CHARACTERISING LANDSLIDE RISK IN CANADA

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ABSTRACT
The most damaging landslide types in Canada have been identified and include rockfalls and low magnitude rockslides, earthflows in Leda Clay, landslides from built slopes, rock avalanches, and debris flows/debris avalanches. They range in volume over six orders of magnitude from $10^1 m^3$ to $10^7 m^3$ and have impacted on communities and infrastructure mainly in the southern Cordillera (Alberta and British Columbia) and the St. Lawrence Lowlands of Québec. The fatal landslide risk envelope for Canada approximates a power law with an exponent of –1. The Landslide Destructiveness Index (LDI) is introduced and expresses losses in terms of the source volume of the landslide or area of resultant debris. The LDI, which is a proxy for population density, is used to explore the comparative destructiveness of landslide types and to identify a landslide-disaster threshold based on population density. Limitations of raw landslide magnitude and frequency data prevent, as yet, a complete characterisation of landslide risk.

RÉSUMÉ
Les types de glissements de terrain les plus destructeurs au Canada sont les chutes de blocs et les glissements rocheux de faible volume, les coulées dans les argiles à Leda, les glissements dans les pentes construites, les avalanches rocheuses, et les coulées de débris/avalanches de débris. Leurs volumes s'entendent sur six ordres de magnitude de $10^1 m^3$ à $10^7 m^3$ et ont affecté la population et les infrastructures principalement dans le sud-est de la Cordillère (Alberta et Colombie-Britannique) et les Basses-Terres du St-Laurent au Québec. L'enveloppe de risque des glissements de terrain mortels pour le Canada s'exprime par une loi de puissance avec un exposant de valeur –1. L'indice de capacité de destruction des glissements de terrain (LDI) est introduit et exprime les pertes selon le volume de la zone source d'un glissement de terrain ou la superficie des débris générés. Cet indice, lequel est un indicateur de la densité de population, est utilisé pour comparer la capacité de destruction des types de glissements de terrain et d'identifier un seuil glissement de terrain-désastre basé sur la densité de population. Les limitations des données brutes de la magnitude et le fréquence des glissements de terrain empêchent, jusqu'à présent, une complète caractérisation du risque de glissement de terrain.

1. INTRODUCTION

1.1 Preamble

2003 marks the centenary of the Frank Slide (McConnell and Brock, 1904; Figure 1) which occurred on April 29th, 1903. The rock avalanche killed at least 70 people and remains Canada's worst landslide disaster (Evans, 1997).

Figure 1. Aerial oblique photograph, taken in September 1944, of Turtle Mountain, Alberta, and the 1903 Frank rock avalanche (NAPL T31L-213).

The centenary is a reminder of the potential destructive impact of catastrophic landslides and provides an appropriate backdrop against which to examine landslide risk in Canada. It is also appropriate that the International Strategy For Disaster Reduction (ISDR), a successor to the International Decade of Natural Disaster Reduction (IDNDR) of the 1990s, has launched the concept of living with risk, having at its core a concern with the processes involved in the "awareness, assessment and management of disaster risks" (United Nations, 2002). The recent formalization of quantitative frameworks for characterizing the occurrence of natural catastrophes (e.g., Woo, 1999) has led to an increased understanding of disaster systems (e.g., Newhall and Hoblitt, 2002) which forms the basis of enhanced crisis management and risk assessment.

In the case of landslides, the results of analyses of magnitude/frequency data on landslide occurrence in time (e.g., Hungr et al., 1999; Dai and Lee, 2001) and space (e.g., Hovius et al., 1997; Guzzetti et al., 2002) in conjunction with landslide geometry statistics and models of landslide behaviour (e.g., Iverson et al. 1998) have created new opportunities to formalize risk assessment at global, national, regional, and site scales. A concomitant activity, based on similar power-law statistics, has been the recent analysis of historical disaster data sets (e.g., Knopoff and Sornett, 1995; Evans, 1997; Pyle, 1998). A requirement for this approach is the availability of temporal and/or spatial data sets of landslide occurrence and complete historical records of damaging landslides in a given domain. In the Canadian case, several well constrained temporal and spatial data sets have recently been assembled (e.g., Hungr et al., 1999; Martin et al., 2002). Further, the chronicle of destructive landslide events in Canada (Evans, 2001), since at least 1840, is now sufficiently well developed that a reasonable regional and thematic picture of the architecture of landslide hazard can be drawn.

1.2 Landslides in Canada

The present paper follows a succession of work began in 1928 by D.A. Nichols of the Geological Survey of Canada, who sketched out the first national survey of landslides in Canada (Nichols, 1928). The first substantive national survey of landslide types was undertaken by Mollard (1977) in which he identified a number of regional landslide types including rock avalanches, bedrock slides and the deformation of mountain slopes, retrogressive slope failures in argillaceous bedrock in the Interior Plains, earthflows in sensitive clays in eastern Canada, and slope failures in permafrost. This work was followed by that of Cruden et al. (1989), who made the first attempt to assess the cost and regional extent of landslides in Canada, including the offshore. Cruden et al. (1989) suggested that direct losses due to landslides could be in the order of hundreds of millions of dollars per year. Evans (1997, 2000b) made a first approximation to the nature of damaging landslides and fatal landslide risk in Canada. Most recently, Evans (2001) completed a national survey of landslide styles, the secondary effects of landslides, landslide disasters, and the interaction between landslides and the environment.

Poster-Maps featuring locations of damaging natural hazard events and descriptions of hazard processes, including landslides, were recently published for Canada and the NAFTA countries (Government of Canada, 2001; National Geographic, 1998). These have contributed to the public awareness of geohazards in Canada, including landslides, which, as seen below, is a component of risk reduction.

After 75 years of study, it is suggested that we have a well developed view of the range of landslide types in Canada, their general behaviour and their geography of distribution, particularly within, the settled area of southern Canada, known as the “population ecumene”. This view forms the point of departure for a characterization of landslide risk in Canada.

1.3 Objectives

The objectives of this paper are threefold i) to review the record of damaging landslides in Canada ii) to evaluate landslide risk in Canada using historical data and iiii) to introduce the Landslide Destructiveness Index (LDI) as a means of linking hazard and risk.

2. LANDSLIDE RISK

2.1 Risk, Hazard, and Vulnerability

The definition and scope of risk, hazard and vulnerability have evolved over the last thirty years. Risk from natural hazards has been recently defined (United Nations, 2002, p. 341) as “the probability of harmful consequences, or expected loss (of lives, people injured, property, livelihoods, trauma, economic activity disrupted or environment damaged) resulting from interactions between natural or human induced hazards and vulnerable/capable conditions”. Risk (R) is commonly expressed as the product of hazard (H) and vulnerability (V), where vulnerability may be seen as the ratio of susceptibility to resistance (Equation 1).

$$R = H * V \quad [1]$$

In turn, hazard is defined (United Nations, 2002) as the probability of “a potentially damaging physical event, phenomenon and /or human activity, which may cause the loss of life (and other elements of risk noted above)” within a given domain within a given period of time. Hazards include latent conditions that may represent future threats.

