economic center. The most severe historical earthquake reported resulted in damage to 300 houses in 1732 with an estimated magnitude 5.8 (Leblanc, 1981). Several other strongly felt events of smaller magnitude having epicenters located close to the island were felt in more recent years (Figure 1). Fifty years of recorded historical seismicity outlines two major seismogenic zones: one along an NE-SW axis following the St Lawrence River passive margin, and the second along a more active SE-NW axis (Adams, 2011). Deaggregation of the seismic hazard at a 2% of exceedance in 50 years shows that earthquakes of magnitude 6 at a distance of 30km are the main contributors to hazards (Adams and Halchuk, 2003). The median PGA and PGV are 0.43g and 0.18m/s, respectively, for this return time in Montreal (Adams and Atkinson, 2003).

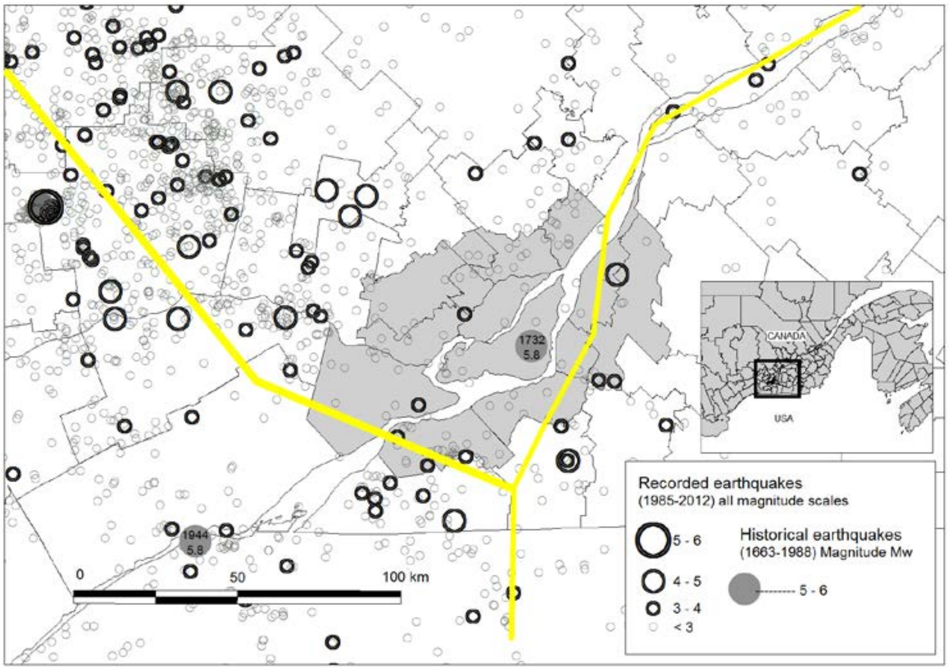

Figure 1: Felt historical and recorded earthquakes around the Great Montreal for the period 1663-2012. Magnitude of the historical earthquake is deduced from reported intensity. Yellow lines delineate the main seismogenic sources and municipalities of Great Montreal are highlighted in grey.

The Montreal region is underlain by limestone and shale from the Cambrian – Ordovician period. The bedrock is overlaid by deposits from a series of glacial episodes during the Wisconsinan period when glaciers retreated and surged forward several times, resulting in the deposition of several different types of glacial tills. After the final retreat of the ice, around 12500 years ago, the Champlain Sea formed and covered the region for 6000 years, and provided the environment for the deposition of the Leda clay. The last period is characterized by erosion and deposition of sand by the Saint-Lawrence River. The map of the Figure 2 locates the different deposits. The clay deposits are most significant in the North-East of the islands of Montreal and Laval where they can reach 20-40m.

