Co-seismic large landslides in sensitive clay in eastern Canada, a search for an initiation threshold

GEOQuébec 2015
Challenges from North to South
Des défis du Nord au Sud

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ABSTRACT
This paper examines the search for a peak horizontal ground acceleration (PGA) threshold for triggering co-seismic landslides in sensitive clay in eastern Canada, with the aim of supporting regional risk assessment using HAZUS. Literature sources document a number of small co-seismic landslides associated with small or moderate earthquakes which produced a PGA between about 0.04 g and 0.15 g at the landslide locations. Two papers describe 46 large, co-seismic, sensitive-clay landslides with measured dates. Many of these are associated with the 1663 Charlevoix M7 earthquake, from which site-specific firm ground PGA can be estimated; these range from about 0.03 g to 0.18 g; the remaining landslides are associated with paleo-earthquakes. A clear PGA threshold for triggering large landslides in sensitive clay cannot be inferred from these available data. Earthquake magnitude and distance appear to provide a somewhat better threshold for co-seismic sensitive clay landslides in the study area.

RÉSUMÉ
Cet article examine la recherche d'un seuil d'accélération horizontale au sol critique (PGA) pour déclencher des glissements de terrain co-sismiques dans les argiles sensibles de l'Est du Canada, dans le but de supporter une analyse régionale de risque utilisant le modèle HAZUS. La littérature documente un certain nombre de petits glissements de terrain co-sismiques associés à des tremblements de terre faibles ou modérés, qui ont produit un PGA entre 0,04 g et 0,15 g aux sites des glissements de terrain. Deux articles décrivent 46 grands glissements de terrain co-sismiques datés dans les argiles sensibles. Beaucoup d'entre eux sont associés au tremblement de terre de 1663 de Charlevoix (Magnitude de 7), à partir duquel le PGA au sol spécifique au site peut être estimé: ceux-ci vont d'environ 0,03 g à 0,18 g. Les glissements de terrain restants sont associés à des paléoséismes. Un seuil de PGA clair pour déclencher de grands glissements de terrain dans l'argile sensible ne peut être déduit à partir des données disponibles. Les relations entre la distance et la magnitude semblent donner de meilleurs seuils pour ces glissements dans cette région.

1 INTRODUCTION

This paper began as a search for a peak ground acceleration (PGA) triggering threshold for co-seismic large landslides in sensitive clay in eastern Canada. The intent was to develop thresholds for use in regional-scale landslide hazard and risk modelling in the Hazards United States (HAZUS) natural hazard loss estimation software package (FEMA, 1995). A review of historic co-seismic landslides revealed no strong correlation between PGA and landslide triggering. This forced the work down different paths, such as exploring relationships between co-seismic landslides and earthquake magnitude (M) and distance (R). This exploration revealed some interesting results: landslides in sensitive clay may be triggered by M-R pairs outside thresholds established in the literature for other landslide types. This may have important implications for risk associated with co-seismic landslides in eastern Canada.

Large landslides in sensitive clay are relatively common in the Saint Lawrence Lowlands of eastern Canada. Damaging landslides occur every few years in eastern Ontario or southern Quebec. Notable landslides include Saint-Jean-Vianney in 1971 and Notre-Dame-de-la-Salette in 1908, each causing more than 30 fatalities. Geomorphic evidence of older and much larger landslide craters includes an approximately 1000-year old landslide complex in Quyon, Quebec interpreted by others as earthquake triggered, and large craters of landslides triggered by the 1663 Charlevoix earthquake at Saint-Jean-Vianney and Shawinigan, Quebec. Craters are in close proximity to urban areas at the latter site. Aylsworth and Lawrence (2003) suggested a moment magnitude (M_w) threshold of ~5.9-6.0 for initiating large landslides in sensitive clay. This paper attempts to extend that prior work by considering first PGA and then M-R thresholds for large landslide triggering. We suggest that an M-R threshold may eventually be combined with landslide susceptibility models to better understand risk associated with large co-seismic landslides.

This paper presents a brief overview of seismic hazard in eastern Ontario and southern Quebec, including the potential for ground motion amplification and co-seismic landslides in the study area. Literature sources document small landslides triggered by small or moderate earthquakes and associate PGA values between about 0.04 g and 0.15 g with them. Brooks (2013) and Locat (2011) collectively describe 46 dated large landslides or other ground movements associated with probable earthquake triggers. We consider the possible PGA felt at the landslide sites and M-R of initiating earthquakes in an attempt to derive a first order estimate for the seismic-load threshold for initiating future large co-seismic landslides. The results may be used with landslide susceptibility maps to examine co-seismic landslide hazard, and may thus be considered for use in regional scale co-seismic landslide risk assessment.

2 SEISMIC HAZARD IN THE SAINT LAWRENCE LOWLANDS

Natural Resources Canada (NRCan, 2014) provides seismic hazard data for the 2010 National Building Code of Canada (NBCC). These include median, firm ground (Site Class C), 5% damped horizontal spectral accelerations at periods of 0.2, 0.5, 1, and 2 seconds ($S_a(0.2)$, $S_a(0.5)$, $S_a(1.0)$, and $S_a(2.0)$, respectively) and PGA for return periods of 100, 475, 1000, and 2475 years. Median, 475-year (i.e. 10 % probability of exceedence in 50 years) and 2475-year (i.e. 2 % in 50 years) PGA (PGA_{475} and PGA_{2475}) for reference (firm ground) conditions are illustrated in Figure 1 and Figure 2.