Importantly, as recent events around the world have shown, hazards can be combined such as in the creation of floods and landslides by heavy rainfall, and earthquake damage to buildings and damage resulting from earthquake-triggered landslides. They can also be sequential, as in the case of the formation and failure of landslide dams, or the case of landslide-generated waves. In a unit region, each hazard is characterized by its location, intensity (cf. Hungr, 1997), frequency, and probability of occurrence.

Vulnerability is defined by the United Nations (2002, p. 342) as “a set of conditions and processes resulting from physical, social, economic, and environmental factors which increase the susceptibility of a community (or infrastructure) to the impact of hazards.” Positive factors that decrease susceptibility (e.g., public education and awareness, warning systems, or built defences), and thus increase resilience, may be considered as resistance, which in turn may decrease vulnerability and therefore total risk.

2.2 Landslide Risk Assessment in Canada; Community v. Infrastructure;

Landslide risk assessment in Canada is complicated by its geography. It is the second largest country in the world (9.012 M km^2) with a population of only 30M people. This gives a population density of 3.3 persons/km^2, one of the lowest of any country in the world. Masked by this statistic is the fact that in 1996 the population ecumene contained 98% of the population in only 10% of the nation’s land area, equivalent to a population density of about 30 persons/km^2. Whilst ten times greater than the national figure, and equivalent to the United States, this density is still much less than many European countries, six times less than Italy and Switzerland and ten times less than Japan (336 persons/km^2).

In contrast, the movement of people, goods and resources takes place along very long lines of critical infrastructure which cross large tracts of uninhabited or sparsely peopled terrain. Canada has over 1M km of linear infrastructure, including railways, roads, and pipelines, which translates into approximately 0.03 km/capita, the highest in the industrialized countries of the world.

These statistics provide initial reference points for the vulnerability of Canada's population and critical infrastructure to landslide hazard.

Formal landslide risk assessment for communities first emerged as an issue in Canada in 1973 when events in the so-called Barrier case were initiated (Berger, 1973). The judgment and subsequent actions, culminating in the compulsory purchase of the Garibaldi properties by the Government of British Columbia, set the scene for work by Morgan et al., (1992). Hungr et al. 1993, Sobkowicz et al., (1995) and other Canadian work summarized in several papers in Cruden and Fell (Editors) (1997). This work contributed to the development of a framework for landslide risk assessment for communities with a focus on the definition of acceptable risk. For linear infrastructure, landslide risk assessment was first carried out by Morgan (1991). This was followed by work on highways (Bunce et al., 1997; Hungr et al., 1999) and railways (e.g., Abbott et al., 1998) in which the use of historical rockfall data emerged as an important tool in risk assessment. McClung (1999) examined the statistics of encounter probability in linear transportation corridors.

3. DAMAGING LANDSLIDES IN CANADA – THE RECORD OF HARMFUL CONSEQUENCES

In order to decipher the signature of landslide risk in Canada, it is first necessary to examine the record of historical landslide damage and develop a broad model of where losses have occurred, what landslide types have caused these losses, and how frequently these losses have occurred. The architecture of the model integrates the natural landslide response of the landscape as well as the influence of human, climatic and seismic forcing.

In making progress towards a model of historical landslide damage in Canada, two areas of losses due to landslides are appropriate to review 1) loss of life over a disaster threshold and 2) impacts on communities and critical infrastructure below that threshold.

3.1 Loss of life

Mortality caused by geologic hazards provides a robust comparative measure of loss (Latter, 1969; Knopoff and Sornette, 1995). As a contribution to the IDNDR a verified data base of disastrous landslides and geotechnical failures in the historical period was assembled (Evans, 1997; 1999; 2001, Evans et al., 1997). These events are located in Evans (2001). Events in the database included landslides in natural slopes and failures of artificial slopes, either built or excavated. Occurrences in the latter group are termed geotechnical failures. Here the database (see Appendix) is reviewed to identify a) the regions of Canada that are most susceptible to landslide damage, and b) the major damaging landslide types. A re-evaluation of the 1915 Jane Camp event (Evans, 2000a) has led to conclusions that differ from those reported previously (Evans, 1997).

Evans (1997) defined a disastrous landslide event in the Canadian context, as a single event failure which resulted, directly or indirectly, in the deaths of 3 or more people. A total of 43 events that met the nominal national landslide disaster criterion defined above, occurred in Canada in a period of 161 years between 1840 and 2000 (see Appendix). This record is considered to be complete and is thus equivalent to a landslide disaster frequency of one every 3.7 years, or an annual frequency of 0.27. These disasters resulted in a minimum of 570 deaths. Based on this criterion, landslides are the most destructive geological hazard in Canada.

Landslide damage, measured by landslide fatalities, is heavily concentrated in two regions; the St. Lawrence Lowlands of Québec and the Canadian Cordillera south of 55°N in the provinces of British Columbia and Alberta. However, an important number of landslide deaths have occurred in Newfoundland as documented by Batterson et al. (1995), Liverman et al. (1998), and Liverman et al. (2003).

In identifying the most damaging landslide types in Canada, the most destructive were small-scale rockslides and rockfalls involving volumes of less than 100,000 m^3. Characteristics of this type include (Table 1) extremely rapid primary rock slide/rock fall movement as well as the effects of entrainment of material along its path. Augmented by entrainment, the reach of such movements may exceed 1 km and maximum velocities in the range 20-40 m/s have been indicated by back-analyses of well-documented case histories (e.g., Evans and Hungr, 1993). These characteristics place such movements in Response Class 1 in the Landslide Destructiveness Scale proposed by Hungr (1981) and Morgenstern (1985).

These types of landslides caused 27% (155) of the deaths in 7 events across Canada (Table 1; Cases 1, 2, 3, 5, 17, 35, and 37 in Appendix). The worst cases occurred at Jane Camp, Howe Sound, B.C. in 1915 (56 deaths) and in Québec City in 1889 (45 deaths). These events are worthy of more detailed description.

Jane Camp was established in 1903 within Jane Basin, a cirque-like bowl, within the watershed of Britannia Creek (Evans, 2000a) and in 1915 housed a substantial number of miners in bunkhouses and miners' families in other buildings (Figure 2).

Figure 2. A panorama of contemporary photographs of the 1915 Jane Camp landslide disaster showing source area at top right and impact on mining camp buildings, including bunkhouses at left (Photographs courtesy of Britannia Museum and Vancouver Public Library).

Table 1. Ranking and characteristics of Canada's most destructive landslide styles based on historical record of landslide deaths 1840-2002.