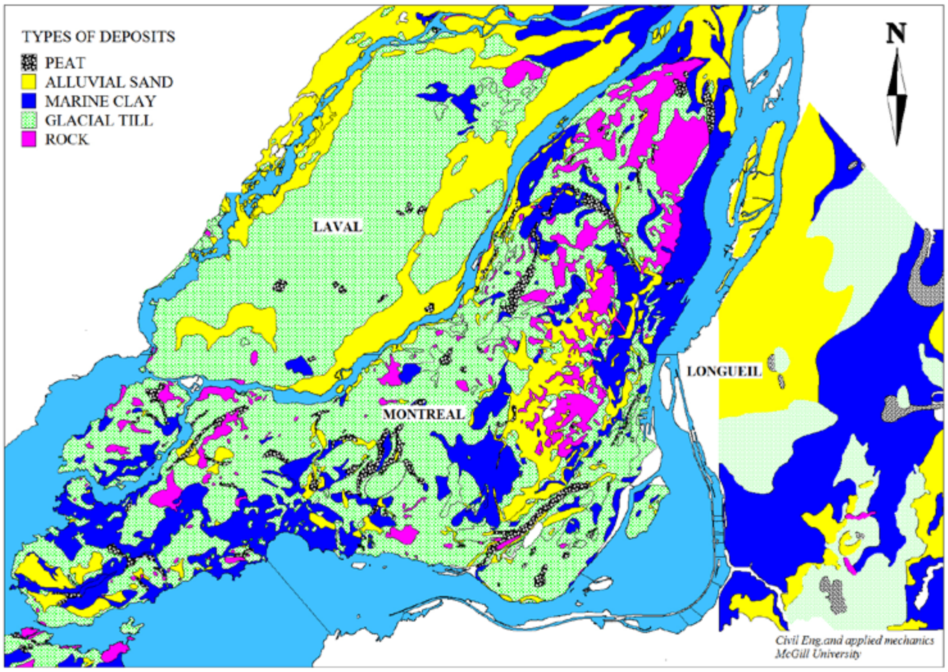

Figure 2: Geology of the Great Montreal (adapted from Prest and Hode-Keyser 1977).

The 25th November 1988 Mw5.9 earthquake hit severely the Saguenay region, 350km NE of Montreal. Despite the large epicenter distance, severe damage was observed to the masonry cladding of the former Montreal East City Hall which is attributed to the combined effect of soil amplification due to the presence of a 17m layer of Leda clay and the advanced state of deterioration of the facade (Chouinard and Rosset, 2011; Mitchell et al., 1990).

The seismic context coupled with the population at risk ranks Montreal second in Canada after Vancouver for seismic risks in an analysis done by Adams et al. (2002) which did not explicitly consider the influence of soil amplification as well as the level of vulnerability of buildings.

2 Influence of soil conditions on ground motion

The amplification of ground motions as exemplified by the damage to the Montreal-East City Hall in 1988 is a well-known phenomenon which amplifies ground motion at a frequency range that depends on the thickness of the deposits. Over the last decade, several field measurement campaigns were performed in the Greater Montreal area to investigate soil conditions and their effect on seismic ground motions particularly relative to frequency content and amplification. In addition, investigated sites were classified using V_{S30} (average shear wave velocity V_s over the first 30m of soil) as specified by the National Building Code of Canada (NBCC2010).

A first site characterization is based on the analysis of ambient noise records with the H/V method for more than 2300 sites and 1D shear wave modeling using a database of 26600 boreholes (Rosset and Chouinard, 2009; Chouinard and Rosset, 2007). This data base was complemented with several invasive and non-invasive seismic surveys to estimate the shear wave velocity (Vs) profile at targeted sites in Montreal, Longueil and Laval. These consist of: 1) MASW (Multichannel Analyses of Surface Waves) measurements at 12 sites, 2) downhole seismic measurements on 2 boreholes, and 3) high resolution multichannel seismic reflection records using a land streamer over 3 segments for a total distance of 7.5 km. Vs profiles for the different soil deposits have been proposed (Rosset et al., 2013) as well as a relationship between V_{s30} and f_0 (Chouinard and Rosset, 2011 and 2012). Talukder et al. (2013) improved those relations by performing forward modeling on H/V spectra on a set of 150 well-documented sites. The map of the Figure 3 locates the sites investigated with the various methods.