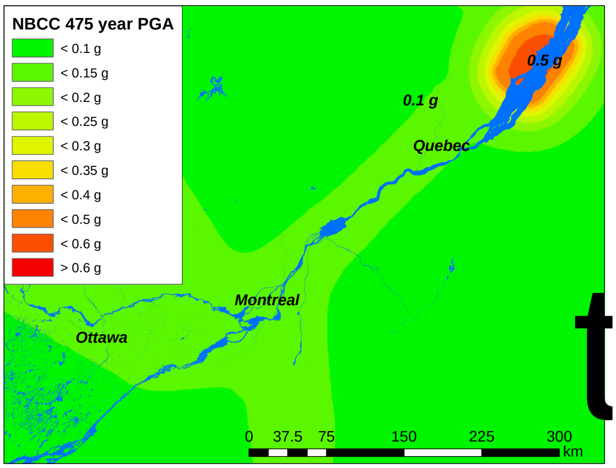

Figure 1. NBCC 10 % in 50 years (475 year) PGA for uniform firm ground (Site Class C)

Ground motion amplitudes experienced at a given site may be larger or smaller than those predicted for firm ground conditions if softer or stiffer soil or rock underlies a site. The amount of amplification or de-amplification depends on: the thickness, shear modulus, and geometry of soil or rock deposits; site topography; reference ground motion amplitudes; and the ground-motion parameter of interest. NBCC 2010 (NRCan 2014) defines five site classes on the basis of the time-averaged shear wave velocity in the top 30 m of a site (V_{s30}): these range from hard rock (Site Class A; V_{s30} > 1500 m/s) to soft soils (Site Class E; V_{s30} < 180 m/s). A sixth class (F) is reserved for especially soft soils. Finn and Wightman (2003) provide amplification factors for use with NBCC accelerations: these relate site response to the site class and the amplitude and period of ground motions for reference conditions (i.e. firm ground: class C, V_{s30} = 360 m/s to 760 m/s).

Figure 3 shows site classes for part of the study area inferred by Nastev et al. (2014). Amplification factors from Finn and Wightman (2003) have been applied to modify the NBCC firm ground PGA values and yield site class-modified PGA values, $(PGA)_{sc\text{-}mod}$. These are shown in Figure 4 for $(PGA_{475})_{sc\text{-}mod}$ and in Figure 5 for $(PGA_{2475})_{sc\text{-}mod}$. In the area east of Ottawa, thick soft sediments (Site Class E) amplify the 475 year PGA from about 0.12 g to 0.26 g, and the 2475 year PGA from about 0.32 g to 0.41 g. Conversely, site class-modified 475- and 2475-year PGA in areas with shallow rock (e.g. the Canadian Shield in Quebec north of Ottawa) are lower than the reference accelerations.

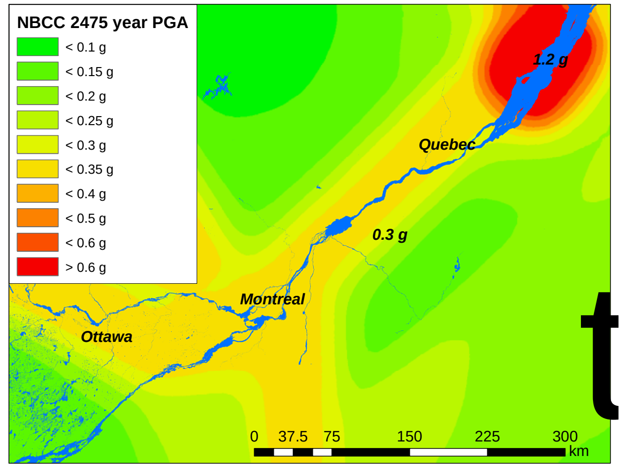

Figure 2. NBCC 2 % in 50 years (2475 year) PGA for uniform firm ground (Site Class C)

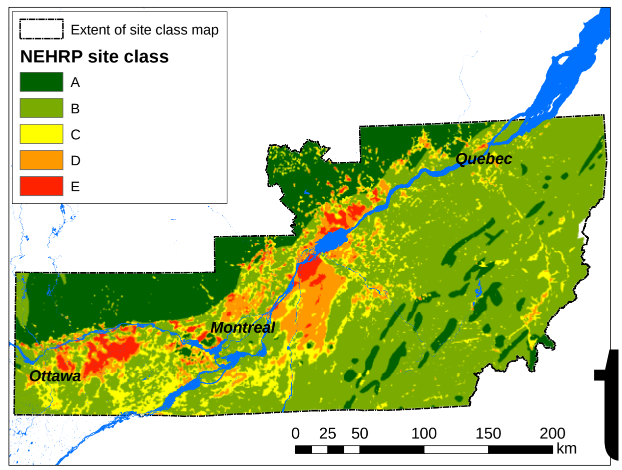

Figure 3. Site Class for the western half of the study area inferred from 3D Geological Model (Nastev et al. 2014)

