



Natural Resources
Canada

Ressources naturelles
Canada

**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7897**

**EXAMPLES OF COMMON LANDSLIDE TYPES
IN CANADA**

**Canadian Technical Guidelines and Best Practices related
to Landslides: a national initiative for loss reduction**

O. Hungr and J. Locat

2015

Canada



**GEOLOGICAL SURVEY OF CANADA
OPEN FILE 7897**

EXAMPLES OF COMMON LANDSLIDE TYPES IN CANADA

Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction

O. Hungr¹ and J. Locat²

¹ University of British Columbia, Vancouver, British Columbia

² Laval University, Québec, Québec

2015

© Her Majesty the Queen in Right of Canada, as represented by the Minister of Natural Resources Canada, 2015

doi:10.4095/296666

This publication is available for free download through GEOSCAN (<http://geoscan.nrcan.gc.ca/>).

Recommended citation

Hungr, O. and Locat, J., 2015. Examples of Common Landslide Types in Canada – Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction; Geological Survey of Canada, Open File 7897, 90 p. doi:10.4095/296666

Publications in this series have not been edited; they are released as submitted by the authors.

Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction

EXAMPLES OF COMMON LANDSLIDE TYPES IN CANADA

Note to Reader

This is the tenth publication in a series of Geological Survey of Canada Open Files that has appeared during the past 3 years. The series forms the basis of the *Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction*. Once all Open Files have been published, they will be further edited, compiled and published as a GSC Bulletin. Each open file in the series corresponds to a chapter in the bulletin.

Comments on this Open File, or others in this series should be sent to Dr. P. Bobrowsky at pbobrows@NRCan.gc.ca.

1. INTRODUCTION

The second largest country in the world, Canada has an area of nearly 10 million km². A wide variety of landslides occur in the mountains, along river valleys, on hills and escarpments, in the extensive areas of permafrost, along the shores of oceans and lakes, and under water. Landslides are associated with both natural slopes and engineered excavations and fill slopes.

Summaries of landslides in Canada are available elsewhere (for example, Mollard, 1977; Cruden et al., 1989b and Evans, 2001). The purpose of this report is to update the record with recent examples, present the landslides in the context of both geographic distribution and physical characteristics, and describe loss reduction approaches.

As noted elsewhere, landslides in Canada correlate, to some extent, with the broad physiographic regions of the country: 1) Canadian Cordillera, 2) Interior Plains, 3) Canadian Shield, 4) St. Lawrence Lowlands, 5) Appalachian Mountains, 6) Arctic Lowlands, and 7) Inuitian Mountains (physiographic regions after Guthrie, 2013). Mollard (1977) reviewed regional landslide types in four of these regions that he referred to as (paraphrased): 1) Cordillera, 2) Cretaceous rocks of the Prairie river valleys, 3) raised Pleistocene marine clay deposits of the Ottawa-St. Lawrence Lowlands, and 4) the periglacial terrains of the Arctic and sub-arctic Canada. The implication is that the Canadian Shield, the Appalachian Mountains and the Inuitian Mountains have relatively few landslides. As such, a discussion of landslides based strictly on physiographic regions gives an incomplete picture.

In addition, some types of landslides are common in a number of physiographic regions of Canada. For example, glaciomarine clay slides and flows occur both in the St. Lawrence Lowlands and in the Cordillera. Similar landslides are also common in freshwater glaciolacustrine clays and silts of the Interior Plains. Debris flows and debris avalanches are ubiquitous in the Cordillera, but have also caused damage and fatalities in the Appalachian Mountains. Small debris avalanches occur in all parts of Canada, including those along eroded river banks and lake shorelines, and in connection with engineered excavations and fill slopes. Rock falls and rock slides also occur in all parts of Canada, including those along road and railway cuts and in mining excavations.

Although this contribution refers to the physiographic regions where the landslide types are most common, its primary organization focuses on: occurrence; identification; characterization; hazard and/or risk analysis and assessment; and management and mitigation.

The landslide terminology used here is, for the most part, based on the WP/WLI Classification or Working Classification as it is commonly known (Cruden and VanDine, 2013).