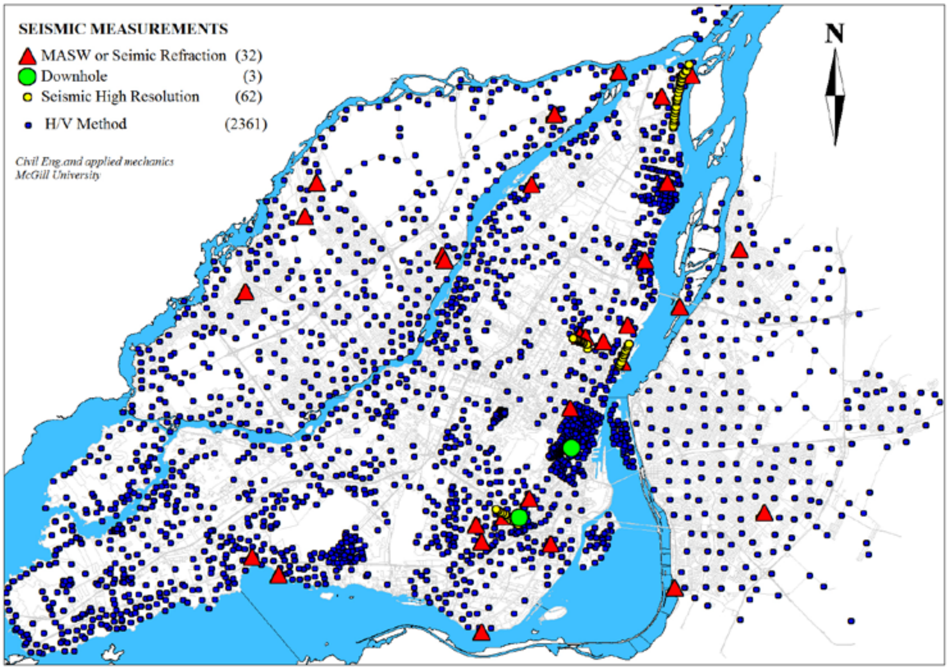

Figure 3: Sites Investigated using invasive and non-invasive seismic measurements methods.

For 1D horizontally layered structures, the H/V peak frequency was shown to provide a good estimate of the fundamental resonance frequency F_0 of a site (Bard 1999; Nakamura 2000; Chouinard and Rosset, 2012). Figure 4 summarizes the period of resonance T_0=1/f_0 derived from H/V site measurements. Such a map is useful in identifying potential zones of strong soil-structure interactions for buildings or infrastructures with predominant periods of vibration that match the site response.

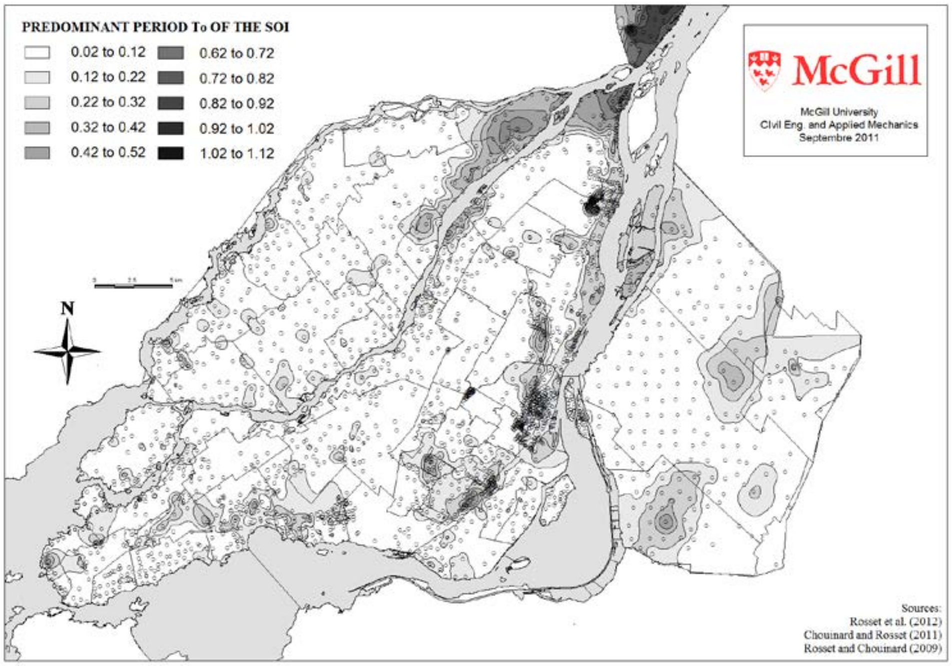

Figure 4: Fundamental period of resonance T_0 in the Greater Montreal using H/V method.