HAZUS (FEMA, 1995) includes a module for estimating risk due to earthquake shaking. NRCan is currently adapting HAZUS for use in Canada and developing an earthquake model for the study area (Nastev 2014). In contrast with the median, Site Class C hazard values used by the 2010 NBCC (NRCan 2014), HAZUS uses mean hazard values at the class B/C boundary (V_{s30} = 760 m/s) for $S_a(0.3)$, $S_a(1.0)$), PGA, and peak ground velocity (PGV) (Halchuk 2011). Because mean hazard amplitudes are typically larger than median, PGA values used in HAZUS are higher than those for NBCC at equivalent hazard levels. We use median PGA from the 2010 NBCC (PGA_{2475} for reference conditions and $(PGA_{2475})_{sc\text{-}mod}$ for site class modified conditions) for our analysis and illustrations in this study. HAZUS PGA, although typically higher than NBCC PGA, shows the same general trends in amplitude distribution across the study area.

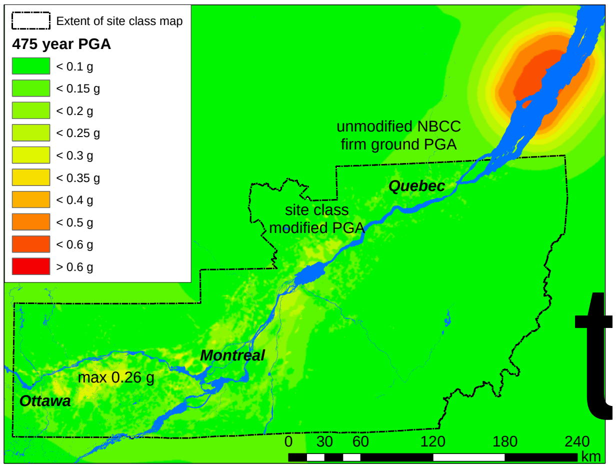

Figure 4. Site Class-modified 475 year PGA

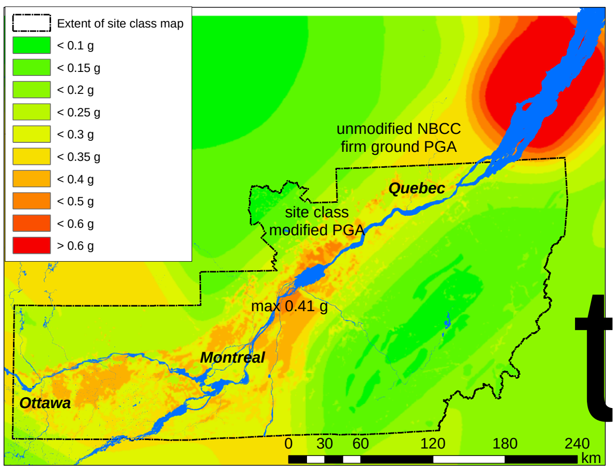

Figure 5. Site Class-modified 2475 year PGA

3 CO-SEISMIC LANDSLIDES

3.1 Background

The Saint Lawrence Lowlands in eastern Canada contain substantial deposits of glaciomarine soils laid down in the late-glacial Champlain Sea some 10,000 years ago. These deposits are composed of silts and clays that, in places, are sensitive: they lose much of their strength when disturbed. A distinct type of geological hazard – large earth flows or spreads in glaciomarine sensitive clay – is present throughout this area. These landslides tend to occur rapidly and can affect large areas of gently sloped terrain. Large landslides in sensitive clay can threaten existing buildings, may disrupt transportation corridors or other linear infrastructure, and have occasionally caused fatalities

Natural landslides in sensitive clay may be divided broadly into two categories: larger landslides that evolve as flows or spreads (i.e. typically > 0.5 ha); and smaller, local, rotational or translational slides. Most sensitive clay landslides in eastern Canada are small rotational or translational failures along existing river banks or other natural slopes (e.g. Demers et al. 1999). Examples of earth flows and spreads are documented by Bjerrum (1955), Tavenas et al. (1971), and Evans and Brooks (1994). Extremely large earth flows and spreads (i.e. typically > 100 ha) have occurred in pre-historic times in the Ottawa area (Aylsworth and Lawrence 2003) and at Saint-Jean-Vianney (Tavenas et al. 1971). Other landslide processes, including rock falls and rock slides, also occur in the study area. However, the most damaging landslides have been large earth flows or earth spreads in sensitive glaciomarine clay. In this paper, large landslides have a minimum length or width of about 100 m, or minimum area of about 0.5 ha.

About 20 % of large landslides in eastern Canada are triggered by human activity, and most others are generally considered to be triggered by river erosion (Lebuis and Rissmann 1983). The largest known landslides, however (e.g. Aylsworth and Lawrence 2003, Brooks 2013; Desjardins 1980, Eden 1967, Hodgson 1927, Leggett and LaSalle 1978), may have been triggered by earthquakes. Earthquake-triggered large landslides in sensitive clay might represent the extreme landslide events in the study area.

Keefer (1984) provides an overview of the distribution and characteristics of co-seismic landslides, including relationships between earthquake magnitude and maximum epicentral distance for three different broad landslide categories: disrupted slides or falls; coherent slides; and lateral spreads or flows. Rapid earth flows and lateral spreads are the dominant failure modes in large landslides in eastern Canada sensitive clay.