2. EXAMPLES OF COMMON LANDSLIDE TYPES

2.1 Glaciomarine Clay Slides, Flows, and Spreads

2.1.1 Occurrence and Identification

Landslides in glaciomarine clay are found in sedimentary basins that have been glaciated and subsequently submerged by shallow seas. Such a marine environment favoured the formation of flocculated structures in the sediment, with a liquidity index close to 1.0 (Locat, 1995). After land emersion and sea regression, much of the residual salt was leached from the porewater in the soil resulting in a salinity < 1.0 g/l, with a consequent increase in the liquidity index as high as 9.0 (Saihi et al., 2002). This process explains the low remolded undrained shear strength and high sensitivity nature of such soils (Figure 1). According to the Canadian Foundation Engineering Manual (Canadian Geotechnical Society, 2006), most leached clays in eastern Canada have a medium (10 to 40) to high (> 40) sensitivity. In some cases, the sensitivity can reach values up to 500.

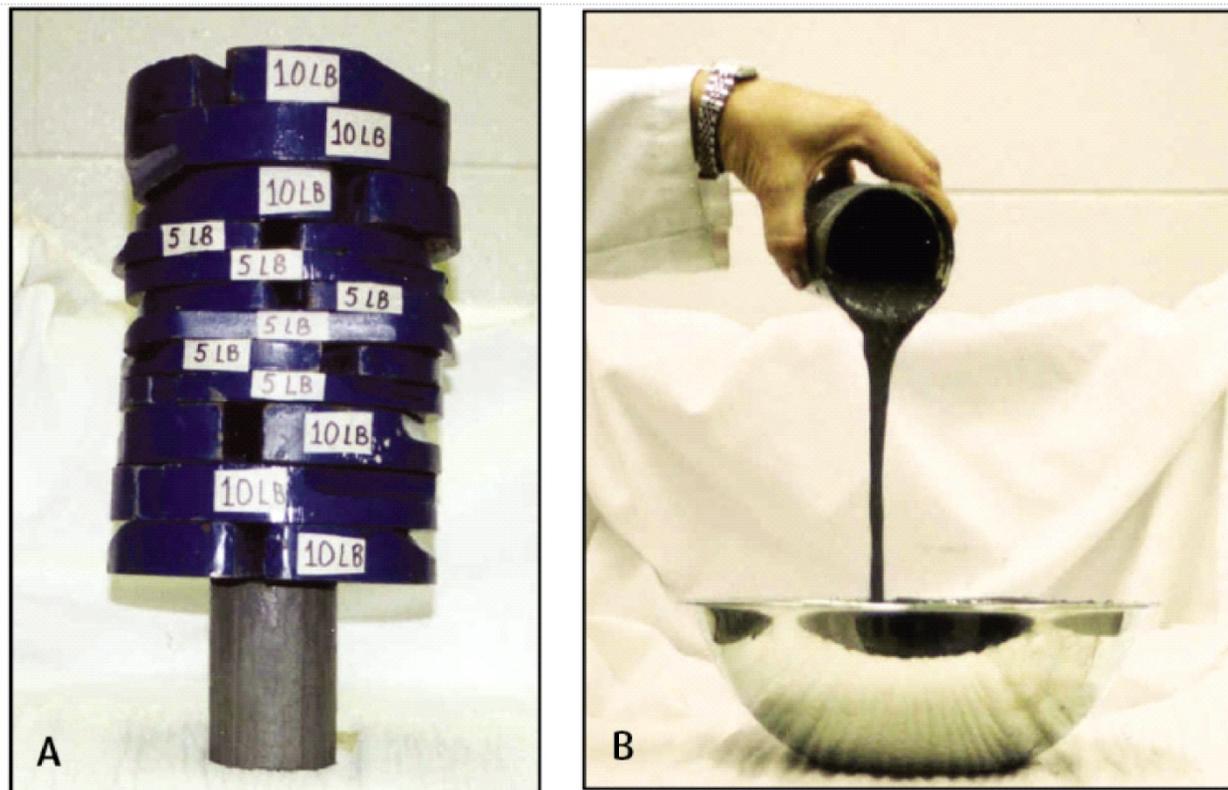


Figure 1. Demonstration of the sensitivity of Lake Champlain Sea clay: a) intact sample; b) remolded sample (photo Ministère des Transports de Québec (MTQ), used with permission).

In Canada, sensitive clay is found mostly in Quebec, Ontario and Labrador, but also occurs in some marine and former marine valleys of BC. Until the 1980s, sensitive clay in eastern Canada was often referred to as Leda clay (from the name of a fossil it often contains, *Leda lampsilis*). Today the name of the clay is referenced to its corresponding sedimentary basin (e.g. Champlain Sea clay) to better describe the sedimentary environment and physico-chemical characteristics of the deposits (Locat, 1995; Locat et al., 2003).

