Risk to Linear Infrastructure Associated with Large Landslides in Sensitive Clay

Pete Quinn
BGC Engineering Inc., Ottawa, Ontario, Canada
D. Jean Hutchinson[1], Mark S. Diederichs[1], R. Kerry Rowe[1], Tim Keegan[2]
[1]GeoEngineering Centre at Queen's-RMC, Kingston, Ontario, Canada
[2]BGC Engineering Inc., Edmonton, Alberta, Canada

ABSTRACT
The bulk of the population of eastern Ontario and Quebec resides in the Saint Lawrence Lowlands, within a narrow corridor along the Saint Lawrence and Ottawa Rivers. Marine soils deposited in this area during the retreat of the Wisconsin ice sheet are susceptible to large retrogressive landslides. This geological hazard tends to occur suddenly, without any obvious warning signs, often involving many hectares of gentle terrain. Numerous primary transportation and communication corridors pass through this region, and are thus potentially affected by this hazard. This paper presents a method for assessing the aggregate risk to a system of linear infrastructure, and proposes a systematic approach for identifying higher risk locations, and then assessing these in a phased approach with progressively increasing level of detail.

RÉSUMÉ
La majeure partie de la population de l'Est de l'Ontario et du Québec réside dans les basses terres du Saint-Laurent, dans un étroit couloir le long du Saint-Laurent et la rivière des Outaouais. Marine sols déposés dans ce domaine au cours du recul de la calotte glaciaire du Wisconsin sont sensibles à de grands glissements de terrain en arrière. Cette risques géologiques tend à survenir brutalement, sans signes évidents, impliquant souvent de nombreux hectares de terrain en douceur. De nombreux primaire corridors de transport et de communication passent par cette région, et sont donc susceptibles d'être touchés par ce danger. Ce document présente une méthode d'évaluation du risque global d'un système linéaire de l'infrastructure, et propose une approche systématique pour identifier les endroits à risque plus élevé, puis d'évaluer dans une approche par étapes avec les augmenter progressivement le niveau de détail.

1 INTRODUCTION

Many of the most damaging landslides in Canadian history have occurred in the gentle clay plains of the Saint Lawrence Lowlands, which contain extensive deposits of marine soils. Fine grained marine deposits (i.e. silt and clay) can be very sensitive, meaning that the remoulded undrained strength is much lower than the intact undrained strength. Large retrogressive landslides occur frequently in these soil deposits, generally occurring at a steep natural slope (e.g. riverbank), and involving very gentle terrain beyond the crest of the slope. These landslides occur very quickly, generally without warning. Figure 1 shows an outline of the study area, which encompasses the extent of post-Wisconsin marine invasion plus a 10 km buffer. Figure 1 also shows the extent of landslide susceptibility mapping conducted by Quinn (2009), covering the western half of the study area.

The bulk of the population of eastern Ontario and Québec live along a narrow corridor containing the Saint Lawrence and Ottawa Rivers. This region therefore contains vital transportation, power and oil and gas transmission infrastructure, as illustrated in Figure 2. A large landslide in sensitive clay affecting a railway line or transmission line could have significant economic consequences. For example, a large landslide in the 1970s disrupted service to CN Rail's main line for six months (Mario Ruel, pers. comm.. 2005). Similarly, a large landslide in sensitive clay in British Columbia, the Khyex River slide, severed a pipeline and disrupted gas service to Prince Rupert for 10 days (Schwab et al. 2004). Such events, resulting in significant damage or casualties, happen with some regularity in eastern Canada. According to Morin (1947), a "notorious" landslide occurs in Québec every ten years, on average. This type of risk, with a moderately long return period but potentially disastrous consequences, is difficult to manage.

This paper examines the level of risk associated with large landslides in sensitive clay affecting vital linear infrastructure, including railway lines, power transmission lines, and pipelines. The work shows that system failure can be expected to occur with return periods of some decades for these various networks, varying with their spatial extent and specific location. It then presents a phased approach for more detailed examination of more threatened components, as a first step in managing the identified risk.

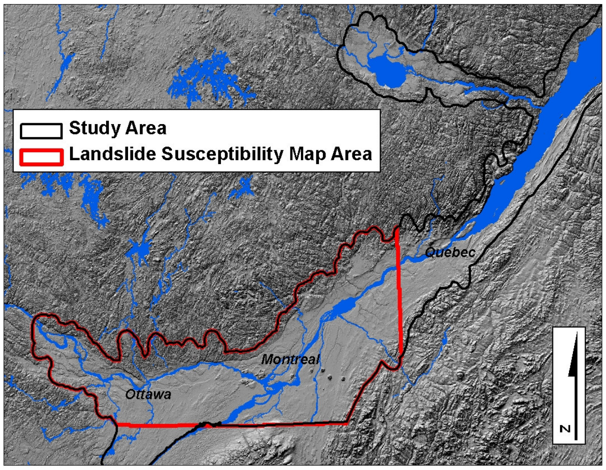

Figure 1. Project study area.