Co-seismic landslides in sensitive clay in eastern Canada have been documented by a number of authors. Lefebvre and Leboeuf (1992) and Jacob (1989) describe landslides triggered by the M5.9 Saguenay earthquake of 1988. Documented landslides ranged in epicentral distance from 50 to 175 km, and occurred with local PGA estimated by Lefebvre and Leboeuf (1992) to have ranged between 0.04 g and 0.15 g. All of these landslides were small or moderate local failures; no large earth flows or spreads resulted from this event. Aylsworth and Lawrence (2003) discuss recorded landslides associated with several historic earthquakes, including: the M5.9 Saguenay earthquake of 1988, discussed previously; the M6.3 Temiskaming earthquake of 1935, which produced subaqueous slumps; and the M5.8 Cornwall-Massena earthquake of 1944 and M5.3 western Quebec earthquake of 1914, neither of which produced recorded landslides. They propose a threshold of about M5.9-6.0, below which only minor local landslides are expected, and above which large landslides in sensitive clay may be triggered.

HAZUS relates earthquake-generated PGA to yield acceleration at each site to determine whether a landslide is likely to occur. Earthquake magnitude is used by HAZUS to estimate displacement but not directly in assessing triggering. Thus, the magnitude thresholds described above cannot be applied directly in HAZUS. Furthermore, available seismic hazard data provide probabilistic values of PGA and spectral accelerations, but return periods for specific magnitudes are not available. Thus, a PGA criterion for landslide triggering is desired, to aid in co-seismic landslide hazard and risk assessment.

3.2 Inferring a triggering threshold for co-seismic landslides

The literature provides no clear basis for selecting yield accelerations for large landslides in sensitive clay. An available regional scale landslide susceptibility map (Quinn et al. 2010, Quinn 2013) provides an indication of the expected future spatial distribution of large landslides in the study area without specific reference to the magnitude or type of triggers, whether anthropogenic, related to drainage (i.e. groundwater fluctuations or bank erosion), or seismic. The following paragraphs attempt to develop a link between seismic load and large landslide occurrence in the study area.

Brooks (2013) compiled radiocarbon dates for 38 large landslides and three areas of ground disturbance in the Ottawa-Gatineau area. Many of the occurrence dates are clustered around 1000, 4500 and 7000 years before present (YBP), implying that multiple landslides may have had a common trigger. An earthquake trigger was proposed by Brooks (2013) for the 1000 YBP cluster and by Aylsworth and Lawrence (2003) for the other two clusters. These dated landslides are shown in Figure 6, superimposed over the PGA_{2475} values for the NBCC reference site class. There is no obvious spatial correlation between landslide occurrence and PGA_{2475}. There is a stronger spatial association (i.e. more landslides are present where amplified PGA is higher) when these same landslide locations are plotted in Figure 7 over the $(PGA_{2475})_{sc\text{-}mod}$ values from Figure 5.

Thirty dated ground movement sites (Brooks 2013) fall within the site class map area (Nastev et al. 2014) and can be assigned $(PGA_{2475})_{sc\text{-}mod}$ values (Figure 7). The remaining features are outside the site class map area. Table 1 presents decile distributions for $(PGA_{2475})_{sc\text{-}mod}$ associated with these thirty features and associated with site class map area (Nastev et al. 2014). Approximately 90% of the map has $(PGA_{2475})_{sc\text{-}mod} < 0.34$ g, and yet only 20% of the dated features occurred at locations with $(PGA_{2475})_{sc\text{-}mod} \leq 0.34$ g. Therefore, approximately 80% of identified and dated large co-seismic landslides in sensitive clay described by Brooks (2013) were isolated within 10% of the map where $(PGA_{2475})_{sc\text{-}mod} > 0.34$ g. The lowest $(PGA_{2475})_{sc\text{-}mod}$ value associated with a landslide was 0.25 g. Five other landslides occurred with $(PGA_{2475})_{sc\text{-}mod}$ between 0.27 g and 0.32 g. The remaining 24 landslides occurred with $(PGA_{2475})_{sc\text{-}mod}$ between 0.35 g and 0.40 g. It should be noted that the actual PGA felt at each site at the time of the landslide is unknown, and these comparisons provide simply an indication of the PGA hazard associated with these landslide locations.

The return period of these large landslide episodes is probably about 2500 to 3500 years. As a first estimate, the PGA associated with the mapped landslides could be *of a similar order* to the mapped $(PGA_{2475})_{sc\text{-}mod}$ values.

Locat (2011) compiled information about 21 large landslides associated with the 1663 M7 Charlevoix earthquake. Figure 8 illustrates their locations in relation to the earthquake's inferred epicenter and NBCC PGA_{2475} values. Locat (2011) used their spatial distribution to infer probable lower and upper magnitude bounds of about M7.2 and M7.8, respectively, for the earthquake. It may be noted that this earthquake is generally considered to be M7.0 (e.g. Macias-Carrasco et al. 2009).