Rank	Landslide Type (with volume range in m^3)	% of total (Number of deaths)	Velocity Range (m/s)	RC[1]	Most destructive event (with date and number of deaths)
1	Rockfalls and rockslides (< 0.1×10^6)	27 (155)	20-40	1	Jane Camp, British Columbia (1915/56)
2	Earthflows in Leda Clay (0.5 – 200 10^6)	17 (98)	5-15	1-2	Notre-Dame-de-la-Salette, Québec (1908/33)
3	Failure of built slopes/Geotechnical failures (0.01 – 8×10^6)	15 (84)	15-40	1	Britannia Beach, British Columbia (1921/37)
4	Rock avalanches (> 10^6 m^3)	15 (83)	>20	1	Frank, Alberta (1903/70)
5	Debris flows and debris avalanches (0.01- 0.1×10^6)	11 (65)	5-20	1-2	North Pacific Cannery, British Columbia (1891/35)

[1] RC; Hungr- Morgenstern Response Class (see Hungr, 1981; Morgenstern, 1985)

On March 22, 1915, a landslide of rock, mud, and snow suddenly overwhelmed the camp (Figure 2). 56 people were killed when the landslide smashed into a cluster of closely spaced mine buildings. It appears that the landslide was initiated by a small rockslide or large rock fall in Lower Cretaceous schists, approximately 150 m above the Camp (Figure 2). At the base of the slope, the mass changed direction by 90 degrees and travelled about 100 m down a steep slope into a flat-bottomed hollow where it impacted on the mine buildings. Post-slide photographs (Figure 2) show a deep furrow down the slope indicating that the rockslide mobilised a significant volume (ca. 40,000 m^3) of saturated surficial deposits. The landslide, now containing fragments of broken rock and saturated surficial materials, cut a swath about 75 m wide through the mining camp demolishing the buildings as noted above. The deposit at the Camp is estimated to have been about 50,000 m^3. The remainder of the debris flowed down Jane Creek tearing a great rut 15 m deep all the way down to Britannia Creek, a distance of 1.3 km from the source rock slope failure. The total volume of the landslide is thus estimated to be 100,000 m^3. Cracks in the source area rock slope were examined before the disaster and were not considered to pose a threat to the buildings below.

The 1889 rockslide on Champlain Street, Québec City occurred when a large portion of the rock slope, about 85 m in width, fell from beneath the King's Bastion onto houses on the south side of Champlain Street destroying 7 houses (Figure 3) and killing about 50 people (Baillairgé 1893; Drolet et al. 1990)). These deaths brought the total deaths on Champlain Street to 93 in four landslides since 1841 (see Appendix). The volume of the 1889 rockslide was in the order of 53,000 m^3 (Baillairgé, 1893). The presence of "dangerous fissures" in the slope had been reported by C. Baillairgé, City Engineer of Québec City, as early as January 1880. Houses closest to the rock face had been demolished following this report but those on the other side of Champlain Street, those struck in 1889, had been allowed to remain despite the conclusion that houses on both side of the street were in potential danger. In returning its verdict, the coroner's jury found that the deaths were due "to the gross and culpable negligence of the Federal authorities of the Dominion of Canada, in not taking the necessary and timely precautions...." which had been recommended by Baillairgé in his 1880 report. In terms of loss of life, the 1889 Champlain Street rockslide is eastern Canada's most disastrous landslide.

Figure 3. Contemporary photograph of the September 1889 Champlain Street landslide disaster, Québec, Québec. 50 people were crushed to death in the houses at the base of the failed rock slope, below the walls of the Citadel. (Public Archives of Canada Photograph 131073).

Key factors in these disasters were the location of densely populated areas very close to the source rock slopes, the possible role of human forcing in initial failures, and misinterpretation of premonitory signs and/or previous events indicating systemic instability.

Second, in terms of destructiveness are earthflows in Leda Clay which caused 17.0% (98) of the deaths in 9 events in the St. Lawrence Lowlands of Québec (Table 1; Cases 4, 7, 8, 13, 15, 25, 29, 30, and 36 in Appendix). These events included the massive St. Alban landslide (Anonymous, 1898; Evans et al., 1997), the 1908 Notre

Dame de la Salette landslide and displacement wave (Ells, 1908; Lapointe, 1974), and the 1971 St. Jean-Vianney landslide (Figure 4; Tavenas et al., 1971; Potvin et al., 2001). At least 17 landslides in excess of 10^6 m^3 took place in the sensitive marine sediments of the St. Lawrence Lowlands in the period 1842-2000 (Evans et al., 1997), the most recent being the 1996 St. Boniface landslide ($8 \times 10^6 m^3$; Demers et al., 2000).

Figure 4. The St-Jean-Vianney landslide, Québec, May 4th, 1971. Oblique aerial view of the upper part of the landslide scar. Approximately 40 houses were engulfed by retrogression and 31 people died in the Leda Clay earthflow. Some displaced houses are seen in the debris below the scarp. (Canadian Forces Photograph taken on May 7th, 1971).

These landslides are characterized by rapid retrogression at their source (Cases 7, 8, 13, 36) in addition to the extremely rapid flow of remoulded debris emanating from the source crater which, in some cases is transformed into a long reaching destructive distal flow (Cases 4, 15, 29 in Appendix). Evans et al. (1997) found that in the retrogression phase speeds of retrogression could be 5 m/s or greater. The movement of the disintegrating spoil is somewhat faster with velocities between 7-15 m/s being indicated by the testimony of eye witnesses. Leda Clay landslides are thus transitional between Response Class 1 and 2 in the Hungr-Morgenstern Landslide Destructiveness Scale.

The third most destructive type is geotechnical failure, involving the failure of man-made slopes, which accounted for 84 deaths, 15 % of the total, in 7 events (Table 1; Cases 14, 16, 18, 21, 22, 27, and 38 in Appendix). These included the failure of railway embankments (Figure 5), the failure of coal mine waste dumps in southeastern British Columbia (e.g., Hungr at al., 2002), and outburst floods from the failure of embankments that temporarily blocked steep creeks, as in the case of the 1921 Britannia Beach event (Evans, 2000a; Hungr et al., 2001). Characteristics of these failures include rapid failure onset (usually with some meteorological trigger) and extremely rapid velocity with peak velocities in the range of 30-40 m/s. Initial failure volumes vary from small fill failures (~ 0.01×10^6 m^3) to massive waste dump failures involving up to 8×10^6 m^3. In the southeast British Columbia coal mine waste dump failures run-out distances may reach 3 km (Hungr et al., 2002). Geotechnical failures are thus Response Class 1 landslides.

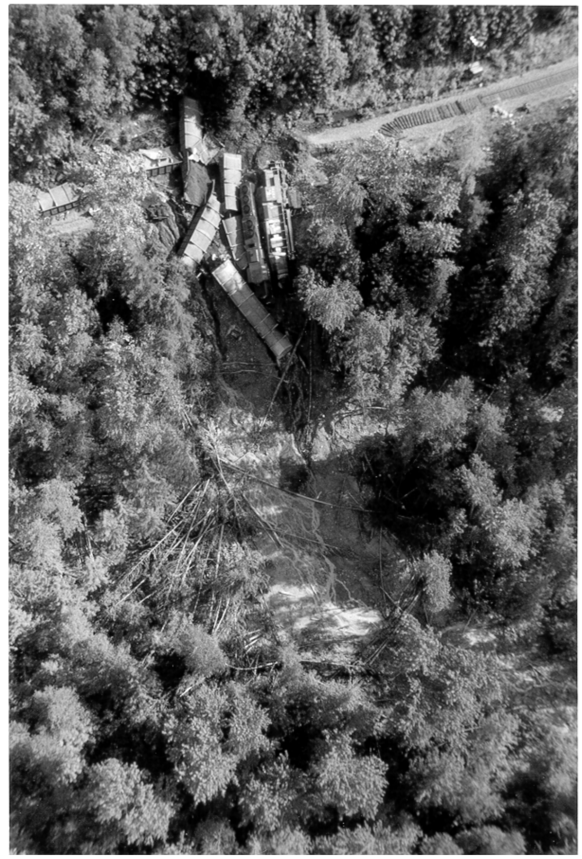

Figure 5. The 1998 failure of a railway fill constructed from glaciolacustrine silt near Creston, British Columbia. The failure, triggered by sustained heavy rainfall, was transformed into an extremely rapid flowslide which swept into the forest below the track up to a distance of 80 m (Transportation Safety Board, 1998).