Landslides in sensitive clay are triggered by erosion in river meanders (the most frequent case; Demers et al., 2008), strong earthquakes (Lefebvre et al., 1992) and human activities (e.g. the 1954 Nicolet landslide; Hurtubise and Rochette, 1956). Most of the landslides caused by erosion occur following spring snowmelt or during the fall rainy season thereby suggesting that high porewater pressure is a precondition, however, erosion rates are also often elevated during these same periods (Lefebvre and Lafleur, 1978; Lebus et al., 1983). Regarding high porewater pressure, Lefebvre and Lafleur (1978) found evapotranspiration to be related to infiltration, and this may explain why the months with the highest precipitation rates do not correspond to months with the greatest number of landslides. Recent studies have shown that high porewater pressure can exist at the toe of a slope to the extent where local effective stresses can be close to zero (e.g. St. Jude landslide; Locat et al., 2012b). Therefore, quantitative slope stability analyses of sensitive clay require that a sufficient network of piezometers be installed, at least near the crest and toe of the slope.

In most sedimentary basins, thick marine clay is often underlain by glaciofluvial sediments or more permeable tills (Locat, 1995). Such stratigraphic sequences favour the development of high hydraulic gradients as shown by the valley formation process described by Lefebvre (1996; Figure 2). The most critical condition occurs where the high hydraulic gradient (i) is directed upwards near the toe of the slope (Figure 2b). The initial landslide often occurs as a slide, typically a shallow or deep rotational slide that can develop into a large flow or spread, or a combination of both. The resulting landslide can involve a large volume of material that can mobilize within minutes (Demers et al., 1999; Demers et al., 2008).

2.1.2 Characterization

Glaciomarine clay slides, flows, and spreads have characteristic morphological features that can be identified on airphotos and/or from airborne light detection and ranging (LiDAR) surveys. LiDAR data are used to generate digital elevation models (DEMs) that often reveal features not readily identifiable on even large scale airphotos (Jaboyedoff et al., 2009). Airphotos and LiDAR surveys should be carried out in the spring or the fall when there is minimal foliage and snow cover (Jaboyedoff et al., 2009; Lévy et al., 2012).

The geotechnical properties of sensitive clays require sophisticated sampling techniques to reduce the amount of remolding during sampling. The two main types of samplers are the Laval sampler (La Rochelle et al., 1981) and the Sherbrooke sampler (Lefebvre and Poulin, 1979). Both collect samples up to 20 cm in diameter to a depth of approximately 20 m. In addition to sampling methods, *in situ* field vane tests are still carried out, however, the piezocone is currently the primary *in situ* test that is integrated into many site investigations of slope stability in sensitive clays (Demers and Leroueil, 2002).

Following detailed investigations of 20 different sites in the St. Lawrence River Valley, Lefebvre (1981 and 1996) proposed a range of strength parameters for the long term analysis of slopes in sensitive clays with varying degrees of over-consolidation (Table 1). Lefebvre (1981) considered that post-peak strength parameters, defined at about 8% of axial deformation, are justified for slope stability analyses because they coincide with a threshold stress above which

landslides will occur. Lefebvre (1981) found that under post-peak strength conditions, cohesion was approximately 7.5 kPa for all sites investigated.