The fundamental period T_0 and Vs_{30} estimated from seismic data were compared for 86 sites where both measurements were available. A weighted linear regression was used to derive a relationship between the two parameters and to develop the V_{s30} map of Figure 5. Estimates obtained at sites of H/V measurements are interpolated following a natural neighborhood method and then classified into one of the 6 soil categories of the NBCC2010. The short-period (T = 0.2 s) and long-period (T = 1.0 s) amplification factors Fa and Fv, respectively, for different levels of peak ground accelerations are applied to the spectral accelerations $S_{0.2}$ and $S_{1.0}$, respectively (Finn and Wigthman, 2003).

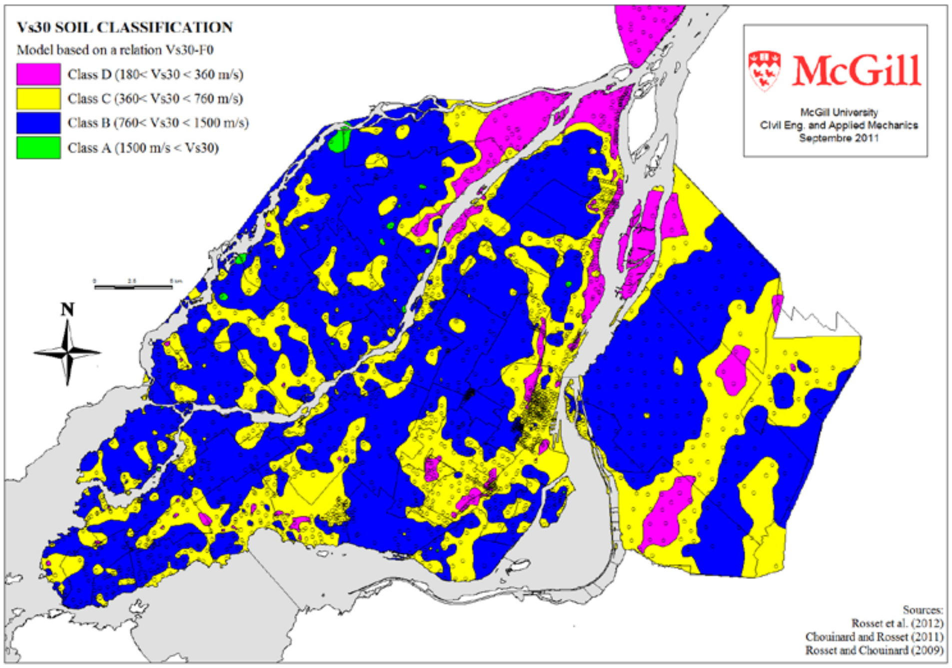

Figure 5: V_{s30} soil classification in the Greater Montreal derived from f_0 obtained with the H/V method.

For a given site, the combination of field measurements and 1D modeling is used to estimate the amplification factor and resonance frequency and to calculate a reference response spectra. Figure 6 illustrates the procedure for a site with a 6m thick clay layer. An average transfer function is calculated using a 1D model and validated with the H/V method. This function is then applied to reference synthetic accelerograms on rock for Eastern Canada to derive a spectra at the surface of the site. The latter is then used to validate or update design response spectra.

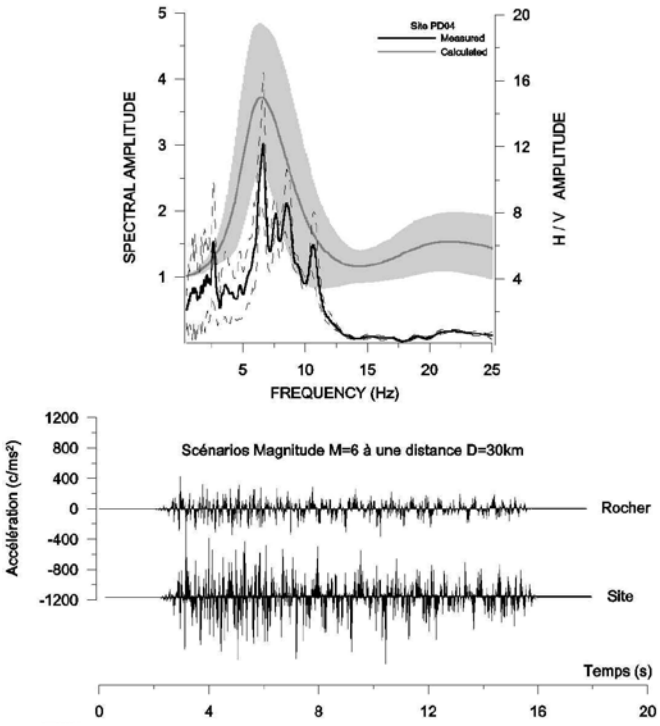

Figure 6: Example of site effect estimates. The influence of the soil profile (6m of clay underlying till) is calculated on two synthetic input seismic records using both instrumental and modeling approaches.