The fourth most destructive landslide type consists of rock avalanches involving volumes in excess of 10×10^6 m^3. Rock avalanches caused 15 % (83) of the total deaths in only 3 disaster events in the Cordillera (Table 1; Cases 11, 32, and 40 in Appendix). These events were the 1903 Frank rock avalanche (Figure 1; McConnell and Brock, 1904, Cruden and Krahn, 1978; Benko and Stead, 1998; estimated volume 30×10^6 m^3), the 1965 Hope rock avalanche (Figure 6; Matthews and McTaggart, 1978; estimated volume 48×10^6 m^3) and the 1975 Devastation Glacier rockslide/debris avalanche (estimated volume 13×10^6 m^3) in the Mount Meager Volcanic Complex, B.C.

Rock avalanches occur with measurable frequency in the mountain regions of western Canada. In the Coast Mountains of British Columbia, for example, rock avalanches, with volumes in excess of 1 x 10^6 m^3, occurred every 3.5 years in the period 1955 to 1999 (Evans and Clague, 1999). 4 major rock avalanches are known to have occurred in northern British Columbia since 1999 (Schwab et al., 2003). Characteristics of these failures are sudden onset, massive failure volumes, and high velocity in excess of 30m/s. Rock avalanche deposits cover large areas (see below) and, as in the case of the Frank Slide (McConnell and Brock, 1904), damage may occur beyond debris limits as a result of the high velocity movement of liquefied surficial deposits extruded from beneath the debris during emplacement. Rock avalanches belong to Response Class 1.

Figure 6. Aerial view of the 1965 Hope Slide, British Columbia shortly after it occurred. The debris filled up the valley bottom and buried BC Highway 3. Note vehicles at bottom left for scale. Four people were killed in the landslide (British Columbia Archives Photograph).

Fifth, in terms of destructiveness are rain-induced debris flows and debris avalanches involving volumes of ca. 100,000 m^3 or less. These landslides caused 11% (65) of the disaster deaths in 13 events (Table 1; Cases 6, 9, 10, 19, 23, 26, 28, 31, 33, 34, 39, 42, and 43 in Appendix) in British Columbia, Québec, and Newfoundland. In 1996, a debris avalanche triggered by the Saguenay rains impacted a house near La Baie resulting in two deaths (MTQ, 1999). These landslide types are widespread in the Canadian Cordillera (e.g., Schwab,1983; Cass et al., 1992; Couture and Evans, 2001; VanDine and Bovis, 2002; Martin et al. 2002), the uplands of Québec (Dionne and Filion, 1984) and Newfoundland (Liverman et al., 1998). Landslides in this group are characterized by sudden-onset, generally triggered by heavy rains, but velocity varies with landslide type. Debris flows are generally slower (5-10m/s) than debris avalanches (ca. 10 - 20 m/s). This group of landslides is thus transitional between Response Classes 1 and 2.

Figure 7. The August 1973 Harbour Breton debris avalanche, Newfoundland. The debris avalanche swept into homes adjacent to the seashore killing 4 people (Photograph courtesy of D. Liverman, Geological Survey of Newfoundland and Labrador).

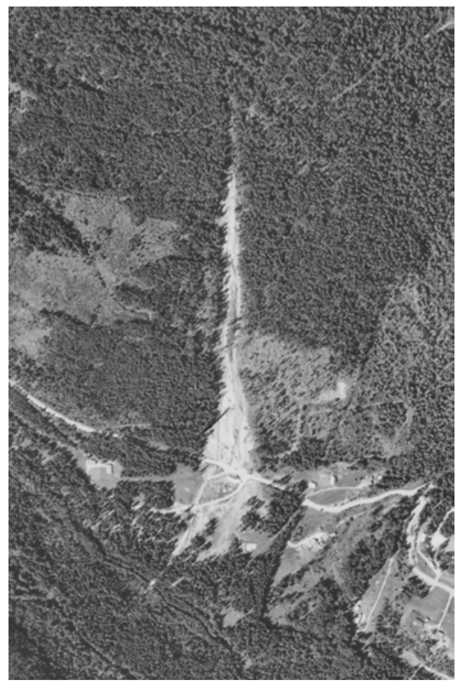

Figure 8. Aerial photograph of the 1990 Belgo Creek debris avalanche, southern British Columbia. 3 people were killed when the debris avalanche crushed their home which was located just upslope from the road. The debris avalanche had a volume of 23,000 m^3 (Province of British Columbia 30BCC93061).

It is worth noting that 125 deaths (22 % of the total) in the Appendix were caused by rapid to extremely rapid flowslide-type movements in Quaternary sediments (glaciolacustrine and glaciomarine) in 12 events in British Columbia and Québec. In two cases (Case 24 and 41) liquefied lacustrine sediments penetrated underground mine workings trapping miners (e.g., Eden, 1964). In addition, many of the landslide deaths in the Appendix were caused by the secondary effects of landslides and related geotechnical failure, *viz.* landslide-generated displacement waves (e.g., Case 13 - the 1908 Notre-Dame-de-la-Salette disaster; Figure 9) and outburst floods (e.g., Case 18 - the 1921 Britannia Beach flood (Evans, 2000a)). These caused 147 (26%) of the total number of deaths in only 5 events.

Figure 9. Destruction caused by the displacement wave generated by Leda Clay landslide at Notre-Dame-de-la-Salette, Québec in April 1908. Landslide occurred on opposite bank of Lièvre River. 33 people were killed (National Archives of Québec Photograph).

3.2 Impact on Communities and Critical Infrastructure

The record of landslide impacts on communities and critical infrastructure involving the loss of less than three lives is less than complete and the direct and indirect costs associated with them are not well known. Here it is sufficient to mention instructive examples.

Rockfalls have impacted on communities in several locations in British Columbia, (Evans and Hungr, 1993), Québec (Ballivy et al., 1984) and Newfoundland (Liverman et al., 1998). Rockfalls have also impacted on railways and highways, mainly in the Cordillera, sometimes with fatal results (e.g., Theodore, 1986; Transportation Safety Board, 1995; Bunce et al. 1997; McKay 1997).