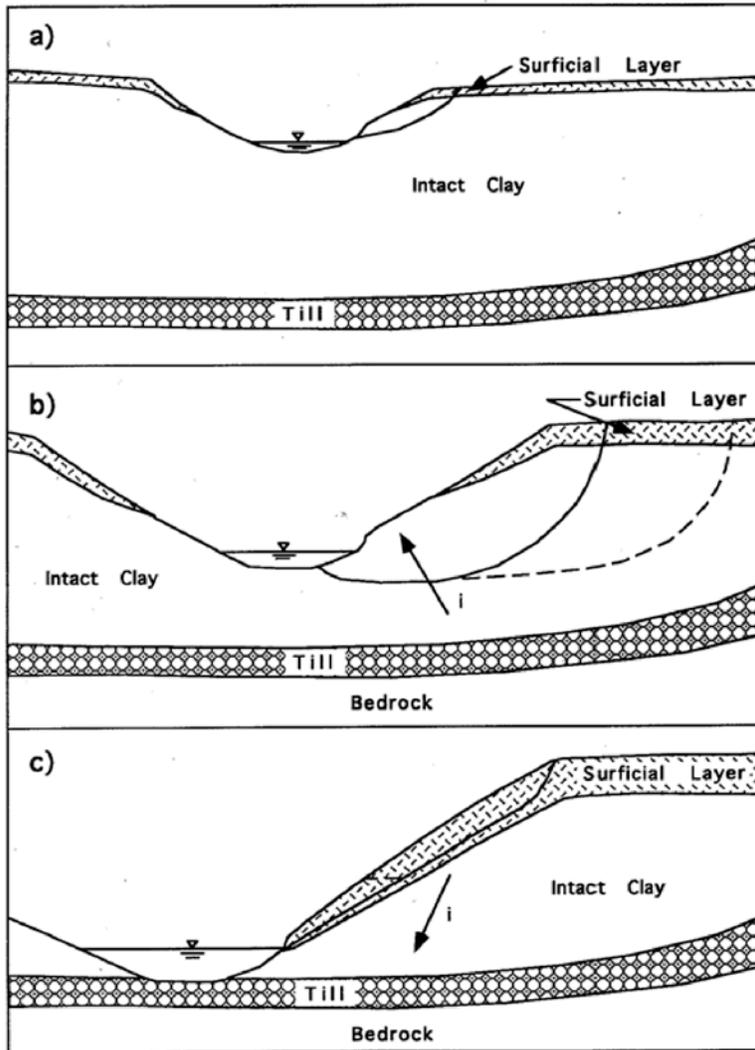


Figure 2. Stages of valley formation in marine clay deposits: a) early phase, b) intermediate phase, c) advanced phase. ('i' is hydraulic gradient) (Lefebvre, 1996).

Table 1. Mobilized average post-peak strength parameters for sensitive clay for Champlain Sea deposits for use in drained analysis (modified from Lefebvre, 1996).

Over-consolidation	Cohesion	Friction angle
σ_p (kPa)	c_m' (kPa)	ϕ_m' (degrees)
100	7.4	28.7
200	7.7	34.7
300	7.7	39.8
400	7.5	43.6

Locat (2012) has shown that sensitive clays exhibit a strong strain softening behavior, particularly under low stress, which is the case for most slopes in the St. Lawrence River Valley.

2.1.3 Analysis and Modeling

The analysis and modeling of landslides in sensitive clay are related to the mode of movement: slide, flow or spread. In all cases the porewater pressure condition of the slope is important. There are certain conditions that favour the development of complex types of movement; for example, a “first slide” (see following) can evolve into a flow or spread.

Before addressing specific analyses, the general approach to the overall slope stability analysis, as proposed by Lefebvre et al. (2008), is reviewed (Figure 3). The approach integrates field observations with slope classification to optimize the information provided by the morphology and landslide history of an area. Then, based on this preliminary analysis, the stability can be qualitatively assessed and further studies and treatment considered. In this context, the long term stability of the eroded slope is critical. That is, over time the slope will come to equilibrium (factor of safety approaches 1.0), with the slope forming processes (Locat, 2001).

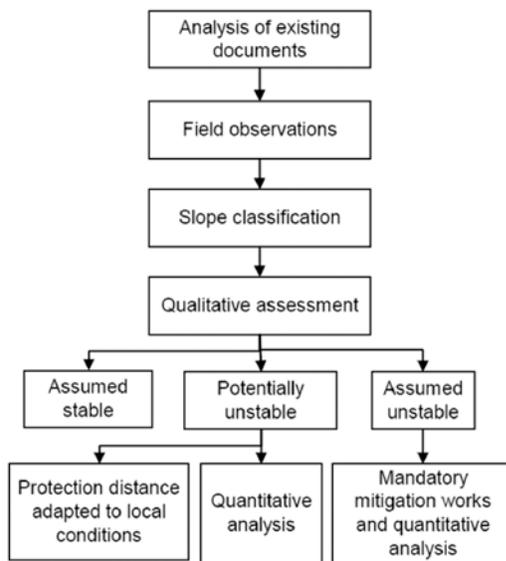


Figure 3. General approach to the overall assessment of the stability of a slope (Lefebvre et al., 2008).