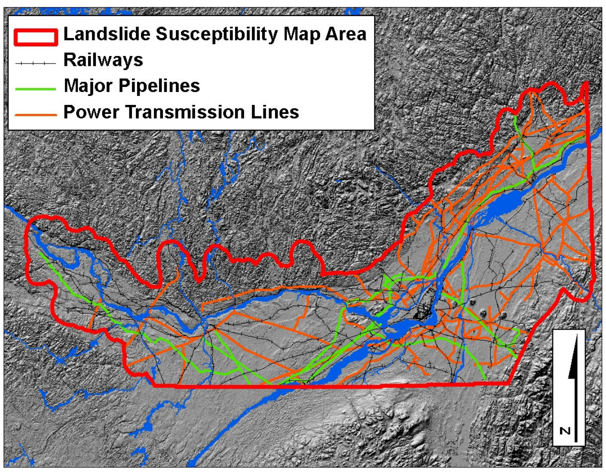

Figure 2. Transportation and utility corridors.

2 ESTIMATION OF HAZARD AND RISK

2.1 Spatial Distribution of Landslides

Quinn (2009) presented an inventory of large landslides in a selected part of the study area (i.e. NTS 31H), and also presented a method for mapping landslide susceptibility on the basis of statistical comparison of landslide occurrence with specific geospatial data within a GIS framework, using the weights of evidence method. A total of 1259 large retrogressive landslides were identified within NTS 31H. The spatial distribution is shown in Figure 3, and the landslide susceptibility map is shown in Figure 4, focusing only on NTS 31H.

The landslide susceptibility map extends outside NTS 31H to cover the area outlined in red in Figures 1 and 2, well beyond the area shown in Figure 4. There are three descriptive susceptibility categories: low, low to moderate, and moderate to high. These descriptive categories have specific statistical meaning in relation to the likelihood of encountering an existing large landslide within certain distances. Table 1 presents the probabilistic relationship between susceptibility category and proximity to an existing large landslide. Note that this susceptibility map is intended as a screening tool at the regional level, to identify areas of higher susceptibility for further study. It is not intended to yield an accurate estimate of landslide susceptibility at a large scale, for example at a specific location along a given river.

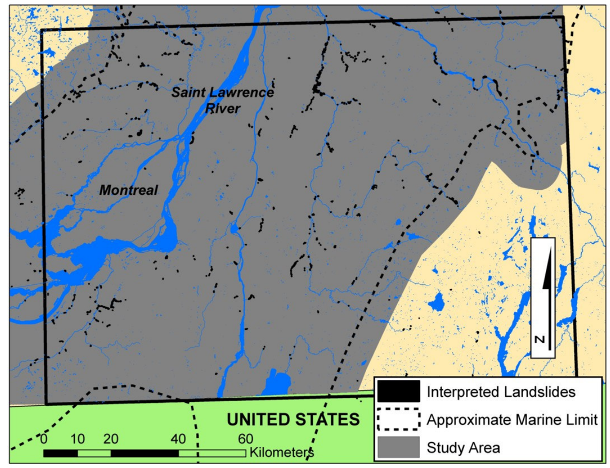

Figure 3. Large landslides in NTS 31H.

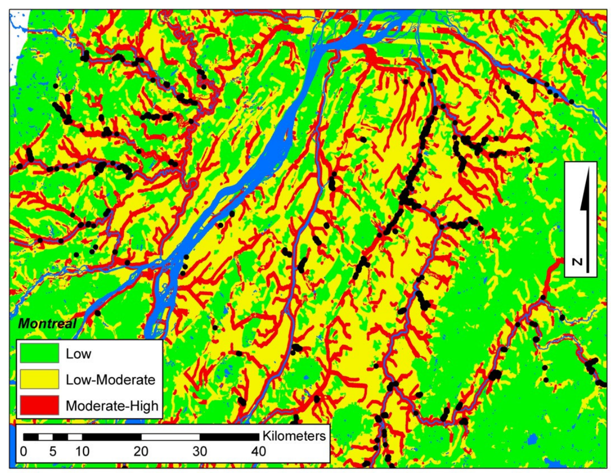

Figure 4. Landslide susceptibility map (black dots are landslides).

Table 1. Statistical meaning of susceptibility categories.