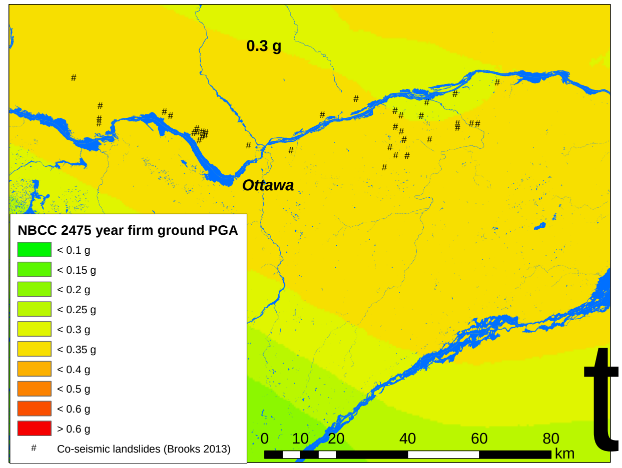

Figure 6. Ottawa area dated large landslides (from Brooks, 2013) and firm ground 2475-yr PGA.

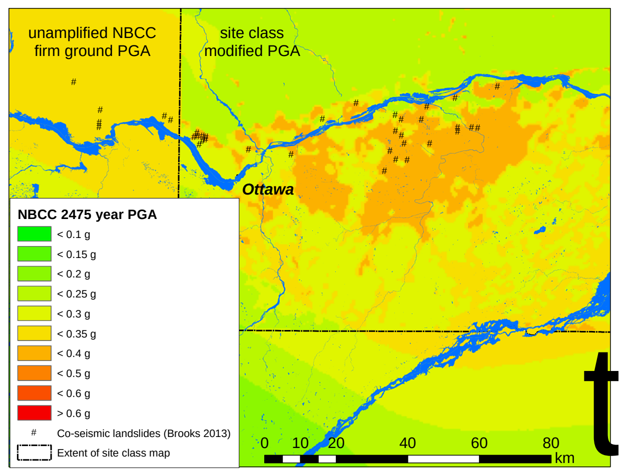

Figure 7. Ottawa area dated large landslides and amplified 2475 year PGA

Ground motions at specific distances from the earthquake can be estimated from published ground-motion prediction equations (GMPEs). We used the GMPE for eastern North America by Atkinson and Boore (2006) to estimate firm ground (site class B/C boundary) and site class E PGA values at each landslide site caused by the 1663 M7 earthquake. Because the earthquake's causative fault is not known, we used epicentral distances as approximations for the fault distances required by the GMPE. Table 2 presents estimated Site Class B/C and Site Class E PGA values at each landslide location.

The inferred firm ground PGA values range up to 0.19 g for the nearest landslide sites. Several values are much lower, with 0.02 g inferred at Shawinigan, 0.03 g inferred at Colombier, and 0.04 g inferred at many other sites. These values are derived for firm ground, and actual PGA felt at the site was likely higher, due to the presence of thick sediments involved in the landslide. PGA values estimated for site class E from the GMPE of Atkinson and Boore (2006) range up to 0.21 g. These site class E PGA values may be taken as an estimate of likely upper bound PGA associated with landslide triggering. The lowest values, at Shawinigan, would be estimated as 0.04 g and 0.09 g for Site Class B/C or E, respectively, assuming the earthquake was M7.8 rather than M7, as postulated by Locat (2011).

Table 1. Site Specific (site class-modified) 2475-year PGA for large co-seismic landslides in the Ottawa area

Percentile rank (%)	Amplified PGA at large dated landslides (g)	Amplified PGA: whole affected map area (g)
100%	0.39	0.41
90%	0.39	0.34
80%	0.38	0.29
70%	0.38	0.27
60%	0.37	0.24
50%	0.37	0.22
40%	0.36	0.18
30%	0.35	0.15
20%	0.34	0.13
10%	0.28	0.11

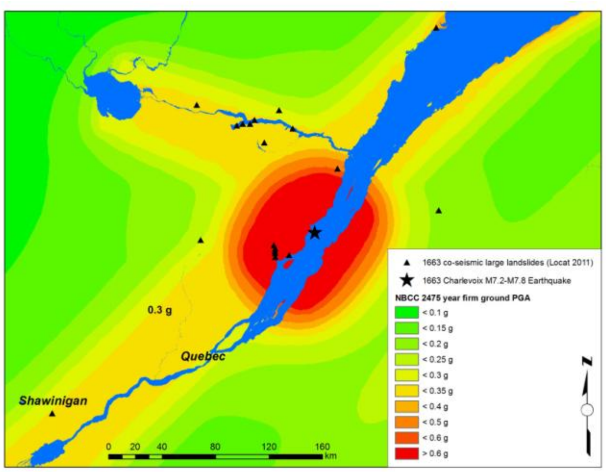

Figure 8. Large Co-Seismic Landslides Associated with 1663 Charlevoix Earthquake (from Locat 2011)

As discussed previously, PGA values between about 0.04 g and 0.15 g have been associated with small co-seismic landslides in eastern Canada by Lefebvre and Leboeuf (1992). The range of PGA values believed to have been experienced at large co-seismic sensitive clay landslides associated with the 1663 Charlevoix M7 (or possibly up to M7.8) earthquake is very similar. We therefore conclude that the two different classes of landslide in sensitive clay – large flows or spreads, and small rotational or translational slides – cannot be separated reliably on the basis of a PGA threshold. We further conclude that no clear lower PGA limit exists for sensitive clay landslide triggering in eastern Canada.