Landslides in Leda Clay have impacted on a number of communities in Québec (e.g., Grondin and Demers, 1996) resulting in the destruction of homes, community buildings (Figure 10), farmland, and the transportation infrastructure (Figure 11). Indeed, the first recorded fatal landslide in Canada occurred at St-Pierre-de-la-Rivière-du-Sud, Québec in 1771. One person was killed when a farmhouse was buried in the debris of a retrogressive earthflow (Evans et al., 1997). In eastern Ontario, four major earthflows occurred along a 20 km reach of the South Nation River near Casselman, between 1895 and 1993 (Evans and Brooks, 1994; Lawrence et al., 1996). The landslides resulted in the loss of productive land. Prior to the 1993 Lemieux landslide, the village of Lemieux had been removed to mitigate the risk of potential losses from future landslides which had been established through geotechnical investigation. The 1993 landslide occurred within 700 m of the former townsite (Lawrence et al., 1996). It is noted that the 1971 and 1993 earthflows temporarily blocked the South Nation River causing extensive upstream flooding which contributed to the losses caused by the landslides (cf. Barlow, 1905).

Figure 10. Impact of landslide on community: the November 1955 Nicolet landslide, Québec, a rapid earthflow in Leda Clay. Three people were killed in the landslide which partially destroyed a church complex. The 147-year-old Cathedral of St-Jean-Baptiste, which stood on the edge of the crater, had to be demolished following the landslide. Total damage was estimated to be in the order of $10M (1955)/$71M (2002) (Province of Québec 377-24)

The mitigation of landslide damming is an important part of the response to river blocking Leda Clay landslides (e.g., Grondin and Demers, 1996).

Most of the recorded historical rock avalanches in the Canadian Cordillera have occurred in remote areas (Evans, 2001). However, where linear infrastructure crosses such areas it may be impacted by these large magnitude events. In the Telkwa Pass area two rock avalanches, in 1999 and 2002, ruptured a major gas pipeline that runs through the area, at two separate locations (Figure 12). Total direct and indirect costs associated events, which occurred in remote mountain locations, has been estimated at nearly $50M in plant closures, interrupted access to forestry and tourist resources, and other costs (Schwab et al., 2003).

Failures in built slopes that are part of Canada’s infrastructure have significant economic impact through losses of equipment, the costs of reconstruction and those associated with delays and demurrage (Figure 5; Evans, 2001).

Debris avalanches and debris flows frequently impact on communities and infrastructure, mainly in British Columbia and Alberta (Figure 13; e.g., VanDine, 1985; VanDine and Bovis, 2002; Couture and Evans, 2000).

Figure 11. Impact of landslide on highway infrastructure: the 1980 Havre St-Pierrre landslide, a retrogressive earthflow in Leda Clay on the north shore of the St. Lawrence, that severed Québec route 138 (AeroPhoto AP8035-087).

Landslides in glaciolacustrine sediments have impacted on communities and infrastructure (Figure 14) in the many parts of Canada underlain by these Pleistocene sediments (Karrow and White, (Editors) 1998). Cases have been documented in northern Québec (e.g., Eden, 1964), northern Ontario (e.g., Nicholl, 1928; Radhakrishna et al. 1992), the Prairie Provinces (e.g., Baracos and Graham, 1981, Miller and Cruden, 2002) and British Columbia (e.g., McCarty and Cavers. 1998; Polysou et al., 1998; Clague and Evans, In Press). Ice rich glaciolacustrine sediments are a major landslide hazard to northern pipelines (Dyke, 2001) traversing permafrost terrain.

In the Prairie Provinces and northeastern British Columbia landslides in Cretaceous shales have impacted on the stability of numerous bridge crossings (e.g., Thomson and Hayley, 1975; Hardy, 1963). The 1957 failure of the Peace River Bridge at Taylor, British Columbia, occurred when the north anchor block moved and caused the suspension bridge to collapse (Figure 15; Hardy, 1963; Brooker and Peck, 1993). Total costs of the failure are estimated to be $80M (1986 dollars) including $60M of direct costs (Cruden et al., 1989). Instability in Cretaceous bedrock has also impacted on urban communities and pipelines. Barlow et al. (2002), for example, summarized the impact of bedrock landslides on homes in the Edmonton area including the 1999 Whitemud Road landslide, which has been the subject of litigation. In 1997, a bedrock landslide on the north valley wall of the Peace River near Fort St. John, B.C., caused a natural gas pipeline rupture and explosion (Transportation Safety Board, 1998).

Figure 12. Oblique aerial photograph of 2002 rock avalanche - debris flow in the Coast Mountains, British Columbia. Initial failure volume was ca. 1.4 x $10^6 m^3$. The rock avalanche and debris entrained from the channel travelled 3.7 km from the base of the failed slope and dammed the Zymoetz River (centre bottom left). Source of rock avalanche is indicated by arrow. Just above the river the debris ruptured a natural gas pipeline supplying Terrace, Kitimat and other areas in northwestern British Columbia. Total direct and indirect costs associated with the event are approximately $33.4 M (Schwab et al., 2003).

4. FATAL LANDSLIDE RISK

Historical databases of damaging landslides may be analysed by plotting the cumulative frequency per year of a disastrous consequence of a landslide (in this case deaths), commonly termed an F/N plot (see references in Cruden and Fell (Editors) 1997). This was first attempted for the Canadian fatal landslide record by Evans (1997). The method was subsequently applied to Italian and other landslide data by Guzzetti (2000). The line formed by the F/N plot is termed a risk envelope (Evans, 2000) and more than defining a line of acceptable risk forms an envelope of unacceptable risk formed by failures.

4.1 The Canada Fatal Landslide Risk Envelope

Figure 13. Vertical aerial photograph of the path of the 1997 Hummingbird Creek debris flow, British Columbia. The debris flow was initiated as a 25,000 m^3 debris avalanche in the upper part of the drainage basin (arrow) and flowed down the creek damaging houses on the fan at Swansea Point. 92,000 m^3 of sediment was deposited in the event (Jakob et al., 2000). (British Columbia aerial photograph 15BCCB97069-33).

Figure 14. First phase of landslide in glaciolacustrine silts and clays, Beatton River valley, near Fort St, John, B.C. (Raymond et al., 2003). The landslide severed BC Road 103 in 2001 interrupting agricultural and oilfield traffic. Soon after this photograph was taken, the landslide developed into a more complex failure (photograph courtesy of BC Ministry of Transportation and Highways).

In the Canada Landslide risk envelope (Figure 16), the probability of fatalities is related to the number of fatalities in an event through a power law (Equation 2)

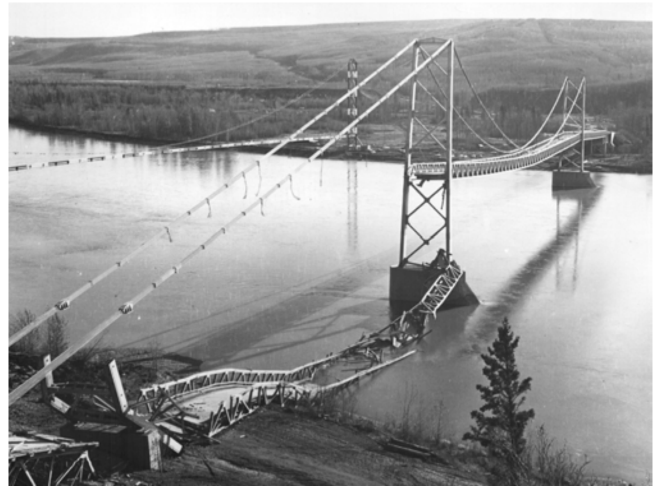

Figure 15. The 1957 collapse of the Peace River Bridge, Alaska Highway, Taylor, British Columbia, caused by sliding of the north anchor block (left foreground) in Cretaceous bedrock (photograph courtesy of the North Peace Historical Society).

$$F = aN^b \qquad [2]$$

where F is the annual probability of a disaster occurring with N or more deaths, and a is a constant.