Susceptibility Category	Probability of Encountering a Retrogressive Landslide: Within 500 m	Within 1 km	Within 2 km
Low	0.6 %	3 %	10 %
Low to Moderate	3 %	10 %	26 %
Moderate to High	15 %	26 %	44 %

Quinn (2009) also showed that large landslides in sensitive clay in eastern Canada tend to occur close to existing old large landslides. This is illustrated in Table 2, which shows, for example, that if a new landslide is observed, there is a 91 % probability that an older large landslide exists within 500 m. Similarly, there is only a 3.3 % probability that the nearest older landslide is further than 2000 m. New landslides are therefore much more likely to occur close to other large landslides, and are very unlikely to occur in areas where no older landslides are observed. This information can be used to refine the understanding of future landslide occurrence, beyond that which might be interpreted solely on the basis of the susceptibility map.

Table 2. Proximity of new large landslides to existing older large landslides in sensitive clay.

Distance (m)	Probability (%)
< 50	49.2
< 100	72.3
< 200	82.2
< 500	91.0
< 1000	94.2
< 2000	96.7

2.2 Geometric Characteristics of Landslides

Quinn (2009) presented some statistical analysis of the geometric properties of the digital landslide inventory for NTS 31H. The size distribution of mapped landslides is shown in Figure 5. Landslide magnitude, M_{LS}, is defined as $\log_{10}(A)$, where A is the surface area of the landslide depletion zone, expressed in square metres. $M_{LS} = 5.0$ is therefore equivalent to a landslide depletion zone area of 10^5 m^2, which is slightly smaller than the Lemieux landslide of 1993, which had an area of about 1.7×10^5 m^2 (Evans and Brooks 1993). Note that size distribution is shown for all large landslides, and is then presented for "spreads and flakes" and "earth flows." These general categories recognize the difference between large landslides that occur as lateral spreads and those that involve a substantial flow of liquid clay. Quinn (2009) showed that at least 90 % of the large landslides documented in NTS 31H occurred as lateral spreads, and up to 10 % occurred as earth flows.

Large landslides in sensitive clay occur most commonly at an existing riverbank, and then retrogress from the crest of the bank, involving the gentle plains beyond. Figure 6 shows two key landslide dimensions: the length of the depletion zone, or crater, L_{cr}, and the length of travel, L_T, of the landslide debris. Quinn (2009) showed that for a number of large landslides documented in the literature (n = 32), L_{cr} and L_T both tend to be similar, on average, to the square root of landslide area for lateral spreads. Similarly, L_{cr} and L_T tend to be 1.5 and 3 times, respectively, the square root of landslide area for earth flows.

Given the findings in the previous paragraphs, if a landslide is to occur, it is possible to estimate the likelihood that it will be a lateral spread or flow slide. Given the landslide type, it is then possible to determine the probability that it will exceed a certain size on the basis of Figure 5. If the probable size is known, it is then possible to estimate the probable lengths of retrogression and debris travel.

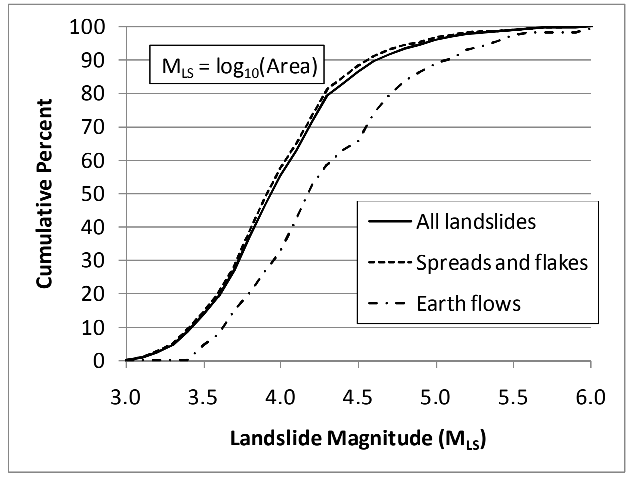

Figure 5. Size distribution of large landslides in sensitive clay.

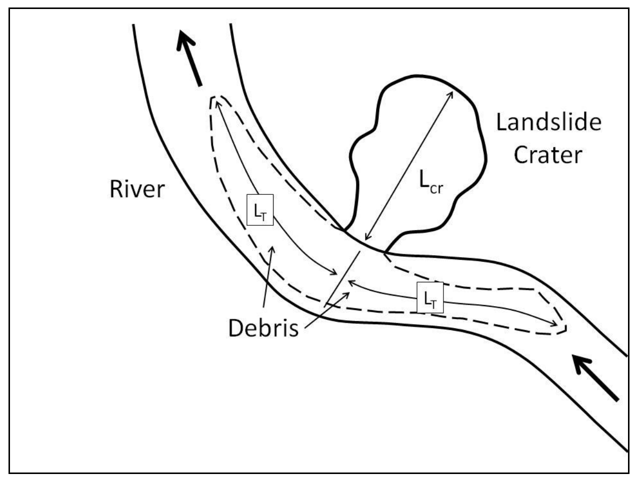

Figure 6. Key landslide dimensions.