An alternate form of co-seismic landslide threshold has been presented by Keefer (1984), who compiled data on different types of landslide process, plotted the data according to magnitude and distance, and interpreted upper envelopes or threshold curves. The Keefer curves are redrawn in Figure 9 for "disrupted falls," "coherent slides'" and "spreads and flows." In the case histories studied by Keefer, all landslides of those types were associated with earthquakes plotting left of the curves in Figure 9.

Table 2. Large co-seismic landslides associated with the 1663 Charlevoix earthquake, summarized by Locat (2011)

Name	**Type**	**Epi-central distance (km)**	**Estimated PGA[1] (g)**
Riviere du Gouffre D1	Flow slide	35	0.12 / 0.18
Riviere du Gouffre D2	Flow slide	34	0.12 / 0.18
Riviere du Gouffre C	Flow slide	33	0.13 / 0.19
Riviere du Gouffre B	Flow slide	32	0.14 / 0.19
Riviere du Gouffre A	Flow slide	32	0.14 / 0.19
Shawinigan LB	Spread	240	0.02 / 0.05
Shawinigan SB	Spread	240	0.02 / 0.05
Saint-Joseph-de-la Rive	Spread	26	0.18 / 0.21
Mont Éboulé	Spread	95	0.04 / 0.10
Saint-Jean-Vianney	Spread	130	0.04 / .009
Colombier	Spread	178	0.03 / 0.07
Bassin Central C8	Flow slide	94	0.04 / 0.10
Bassin Central C11	Flow slide	95	0.04 / 0.10
Baie des Ha! Ha!	Spread	99	0.04 / 0.10
Point du Fort	Spread	97	0.04 / 0.10
Lac Jacques-Cartier	Undetermined	86	0.04 / 0.10
Temiscouata	Undetermined	94	0.04 / 0.10
Lac du Basque	Undetermined	51	0.07 / 0.15
Lac Eternite	Undetermined	77	0.04 / 0.10
Lac Tadoussac	Undetermined	78	0.04 / 0.10
Bassin Central	Turbidity Slide	79	0.04 / 0.10

Note: 1. From the GMPE by Atkinson and Boore (2006) for the class B/C boundary of $(V_s)_{30}$ = 760 m/s, followed by site class E, 180 m/s.

The magnitude and epicentral distances for four earthquakes that triggered landslides are plotted in Figure 9 from Locat (2011) and Lamontagne et al. (2005). The 1663 M7 earthquake triggered two very large flows or spreads in sensitive clay at Shawinigan (238 km), as well as other very large flows or spreads at 178 km distance (Colombier) and 130 km distance (Saint-Jean-Vianney). The 1988 M5.8 and 2010 M5 triggered small earth slides as far as 175 km and 21 km, respectively. The fourth earthquake – the 1870 M6.6 – is taken from Lamontagne et al. (2005). The landslide was a large earth flow in sensitive clay at 171 km distance, but Lamontagne et al. (2005) suggested that it may have been triggered by something other than the nearly coincident earthquake. It is included here for illustration, as we consider it possible that the M6.6 earthquake either triggered the landslide directly or contributed to weakening the ground and preparing it for failure following some additional trigger, such as heavy rains or bank erosion.

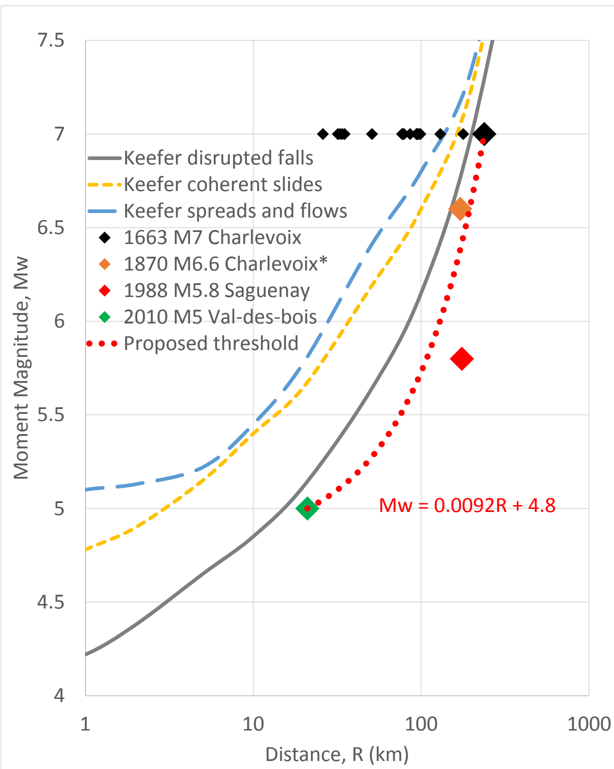

Figure 9. Large earth flows in eastern Canada occurring beyond the Keefer (1984) co-seismic landslide curves. The red point represents small local landslides.