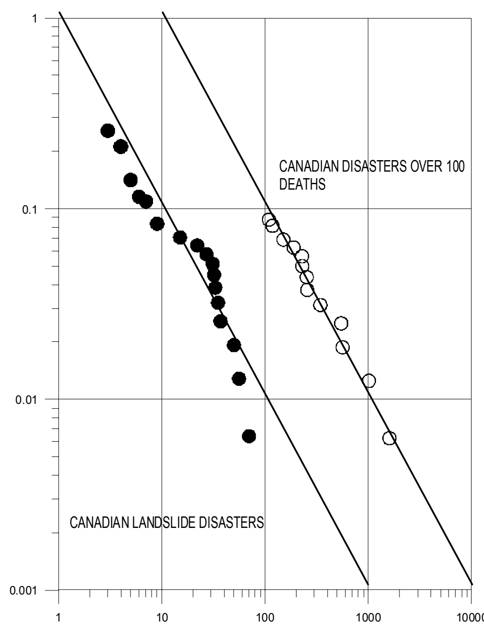

Figure 16. The Fatal Landslide risk envelope for Canada compared for the Disaster Risk Envelope for Canada, which includes the major disasters in the period 1840-2000. Regression lines with b = -1 have been superimposed on the data plot.

Importantly, the Canada landslide risk envelope (Figure 16) derived from the historical database in the Appendix is largely defined by disastrous events that occurred before 1930, in what was essentially an unregulated pre- technical environment in a period of intense resource development (Evans, 2000b). 432 (75% of the total) of the total fatalities in the Canadian landslide record took place before 1930.

There is a strong suggestion that a major portion of the deaths in the record resulted from landslides which were strongly influenced by human activity and landslides resulting from geotechnical failures. In the Canadian context, many disastrous landslides represent a technological failure triggered by an extreme meteorological event. Evans (2000b). It is suggested that their presence in the record represents an element of added risk in the national landslide risk envelope.

For a reference event of 50 deaths for example, the annual probability of this number of fatalities (or greater) is 0.20 (return period of 50 years), compared to 0.48 (return period of ca. 21 years) for Italy, based on Guzzetti's (2000) record of fatal landslides in the period. This to some extent reflects Italy's denser population but may also reflect the higher frequency of damaging landslides in populated areas.

4.2 Indications of constant risk.

In earlier work Evans (1997) suggested that b in Equation 2 was ~ -1 indicating that the risk envelope represented one of constant risk. When the data for historical Canadian disasters which resulted in a death toll of 100 or more is plotted in Figure 16, a similar result is found i.e., b ~ -1. It is noted that Knopoff and Sornette (1995) found a similar result for historical earthquake death tolls.

The strong indications that disaster death toll data sets form robust power laws in which the exponent b is -1 holds some considerable promise for risk assessment at regional and national scales, since, to generate a risk envelope all that is required is the position of the events associated with the greatest losses. In addition, this finding provides an improved quantitative basis for the definition of an acceptable risk for a given domain.

5. LANDSLIDE DESTRUCTIVENESS

5.1 The Landslide Destructiveness Index (Volume)

Investigation of the Las Colinas flowslide triggered by the January 2001 El Salvador earthquake (Evans and Bent, In Press) which caused ca. 600 deaths provided dramatic evidence that a comparatively small landslide (130,000 m^3) can be highly destructive in terms of loss of life when it impacts a densely populated urban area. The fact that smaller landslides are more frequent presents a particular challenge to characterizing landslide risk.

In attempt to link the extent of landslides and their destructiveness, the Landslide Destructiveness Index (LDI) is proposed. The LDI is defined in Equation 3 as the ratio of loss per unit volume of the damaging landslide in question.

$$LDI_{vol} = L/V \quad [3]$$

where L is loss and V is landslide volume measured in cubic metres. Loss can be measured in terms of mortality, monetary cost, damaged dwellings, etc. Where loss is measured in deaths, LDI is a function of the population density of the area struck by the landslide. The LDI tends to 1 in the case of small rockfalls.

To illustrate the application of the LDI, losses in terms of landslide deaths are examined. With reference to the Canadian record, LDI has been calculated on the basis of deaths resulting from landslides in the Appendix and first-order volume estimates of the associated damaging landslide.

A plot of LDI v. landslide volume (Figure 17) shows a negative power - law relationship in which LDI is scaled to landslide volume (V) by Equation 4.

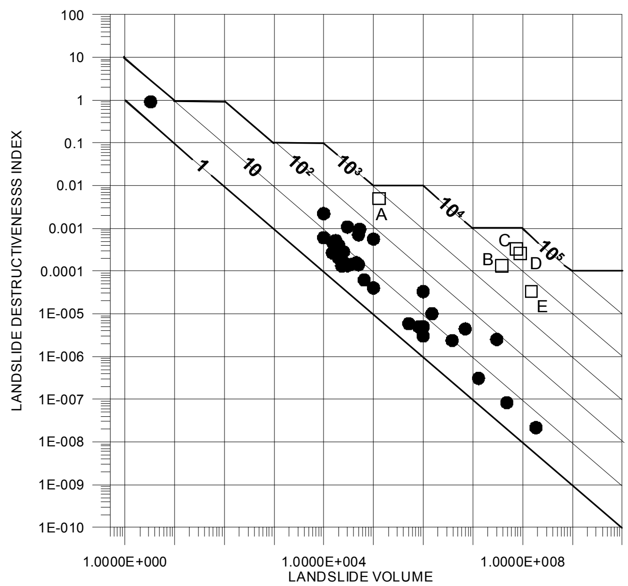

Figure 17. Plot of Landslide Destructiveness Index (LDI_{vol}) based on Equation 3 v. Landslide Volume (V) for Canadian landslide events in Appendix (filled circles). Also included are data points for some highly destructive landslides from other parts of the world (open squares) as follows (dates in brackets); A - Las Colinas, El Salvador (2001); B – Kelud, Indonesia (1919); C – Huascaran, Peru (1970); D – Nevado del Ruiz, Colombia (1985); E - Mont Granier, France (1248). Diagonal lines show loci of equal number of deaths from 1 to 10^5 fatalities.

$$LDI = aV^b \quad [4]$$

where V is volume of deposit in m^3, where a is a constant and b ~ -1 (Figure 17). The relationship is inverse showing that small magnitude-high frequency landslides are more destructive on a per unit volume basis than larger less frequent events.