2.3 Temporal Distribution of Landslides

Lebuis et al. (1983) presented data regarding the temporal distribution of large landslides in sensitive clay. Table 3 summarizes their information regarding ages of landslides, where landslide age was most often determined through carbon dating. A large proportion (i.e. 62 %) occurred within the past 1000 years, and nearly all (i.e. 98 %) occurred within the past 4000 years. If these observations are representative of typical conditions across the study area, then one can conclude that nearly all of the landslides observed by Quinn (2009) in NTS 31H occurred in the last 4000 years, with landslides being more frequent, on average, in recent centuries. These data can be used as a preliminary basis for estimating future probability of landslide occurrence, assuming that future temporal distribution remains similar to that of recent centuries.

Table 3. Distribution of landslides with known ages, from Lebuis et al. (1983).

^{14}C age of landslides	Number of Landslides
> 4500 years before present (YBP)	1
> 4000 YBP	3
> 3500 YBP	2
> 3000 YBP	0
> 2500 YBP	8
> 2000 YBP	4
> 1500 YBP	1
> 1000 YBP	11
> 500 YBP	12
< 500 YBP	8

According to the distribution of landslide magnitude in Figure 5, roughly 45 % of all large landslides observed in NTS 31H were greater than 1 x 10^4 m^2 (M_{LS} = 4.0). Therefore, of the 1259 documented landslides, roughly 567 were greater than 1 ha in surface area. Given that NTS 31H represents approximately one fifth of the total study area, one could expect approximately 2800 large landslides larger than 1 ha within the whole study area, with perhaps 2000 in Québec and 800 in eastern Ontario. If these are assumed to have occurred over 4000 years, one would expect a large landslide exceeding 1 ha to occur every two years, on average, in Québec. According to Leroueil (personal communication 2009), one large landslide exceeding 1 ha occurs about every two years in Québec. This suggests that 4000 years may be used as a good upper bound estimate of the period over which the 1259 landslides in NTS 31H occurred, and can be used in conjunction with the landslide susceptibility map as the initial basis for estimating future frequency of landslide occurrence.

2.4 Potential Consequences of Landslides

Quinn (2009) summarized the effects of 32 large landslides in sensitive clay, as documented in the literature. These effects included damage to infrastructure, loss of productive ground, injuries, and loss of life. Linear infrastructure can be affected by these events in a number of ways, as illustrated in Figure 7. Structures or facilities within the footprint of the landslide depletion zone, or crater, were shown to be destroyed or damaged beyond repair in all cases. Therefore, if a structure is within the limits of landslide retrogression, it will be destroyed. This includes above-ground infrastructure such as roads and railroads, and shallow buried infrastructure (i.e. less than 20-30 m cover, therefore includes most pipelines). Power transmission lines crossing a large landslide would be affected only if a tower existed within the landslide footprint.

Damage can also be caused by the moving debris, which can impact facilities on the opposite riverbank, or can also affect low suspended infrastructure upstream or downstream within the limits of travel. The Saint-Jean-Vianney slide of 1971 destroyed a highway bridge over 2 km downstream (Tavenas et al. 1971). The likelihood of damage due to flowing or sliding debris is less than that associated with loss of ground, since the debris may flow under the potentially affected structure without impacting it. For simplicity, it is nevertheless assumed that damage will occur if the debris flows past a low structure such as a highway or railway bridge. Power transmission lines would not likely be affected due to their height, and pipelines would not likely be affected since they would typically be buried at river crossings. Some pipelines may, however, be attached to bridges, and could thus be similarly affected.

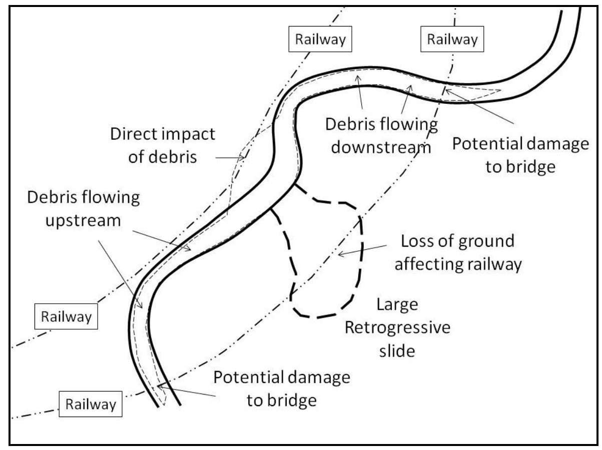

Figure 7. Potential effects to linear infrastructure.