First Slide - A standard slope stability analysis of natural slopes in sensitive clay is carried out initially by considering a circular arc failure (Lefebvre, 1996). Since the slopes are typically the result of erosion, a ‘drained’ analysis is carried out with cohesion approximately 7.5 kPa and a friction angle between 29° and 44°, depending on the degree of over-consolidation of the clay (Table 1). For earthquake-triggered landslides in sensitive clay, ‘undrained’ conditions are analyzed (Lefebvre et al., 1992) with ground acceleration obtained from the Canadian Seismic Network (Adams and Halchuk, 2003). In all cases, the Mohr-Coulomb failure criterion is used.

First time slides were analyzed in detail by Demers et al. (1999), using the 1989 Maskinongé landslide as an example (Figure 4). They concluded that, with time, there is a gradual strength reduction along the failure plane, that is, the plane that gives the lowest factor of safety. They

also demonstrated the potential of the cone penetration test (CPTU) to define a zone of reduced strength. As discussed previously, the porewater pressure distribution in the slope should be investigated and analyzed.



Figure 4. Maskinongé landslide, QC (Demers et al., 1999).

Flows - Flows in sensitive clays consist of rapid, very rapid, to extremely rapid movement of liquefied sensitive clay, due to remoulding during a retrogressive landslide. During this process, the water content of the failed mass remains more or less constant (Hung et al., 2014). During a flow, the landslide material becomes strongly remolded and flows out of the ‘crater’, leaving an unstable scarp. A subsequent landslide can occur with the remolded clay also flowing from the crater, generating another unstable scarp. This process can continue until a final stable back scarp is formed and the retrogression stops. According to Locat et al. (2011), this type of landslide is characterized by an empty crater (minimal landslide material remains in the crater after the movement) having, in some cases, a bottle-neck shape. This type of landslide tends to occur when three conditions are met (Tavenas, 1984):

- (1) a first slide has occurred;
- (2) the potential energy is high enough to remould the clay effectively; that is:

$$\rho\gamma H > XS_u, \quad [1]$$

where $\rho\gamma$ is the unit weight of the soil; H is the height of the slope; X varies between 3 and 8 with a tendency to increase with plasticity; and S_u is the intact undrained shear strength (Leroueil et al., 1996); and

- (3) the remolded clay has to be liquid enough to flow (i.e., liquidity index > 1.2 or remolded shear strength < 1 kPa (Lebuis et al., 1983).

Examples of this type of landslide are the 1971 Saint-Jean-Vianney landslide in Quebec (Tavenas et al., 1971) and the 1993 Lemieux landslide in Ontario (Evans and Brooks, 1994). An example from Labrador is the 1984 Kenamu landslide which shows typical bottle-neck morphology (Figure 5).



Figure 5. Kenamu landslide, NL (photo: unknown source).

Spreads - Spreads consist of rapid to extremely rapid lateral movements of a series of coherent clay blocks, floating and sliding on a layer of remolded sensitive clay. Spreads result from the extension and dislocation of the soil mass above a failure surface, forming ‘horsts’ and ‘grabens’ features that subside in the underlying remolded material that forms the shear zone (Cruden and Varnes, 1996). Such horsts are blocks of more-or-less intact clay, often with a sharp wedge pointing upward; grabens are blocks typically having a flat, horizontal top surface. Those geomorphologic features are key elements in distinguishing spreads from other retrogressive landslides. Such failure surfaces have been identified with piezocone tests (e.g. Ouehb, 2007; Locat et al., 2008 and 2011; Fortin-Rhéaume, 2011).

The actual shape of the spread in sensitive clay varies according to the sinuosity of the river channel and the presence of secondary streams that can limit the lateral expansion of the landslide. In most cases the failure surface is sub-horizontal and starts near the toe of the slope. There are not yet specific methods for evaluating the potential for a spread-type landslide in a

given slope. However, recent work by Locat (2012) shows two main prerequisite properties of the clay for the initiation of a progressive failure leading to a spread: (i) a strain softening behavior, and (ii) a high sensitivity. A higher degree of over-consolidation also favors the development of progressive failure. Typical examples of spreads are the 1978 Rigaud landslide (Carson, 1979), the 1975 Ste-Ambroise landslide (1975), the 1989 St-Liguori landslide (Ouehb, 2007) and the 2010 St. Jude landslide (Figure 6).



Figure 6. St. Jude landslide, QC (Locat et al. 2012b).