The landslide destructiveness space is now mapped out in Figure 17. A lower limit of 1 death per event establishes the lower boundary of the plot envelope. A series of parallel lines with a spacing of one log. cycle may be plotted to the right of the lower boundary (Figure 17). These correspond to 10, 10^2, deaths and so on to a maximum of 10^5 deaths. It is suggested that 10^5 is approaching the maximum credible death toll in a single event landslide. This maximum may be approximated by taking the highest recorded population density in the world (ca. 20,000 persons/km^2 in a part of Tokyo) and the area of a huge landslide. In this case, we may take the debris area (45 km^2) of the 1911 Usoi rockslide, Tajikistan, which is the largest landslide of the twentieth century (Gaziev, 1984). If we assume that this landslide debris buries an area that has a population density corresponding to the maximum recorded on earth, a death toll as high as 200,000 could result. The upper boundary can thus be approximated as seen in Figure 17. The lower and upper boundary thus defines a landslide destructiveness space. Figure 17 is a plot of destructiveness for landslides in Response Class 1 and assumes that vulnerability is equal to susceptibility and that no resistance exists in the system.

Some of the most destructive landslides in the global historical record plot near the upper boundary of the landslide destructiveness space (Figure 17) suggesting that this first approximation to an upper boundary is quite realistic.

In evaluating the possible use of Figure 17 in landslide risk assessment, the relationship between landslide debris area and original landslide volume becomes critical, since as the Usoi calculation showed above, the area of burial by debris, or in other cases, area of loss through retrogression, controls the magnitude of landslide loss.

5.2 Landslide Volume-Area relationships

Data on area-volume relationships for rock avalanches (Li, 1983), Leda Clay earthflows (Evans, unpublished data) and debris flows (Innes, 1983) was plotted in Figure 18. A power law relationship is evident. Area is scaled to volume by Equation 5.

$$\text{Area (A)} = 3.03\ V^{0,6377} \qquad [5]$$

with r^2 = 0.9428. Note that the exponent is very close to 0.67 indicating a scale-invariant self-similar form over a wide range of landslide volumes and landslide styles first noted by Hungr (1990).

5.3 Landslide Destructiveness Index (Area)

We may now use Equation 5 to transform the landslide volume data in Figure 17 to area, thus providing a spatial link between landslide fatalities and population density. In Figure 19 the Landslide Destructiveness Index is expressed in terms of area [Equation 6]

$$LDI_{area} = L/A \qquad [6]$$

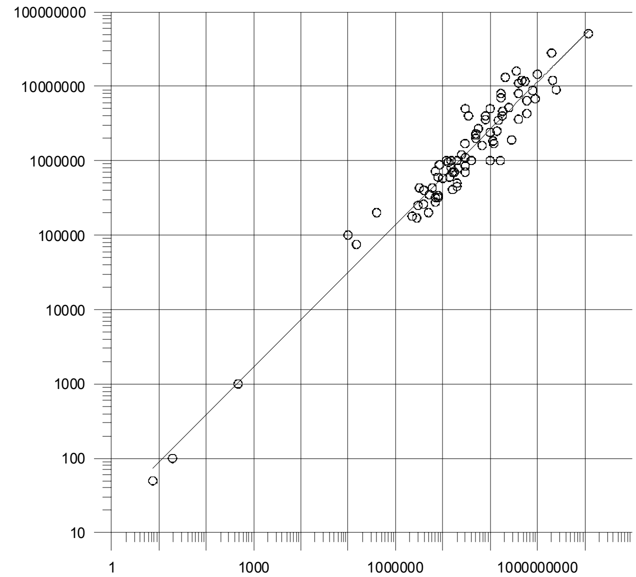

Figure 18. Relationship between landslide volume (V) and landslide area (A) for rock avalanches in the Alps (data from Li, 1983), debris flows (data from Innes, 1983) and Leda Clay earthflows (Evans, unpublished data).

LDI area can also be expressed as an equivalent population density and this is scaled on the right vertical axis in Figure 19.

Also plotted on Figure 19 are the key population density benchmarks that help define the vulnerability of communities to landslide hazard. It is seen that highly destructive landslides, resulting in high mortality, are possible even though overall population density thresholds are comparatively low.

Figure 19 helps identify the conditions for a future major single-event landslide disaster in Canada, defined for the sake of this discussion as a Class 1 landslide event that results in the loss of more than 100 lives, thus exceeding the death toll at Frank. For population densities in excess of 100 p/km^2 (up to a national maximum of ca. 4000 p/km^2), this death toll may be result from Class 1 landslides with an area between 0.11 and 1 x $10^6 m^3$.

At population densities between 10 and 100 p/km^2, a range that includes the ecumene density, the required landslide area ranges between 10^6 and 10^7 m^2. At population densities below 10 p/km^2 down to the national average of 3.3 p/km^2, a landslide area in excess of 10^7 m^3 is required. In the absence of damaging secondary effects beyond landslide limits, only rock avalanches (including rock slope failures in the Quaternary volcanic centres of the southern Cordillera), earthflows in Leda Clay, and large flowslides in some glaciolacustrine sediments reach landslide volumes (cf. Figure 18) sufficient to inflict this magnitude of destruction below population densities of 100 p/km^2.

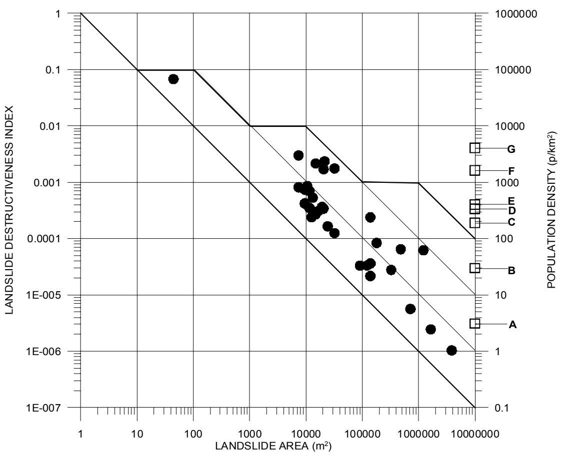

Figure 19. Plot of Landslide Destructiveness Index (LDI_{area}) based on Equation 5, v. Landslide Area for Canadian landslide events in Appendix (black dots). Area for these events was calculated using Equation 5. Equivalent population density is plotted on the right axis and reference population densities are labeled as follows; A - Canada Population Density (3.1 p/km^2); B – Population Density of Canada's population ecumene (30 p/km^2); C: Italy (189.9 p/km^2) D; Japan (336.1 p/km^2) E: Lower limit for urban centres as defined by Statistics Canada (400 p/km^2); F: Average of 9 largest urban centres in Canada (p/km^2); G : Highest in Canada (Vancouver – 4000 p/km^2). [Population density data from Statistics Canada]. Diagonal lines are loci of equal number of deaths, 1, 10, 10^2, 10^3, 10^4 fatalities respectively (cf. Figure 17). Thicker lines define the Landslide Destructiveness Space.