The M-R points shown in Figure 9 represent the eastern Canadian landslides observed at greatest distance from the triggering earthquakes, plus a number of other landslides associated with the 1663 M7 event. It is notable that the most distant landslides fall outside the landslide thresholds of Keefer (1984). A tentative new threshold for earthquake triggering of landslides in sensitive clay is also proposed in Figure 9. A simple linear fit between the 1663 and 2010 M-R pairs yields a curve roughly parallel to the Keefer curves. Alternate forms of curve could be considered but are not justifiable given the sparse data currently available. Note that the suggested relationship from the best fit linear relationship implies a triggering cut off of M4.8 at R = 0 km. Note that there are only data in the range of M5 to M7. This may be relatively unimportant in the study area, where the 1663 M7 Charlevoix earthquake may represent a near-upper bound for plausible earthquakes in the region. It is suggested that the proposed threshold be used only as a general guide until supported by additional data.

The relative utility of the proposed threshold can be examined qualitatively by considering historic seismicity in the region. Macias-Carrasco et al. (2009) describe a database of recorded earthquakes affecting Canada to 2008. Earthquakes felt in eastern Canada are plotted over the full period of record (1534 to 2008 for eastern Canada) in Figure 10. It is evident in this plot that earthquake records become more plentiful with time, presumably with expansion of human habitation into previously undeveloped areas and with installation of recording systems.

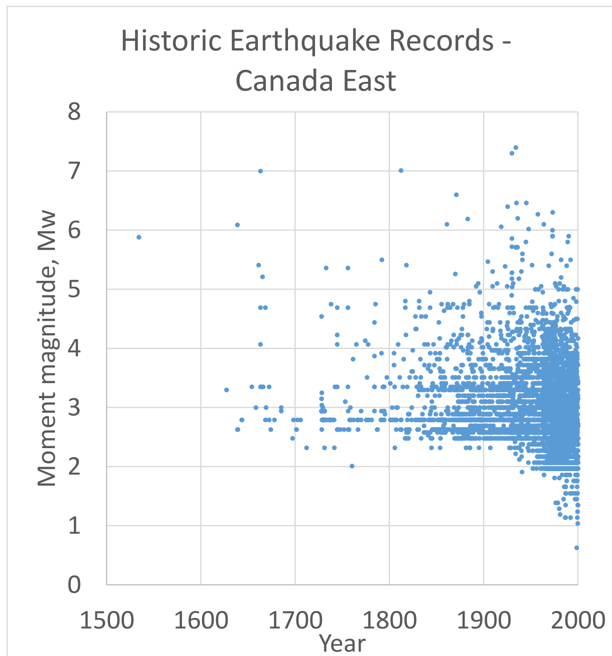

Figure 10. Temporal distribution of recorded earthquakes having affected eastern Canada.

Figure 11 shows the expected range of influence of historic earthquakes, using the proposed landslide threshold from Figure 9. A review of this map suggests that earthquake initiation of landslides in eastern Canada has likely been more frequent along the lower Saint Lawrence and Saguenay Fjord, and also clustered around Ottawa and Montreal. The probabilistic seismic hazard assessment (PSHA) produced by NRCan (2014) for use in the National Building Code of Canada may provide additional information from the deaggregation of the hazard at specific locations of interest within the study area.