3 Structural response and risk analysis

The seismic reliability of a structure can be evaluated by combining seismic hazards at the location of the structure and the fragility function of the structure. Fragility curves represent the state-of-the-art in seismic risk assessment (SRA) and are defined as the conditional probability that a structure will meet or exceed a certain level of damage for a given ground motion intensity.

The fragility analysis includes the following major steps:

1. The probabilistic representation of the structure considering the uncertainty in its properties;
2. The selection of appropriate ground motions representing the effects of local site conditions and seismic inputs;
3. A 3-dimensional nonlinear analysis of the response of the structure; and
4. The estimation of fragility curves from the response of the bridge model under the seismic loads considered.

To select a set of ground motion records from an available database, one can match and compare the spectral acceleration of each ground motion with the target spectral acceleration. The target spectrum can be based on the analysis described above or alternatively based on other procedures that also account for local site conditions. An example is the use of the Uniform Hazard Spectrum or of the Conditional Mean Spectrum. All the ground motion records of the available database can be scaled to match for example, the first period of the structure (Sa(T1)). Figure 7 exemplifies the process for the site of a typical bridge in Montreal (Mahmoudi and Chouinard 2012).

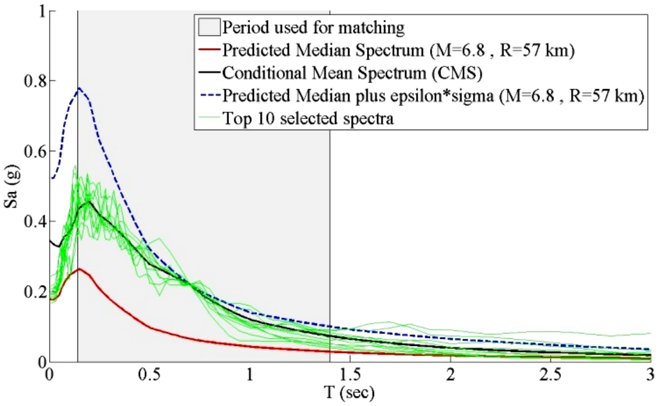

Figure 7 CMS and Sa of the top ten selected ground motion records

The variability in seismic inputs is a significant source of uncertainty in the seismic evaluation of structures. The IDA technique addresses the record-to-record variability by using a set of scaled input ground motions to evaluate the response of a structure. By performing non-linear dynamic analysis under several scaling factors, for each ground motion record, the relationship of the Intensity Measure (IM) and the Engineering Demand Parameter (EDP) is obtained. The selection of the proper ground motion records, EDP and IM for the structure should be done carefully since they can all affect the results.

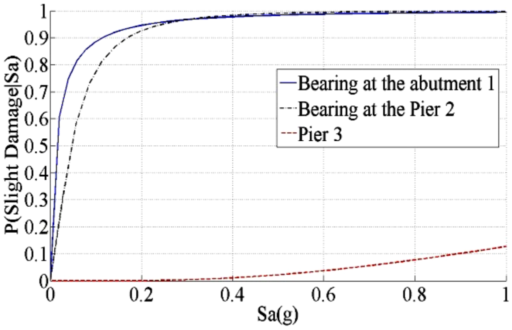

Figure 8 Component fragility curves.

This process is time-consuming and is done for targeted structures. Alternatively, the procedure can be applied to the built environment at the urban scale with software such as HAZUS (Yu et al. 2013). The microzonation is then used to modify ground motion parameters and fragility functions for classes of buildings are used. Uncertainty in ground motion can be accounted for by selecting various earthquake scenarios and attenuation functions while earthquake variability is implicit in the fragility function.

4 Conclusions

Earthquake risk analysis can be performed for single targeted structures or for an entire urban area. This article describes the various steps and studies that have performed over a period of several years for the Montreal area starting from site characterization to detailed non-linear analyses of targeted structures. The results of these analyses can be used to mitigation seismic risks by retrofitting targeted structures or by using scenario earthquakes for performing risk analyses and evaluate potential deficiencies in the infrastructure system and to evaluate the intervention capacity of emergency response services.

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