7. CONCLUSIONS

Landslides are Canada's most destructive geological hazard. The geography of Canada is such that the vulnerability of communities to damaging landslides is largely confined to about 10% of its land area in the population ecumene. In contrast, long lines of linear infrastructure are vulnerable in uninhabited areas subject to landslides. The most damaging landslide styles have been identified based on the record of historical damage. These landslides occur in soil, rock and debris but may be transformed following initial failure into complex flows consisting a mixture of materials. They are characterized by rapid onset and high velocity, and have occurred as a result of a range of triggers including human and climatic forcing. Notably, there is an absence of an earthquake-triggered landslide disaster in the period of record (1840-2000).

The fatal landslide risk envelope for Canada suggests a concept of constant risk, i.e. that the product of consequence and the probability of that consequence being equaled or exceeded over a given period of time is constant. The introduction of the Landslide Destructiveness Index (LDI) shows that smaller landslides are more destructive per unit volume, or per unit area, than larger landslides. A landslide destructiveness space was mapped out and the boundaries set limits for landslide destructiveness. LDI for communities is shown to be a proxy for population density and knowing this property for a domain together with the magnitude and frequency of damaging landslides affecting it completes the framework for quantitative risk assessment at the site, regional, national and global levels. The vulnerability of critical infrastructure is more complex, consisting of fixed (e.g., track or highway) and transitory (e.g., traffic) elements.

Synthetic risk envelopes are not yet achievable beyond the site scale since raw regional magnitude/frequency relations have limited utility; only a certain number of landslides in the magnitude/frequency spectrum actually impact on populated areas with population densities above the disaster threshold.

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APPENDIX – TABLE OF LANDSLIDE DISASTERS IN CANADA (1840-2002) LISTING THOSE LANDSLIDES AND GEOTECHNICAL FAILURES WHICH RESULTED IN 3 OR MORE DEATHS (Modified from Evans (1999, 2000).

No	Date	Location	Prov	Deaths	Comments
1	1841/05/17	Quebec City	Que.	32	Rockslide destroyed houses on Champlain Street
2	1852/07/14	Quebec City	Que.	7	Rockslide destroyed houses on Champlain Street at Cap Blanc
3	1864/10/11	Quebec City	Que.	4	Rockslide destroyed houses on Champlain Street
4	1877/05/01	Ste-Genevieve-de-Batiscan	Que.	5	Earthflow in Leda Clay overwhelmed mill and adjoining house
5	1889/09/19	Quebec City	Que.	50	Rockslide destroyed houses on Champlain Street
6	1891/07/06	North Pacific Cannery	B.C.	35	Workers homes overwhelmed by debris flow or flood caused by breach of landslide dam after heavy rains
7	1894/04/27	St-Alban	Que.	4	Farmhouses carried away by massive landslide in Leda Clay
8	1895/09/21	St-Luc-de-Vincennes	Que.	5	Home destroyed by earthflow in Leda Clay
9	1897/04/20	Sheep Creek, nr. Rossland	B.C.	7	Debris flow struck railway maintenance camp
10	1898/02/?/	Quesnel Forks	B.C.	3	Victims were miners
11	1903/04/29	Frank	Alta.	70	Rock avalanche buried part of the coal mining town of Frank
12	1905/08/13	Spences Bridge	B.C.	15	Landslide into Thompson River caused displacement wave which swept victims away
13	1908/04/26	Notre-Dame-de-la-Salette	Que.	33	Landslide in Leda Clay into Lievre River caused wave containing blocks of ice which destroyed homes
14	1909/11/28	Burnaby	B.C.	22	Slump of railway embankment; work train derailed
15	1910/04/15	St-Alphonse-de-Bagotville	Que	4	Construction camp buried by landslide in Leda Clay caused by blasting during construction of railway
16	1910/04/18	Coucoucache	Que	6	Slump of railway embankment; work train derailed
17	1915/03/22	Jane Camp	B.C.	56	Rock avalanche from above portal of mine swept into mining camp
18	1921/10/28	Britannia Beach	B.C.	37	Outburst flood caused by failure of railway fill swept away more than 50 houses 4.5 km downstream
19	1922/09/30	Elcho Harbour	B.C.	5	Debris avalanche caused by heavy rains destroyed logging camp
20	1929/11/18	Burin Peninsula	Nfl.	27	Tsunami generated by massive earthquake-generated submarine slump destroyed buildings along shore
21	1930/06/26	Capreol	Ont.	4	Slump of railway embankment; passenger train derailed into Vermillion River
22	1930/06/27	Crerar	Ont.	8	Slump of railway embankment; freight train derailed.
23	1938/09/01	St-Gregoire-de-Montmorency	Que.	4	Landslide caused by heavy rains destroyed apartment building below
24	1946/07/19	Beattie Mine, Duparquet	Que.	4	Landslide debris flowed into mine shaft killing miners underground
25	1955/11/12	Nicolet	Que.	3	Earthflow in Leda Clay : $10 M damage including destruction of church complex
26	1957/11/22	Prince Rupert	B.C.	7	Debris avalanche triggered by heavy rains buried 3 houses
27	1959/03/27	Revelstoke	B.C.	4	Landslide triggered by highway construction struck house
28	1960/09/07	McBride	B.C.	3	Debris flow ; victims were highway construction workers
29	1962/05/23	Riviere Toulnustouc	Que.	9	Workers killed by landslide in marine clay caused by blasting
30	1963/12/11	St-Joachim-de-Tourelle	Que.	4	Earthflow in Leda Clay; victims drove into landslide crater
31	1964/09/16	Ramsay Arm	B.C.	5	Debris flow caused by heavy rains struck logging camp
32	1965/01/09	Hope	B.C.	4	Massive rock avalanche buried vehicles on B.C. Highway #3
33	1965/01/14	Ocean Falls	B.C.	7	Slush avalanche/debris flow caused by heavy rains melting snow struck community
34	1968/06/05	Camp Creek	B.C.	4	Debris flow caused by heavy rains struck car on Trans-Canada Highway
35	1969/02/09	Porteau	B.C.	3	Rockfall struck car at Porteau Bluffs on Squamish Highway
36	1971/05/04	St-Jean-Vianney	Que.	31	Rapid retrogressive flowslide in Leda Clay swept away 40 homes
37	1971/05/04	Boothroyd, Fraser Canyon	B.C.	3	CNR train derailed by rockfall.
38	1972/03/20	Michel	B.C.	3	Debris flow from coal mine waste dump struck CPR maintenance crew, 16 km west of Croswnest.
39	1973/08/01	Harbour Breton	Nfl.	4	Debris avalanche struck houses. 4 houses swept into harbour and destroyed.
40	1975/07/22	Devastation Glacier	B.C.	4	Massive rock avalanche buries geophysical survey crew
41	1980/05/20	Belmoral Mine, Val D'Or	Que.	8	Cave-in of mine roof triggered a flow of lacustrine sediments into mine workings
42	1981/10/28	M-Creek Bridge, Highway 99	B.C.	9	4 vehicles plunged into creek after debris flow had destroyed bridge on Squamish Highway during heavy rains
43	1990/06/12	Joe Rich	B.C.	3	Debris avalanche caused by heavy rains destroyed house