Flooding tends to occur upstream of large landslides in sensitive clay, as the landslide debris generally blocks the affected river. This could lead to additional damage beyond that associated with loss of ground and debris impact; however, in the cases studied by Quinn (2009), no significant damage was caused by flooding in any of the 32 documented landslides. This specific issue is therefore not considered further in estimating the risk to networks of linear infrastructure.

2.5 Probability of System Failure – An Estimate of System Risk

The landslide susceptibility map illustrated in Figure 4 may be used as a starting point for examining the risk of a large landslide severing a vital life line, such as a railway, power transmission line or pipeline. The susceptibility mapping study area is approximately 3.3 times as large as NTS 31H. Given that 1259 large landslides were observed in NTS 31H, one can therefore estimate that approximately 4150 large landslides exist within the whole susceptibility mapping area. Of these, 3.6, 16.4 and 80.1 % of the landslide features were observed in low, low to moderate, and moderate to high susceptibility zones, respectively, which each represent 65.2, 23.5 and 11.3 %, respectively, of the study area.

A Monte Carlo simulation was conducted to obtain the locations for approximately 4000 landslides within the study area. This was done by first generating 50,000 random points within the study area, of which about 65, 24 and 11 % fell within the low, low to moderate and moderate to high susceptibility zones. These points were then subject to additional random selection to obtain approximately 150, 650 and 3200 points in the three susceptibility zones, randomly distributed across the study area. The distribution of these randomly selected landslide locations is illustrated in Figure 8.

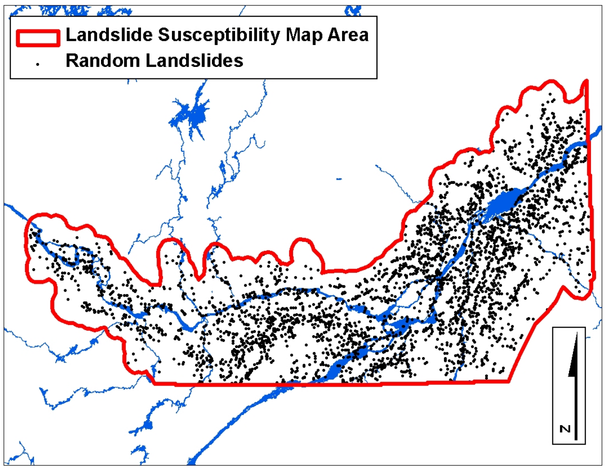

Figure 8. Locations of randomly generated landslides.

Each randomly located landslide location was assigned two additional random numbers to determine landslide type and size. 90 % of the randomly generated landslides were randomly selected as lateral spreads, and the remaining 10 % were identified as flow slides. Landslide size was then assigned randomly, conforming to the size distribution in Table 4, which agrees with the distributions shown in Figure 5.

Table 4. Size distribution of randomly generated landslides.

M_{LS}	Cumulative % Spreads	Cumulative % Flows	Top of Area Range (m^2)	Assumed Area (m^2
3.5	14.7	4.3	3,162	2,000
4.0	57.5	32.8	10,000	6,500
4.5	88.3	65.5	31,623	21,000
5.0	96.7	88.8	100,000	65,000
5.5	98.9	97.4	316,228	210,000
6.1	100	100	1,258,925	800,000

The travel distance and length of retrogression can be calculated directly for each landslide once its type and area are known. Figure 9 shows the potential range of debris travel (runout distance) for randomly located landslides east of Montreal, to illustrate the potential distribution of large landslides of varying size. A similar plot can be obtained for the potential length of landslide retrogression for each randomly generated landslide on the same basis. These can then be compared with the location of physical infrastructure to check to spatial overlap.

A section of railway, pipeline or power transmission line can be assumed to be destroyed if it intersects a landslide crater, or falls within the range of landslide retrogression. A railway crossing structure may be assumed, conservatively, to be damaged or destroyed if it falls within the range of debris travel. Figure 10 shows the distribution of large randomly generated landslides impacting railway lines or structures. Similar maps can be generated for other networks of linear infrastructure.

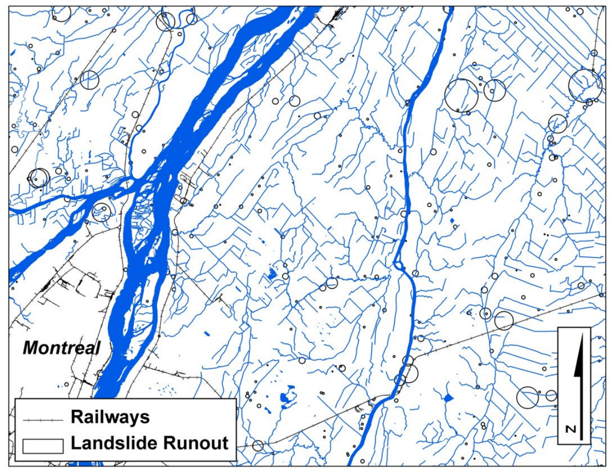

Figure 9. Locations of randomly located landslides showing potential range of debris travel (runout).