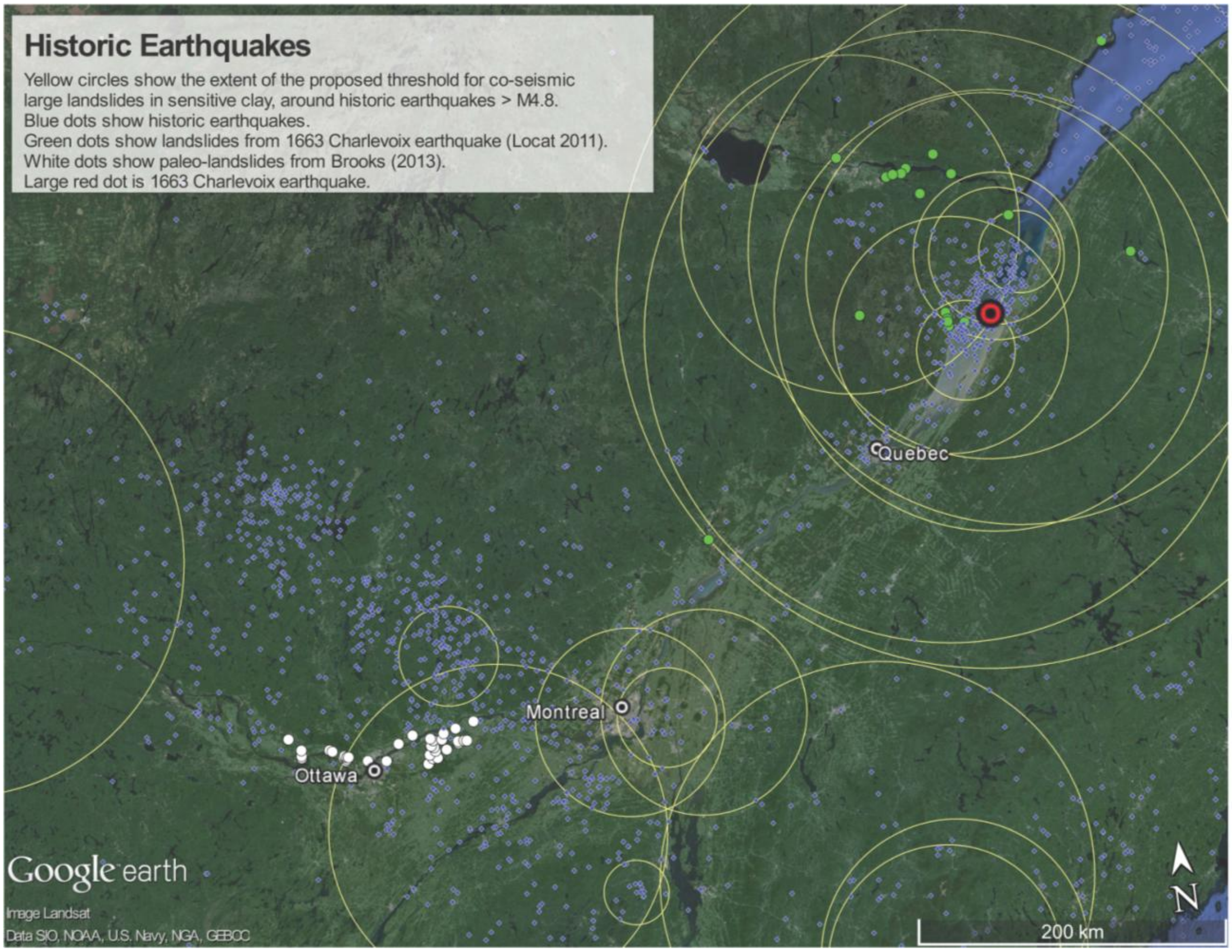

Figure 11. Historic earthquakes affecting eastern Canada and inferred range of historic landslide triggering influence, with selected sets of co-seismic landslides.

4 DISCUSSION

The work described in this paper was initiated with the purpose of identifying a PGA threshold for seismic triggering of large landslides in sensitive clay in eastern Canada. The results from that effort do not appear to be reliable, as landslides in eastern Canada have been triggered with PGA possibly as low as 0.02 g, and there is no clear distinction in PGA trigger for large landslides in sensitive clay, when compared to other types of earthquake triggered landslides.

Examination of landslide occurrence with earthquake magnitude and distance yielded a tentative landslide initiation threshold; however, the threshold is considerably more conservative than those proposed by Keefer (1984), and it may be difficult to implement within a HAZUS framework.

The very large spreads or flows triggered by the 1663 Charlevoix M7 earthquake at Shawinigan occurred at greater than twice the maximum distance expected from the “spreads and flows” threshold of Keefer (1984). Similarly, smaller slides triggered by the 1988 Saguenay M5.8 and the 2010 Val-des-bois M5 occurred at up to three times the maximum distance expected from the “coherent slides” threshold of Keefer (1984). These are notable occurrences, and suggest a different factor, or factors, in these landslides in comparison with the Keefer (1984) datasets.

Four possible reasons for more distant landslide initiation are proposed: unusually small triggering force required; potential amplification of ground motion due to thick soft soils; errors in interpretation of fault distance; and, relatively low attenuation of ground motions. The first two reasons may apply to the large flows or spreads in sensitive clay. Quinn et al. (2013) propose a progressive failure model for these landslides, and suggest that natural clay slopes may degrade through progressive failure to the point of incipient failure, requiring little or no obvious triggering energy. The GMPE of Atkinson and Boore (2006) depends on fault distance, which is not known for the discussed earthquakes and co-seismic landslides. The fault distance may be much lower than epicentral distance for large earthquakes with movement along a long fault trace. Thick soft soils are often present in the study area, and are typically associated with large earth flows and spreads. The distribution of thick soft soils may be seen for part of the study area in the site class zonation map in Figure 3.

Neither of these two factors definitively explains the occurrence of smaller slides, some of which have occurred in rock, although small earth slides may also be assigned similar rationale. The occurrence of these smaller slides beyond the Keefer (1984) limits could be explained by lower attenuation of ground motions with distance from source, compared with the Keefer (1984) data sets. Ground motions attenuate less rapidly with distance in eastern Canada than in western Canada, and this may be particularly true in the Cambrian and Pre-Cambrian Grenville Province rocks north of the Saint Lawrence. The distribution of landslides associated with the 1663 Charlevoix earthquake, shown in Figure 8 and Figure 11, supports this idea. Only one landslide from that event is shown south of the Saint Lawrence, and many distant landslides are shown north of the Saint Lawrence, including all of the most distant ones.

Applying the proposed landslide threshold in HAZUS may be difficult, since that system works with PGA as its primary input for seismic hazard, and since M-R inputs are not immediately available through the NRCan (2014) PSHA. It may be possible to generate a new spatial interpretation of M-R hazard contributions for the study area from deaggregation of the PSHA, and it should be possible to reprogram the HAZUS seismic components to accept M-R as inputs.

ACKNOWLEDGEMENTS

The writers would like to express appreciation to the Geological Survey of Canada for use of in-progress data and interpretations in support of this work, and for funding parts of the work. BGC Engineering Inc. provided financial support for the work. Roy Mayfield of BGC Engineering Inc. provided very thorough and constructive review comments.

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