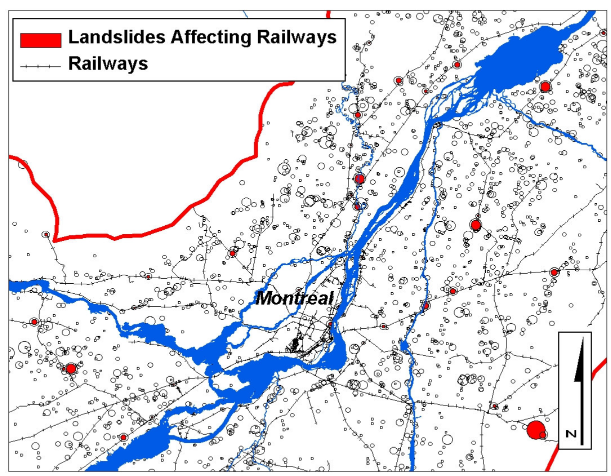

Figure 10. Locations of randomly located landslides affecting railways.

One can now begin to consider the potential landslide risk to a network of linear infrastructure passing through the Saint Lawrence Lowlands. Table 5 shows the number of randomly generated landslide incidents that would potentially affect the various linear networks shown in Figure 2, given their location, and also given the location and size of landslide incidents. The return period and annual probability associated with a major failure are also shown. Note that, since the landslide runout distance is modelled as a circular buffer around the centre of each landslide, rather than oriented away from or along a river, the number of potential damaging events could be overestimated to some degree.

However, it is believed that this method yields an approximately correct result, since landslide retrogression and debris runout would occur in different directions, so that the circular buffer would be a suitable approximate representation of the limits of potential impact.

The return periods for damaging events are relatively long – long enough that they may be forgotten between occurrences, so that effective management approaches might not be put in place. The consequences of these events can be catastrophic, however. A large landslide near Saint-Fabien, Québec in 1976 severed the CN Rail main line, disrupting service for six months. A smaller landslide near Coteau-du-lac, Québec caused a derailment of a freight train, some 30 minutes after a VIA passenger train had passed. (Mario Ruel, personal communication, 2007).

Table 5. Return period for damaging events.

Linear Feature	Number of Incidents[1]	Return Period for Damaging Event[2]	Annual Probability of Damage
All Railways	200	20	0.050
CN Rail Lines	71	56	0.018
Major Pipelines[3]	41	98	0.010
Power Transmission Lines	120	33	0.030

Notes: 1. Number of incidents is extrapolated to include those parts of the study area outside the susceptibility mapping area.
2. Return period is estimated using 4000 years to represent the period of observed landslide occurrence.
3. Available pipeline location data are limited to older major pipelines. The number of incidents is expected to be much higher based on actual current transmission and distribution networks.

The figures in Table 5 represent a numerical representation of the hazard associated with large landslides in sensitive clay. An understanding of risk requires the additional step of understanding the nature of the potential consequences, or the potential value of a loss associated with a damaging incident. A detailed calculation of the potential impacts to specific receptors, such as trains, cargo, crew and passengers and the like is beyond the scope of the present study. However, it can be recognized that any disruption of a railway main line will lead to a substantial economic loss, along with related impacts (e.g. environmental damage, loss of reputation). Similarly, disruption of a gas transmission line can be expected to lead to a substantial cost, particularly if the network has little redundancy, so that a service disruption cannot be mitigated by rerouting gas delivery. Destruction of a power transmission tower can also lead to a substantial loss, however it is likely possible to make more rapid adjustments to the network to mitigate the impacts than is the case with railways and pipelines.

The calculation of risk, for the purpose of this paper, is semi-quantitative: the probability of occurrence has been calculated mathematically, but the nature of the consequences is described qualitatively, being in all cases very high, or potentially catastrophic. A more detailed study of individual systems could lead to a quantitative assessment of the potential losses, leading to a fully quantitative risk assessment.

3 MANAGEMENT OF LANDSLIDE RISK

The first step in managing landslide risk is to assess the level of risk, and the preceding analysis provides insight into the risk of system failure for various networks of linear infrastructure in eastern Canada. This understanding of risk can be refined with further study, and then steps can be taken to manage the risk.

The landslide susceptibility map provides a high level view of the spatial probability of future landslide distribution, and it does a very good job of identifying large areas that do not contain landslides. However, a large proportion of the moderate to high susceptibility areas contain no landslides. Given that large landslides are known to occur more frequently near older existing landslides, these areas with no landslides are likely misclassified at the scale of study. Some potential high susceptibility areas along linear corridors may therefore be downgraded if it can be shown that no, or few, large landslides occur nearby. This can be done through reconnaissance level air photo study.

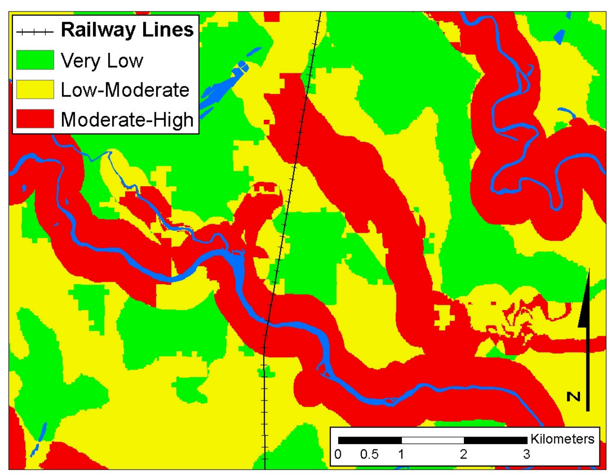

Figure 11. Typical railway crossing through moderate to high susceptibility zones.

Consider a typical length of railway line passing through zones of differing susceptibility, as shown in Figure 11. Where the line passes through the moderate to high susceptibility zones, one can expect a high probability of encountering existing large landslides within 2 km, as outlined in Table 2. Figure 12 shows the locations of landslides identified by Quinn (2009) in the inventory of landslides for NTS 31H, and it can be seen the nearest landslide occurs within about 500 m of the railway line, and there are multiple large landslides within 2 km. In this particular setting, one would anticipate a higher than average probability of future landslide occurrence.

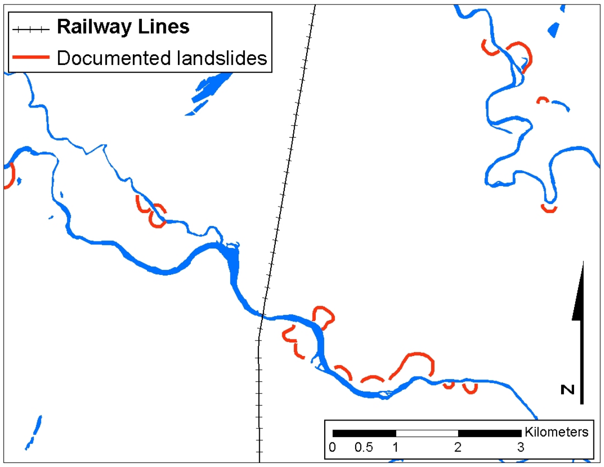

Figure 12. Existing large landslides.

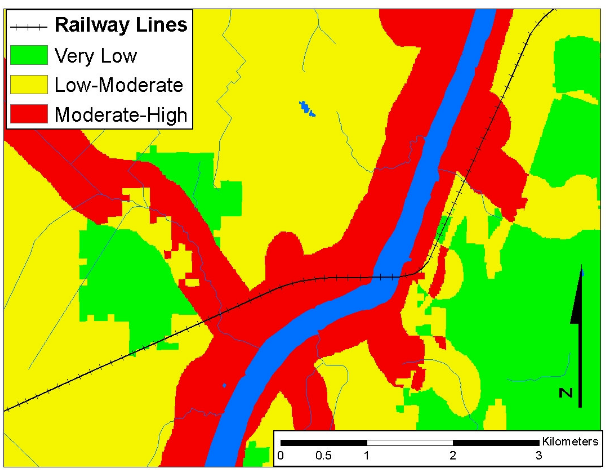

Figure 13. Railway line through moderate to high susceptibility zones along Rivière Richelieu.

Consider now a different example, as illustrated in Figures 13 and 14. Here the railway runs along and crosses the Rivière Richelieu, where no landslides have been observed. In this case, the susceptibility map has misidentified areas as having elevated landslide susceptibility; however, this is easily discerned with a rapid air photo study. The absence of large old landslides in this specific area, and along Rivière Richelieu in general, suggests that landslides are less likely to occur here than in the area outlined in Figures 11 and 12.

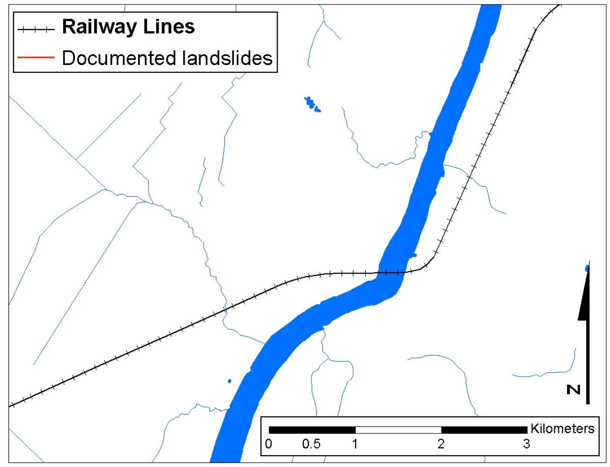

Figure 14. Absence of landslides near railway.

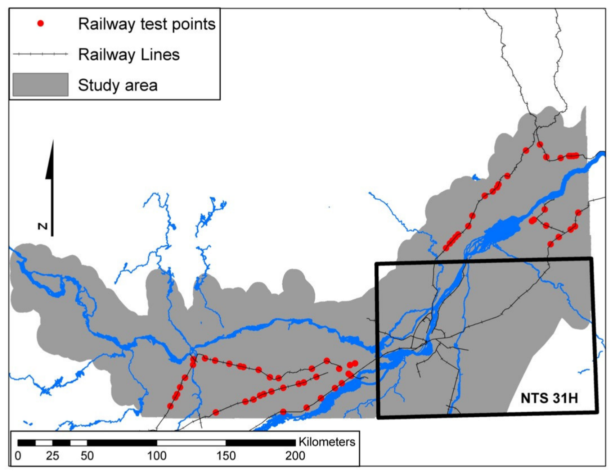

Figure 15. Moderate to high susceptibility sections of railway line examined by air photo study.

One can focus attention to areas of high concern by using the landslide susceptibility map for an initial screening, and then conducting reconnaissance level air photo survey. A number of river crossings (n = 66) along selected railway lines outside NTS 31H were selected for air photo study. These crossings, which included all moderate to high susceptibility zones traversed by the railway lines, are shown in Figure 15. Air photos at each location were examined to determine the presence or absence of existing large landslides within 2 km. Of these 66 crossings, 6, 22 and 38 were in low, low to moderate and moderate to high susceptibility zones, respectively. None of the low susceptibility zones had landslides within 2 km, and 18 % (4) and 34 % (13) of the low to moderate and moderate to high zones, respectively, had landslides within 2 km. The total length of railway line in this example study is 825 km, and the total length of railway line passing through zones containing landslides within 2 km is about 17 km, allowing for 500 m on either side of each river crossing near landslides. This initial screening with the landslide susceptibility map, followed by air photo review, therefore allowed the landslide risk to be focussed toward 2 % of the total system, eliminating 98 % of the system from potential concern.

4 DISCUSSION AND CONCLUSIONS

This paper has presented a semi-quantitative assessment of the risk of large landslides in sensitive clay affecting selected linear infrastructure in eastern Canada. It has been shown that a major event causing system disruption can be expected to occur with a return period ranging between about 20 and 100 years, with the value depending on the extent of the linear system.

Further investigation to refine the understanding of system risk might include the following steps:

- Identify all sections of railway corridor and railway river crossings in areas identified as moderate to high landslide susceptibility;
- Conduct detailed air photo analysis for each identified track section or structure to determine the proximity of the nearest old landslide, and number of old landslides. Rank these sites on the basis of these findings, giving greater weight to sites with closer landslides and more numerous landslides. For example, the crossing in Figure 11 would rank much higher than the Richelieu crossing in Figure 13. Use this ranking to prioritize the subsequent more detailed study;
- Conduct preliminary site reconnaissance, on a priority basis based on the ranked list, to look for signs suggesting the potential for large landslides. Indications of landslide potential may be interpreted on the basis of ranking schemes presented by Lebuis et al. (1983), Gagnon (1972), Thibault et al. (2008), for example. On the basis of this preliminary field reconnaissance, rank these sites for potential more detailed investigation; and
- For those sites identified as the highest priority on the basis of preliminary field reconnaissance, conduct more detailed site survey. This would be designed on a site-specific basis, but could include airborne LiDAR survey to obtain detailed topography, in-stream profile surveys to estimate rates of erosion, and sub-surface investigation to determine soil and groundwater conditions.

These additional investigations would allow the development of a more complete understanding of annual risk associated with large landslides in sensitive clay, which would support the development of rational management plans. Efforts to manage the risk could include measures to reinforce or protect certain elements, construction of redundant facilities, and relocation or abandonment of selected facilities, as examples.

ACKNOWLEDGEMENTS

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