2.1.4 Hazard and Risk Analysis and Assessments

Although landslides in sensitive clays were noted as early as 1663 (Gouin, 2001; Locat, 2011), early attempts to identify and analyze landslide hazards in sensitive clay were based mostly on mapped inventories (e.g. 1:20,000 or smaller scale maps) of landslide occurrences (e.g. Chagnon, 1968; Fransham and Gadd, 1977; Lebus et al., 1983; Geertsema and Schwab, 2006; Quinn et al., 2011). Approaches, like the one developed by Quinn et al. (2011) may be very useful in areas with limited amount of existing geotechnical data and where the required mapping scale is small.

The 1996 Saguenay flood in Quebec prompted the creation of a new law to address various aspects of landslide hazard assessment and public safety. In support of this legislation, the responsibility for landslide hazard mapping in Quebec was given to the ‘Section des mouvements de terrain’, within the Ministère des Transports du Québec, in cooperation with the Ministère de la Sécurité publique du Québec. Guidelines and details about the hazard mapping process and the methodology (scale of 1:2000 to 1:5000) are described in Bilodeau et al. (2005).

This landslide hazard mapping has evolved into evaluating the susceptibility of a certain terrain to generate new landslides and the impact on land management provided by constraint

maps (Demers et al., 2008). Susceptibility is defined here as the qualitative evaluation of the predisposition of a slope to a landslide (Bilodeau et al., 2005). The susceptibility of the terrain is classified taking into account slope angle, slope height and the existence of erosion. Slope angles are classified as steep ($\beta \geq 20^\circ$) or moderate ($14^\circ \leq \beta \leq 20^\circ$). Slope heights and erosion are classified as high to moderate with erosion, and high to moderate without erosion, or low.

Constraint maps also include soil types and the potential for landslide retrogression which are then organized into zones integrating the susceptibility classes. Figure 7, an example, shows seven classes of constraints that integrate the various elements described previously.

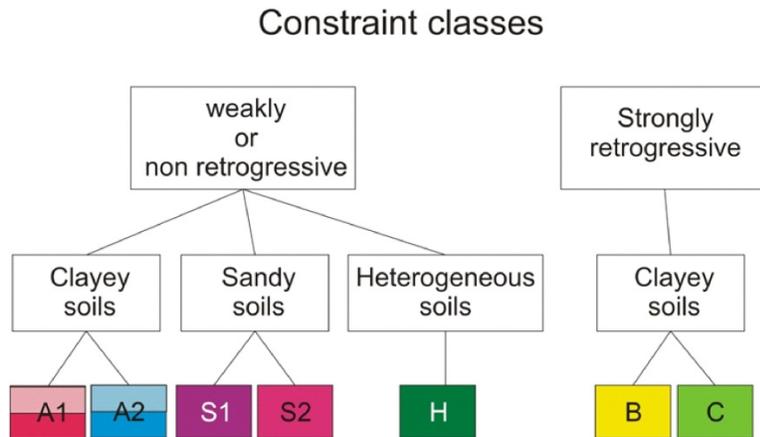


Figure 7. Constraint zones for sensitive clay in Quebec. A1 indicates clayey soil with slopes $> 20^\circ$ with or without erosion and slopes $> 14^\circ$ with a stream at the base; A2 indicates clayey soil with slopes $> 14^\circ$ without a stream at the base; the dark colours represent the slope while the light colours represent the protection zone; S1 and S2 indicate sandy soil slopes with or without a stream at the base ; H indicates a heterogeneous soil slopes with or without a stream at the base; B and C are clayey soil forming a flat band of terrain behind unit A, B for slopes with erosion and C for slopes without signs of erosion (source: MTQ, used with permission).

A protection zone is defined as the land, above or below a slope that has been indicated on the constraint map, within which some limiting land use regulation is required (e.g. avoidance). Based on many years of field observations, Robitaille et al. (2002) proposed criteria for defining the width of the protection zone as a function of the slope height (Table 2). An illustration of the protection zone for a steep slope in sensitive clay with a high retrogression potential is shown in Figure 8. If the potential for retrogression is high, then an additional zone is added to the protection zone at the top of the slope (zone B in Figure 8) and its width is determined from local observations of older retrogressive landslides in the area.

Table 2. Effective width of the protection zone (Modified from Robitaille et al., 2002).

Slope height categories (m)	Width at top of slope (m)	Width at bottom of slope (m)
$5 \leq H \leq 10$	20	20
$10 < H \leq 20$	40	40
$20 < H \leq 40$	40	80
$H > 40$	40	$2H$

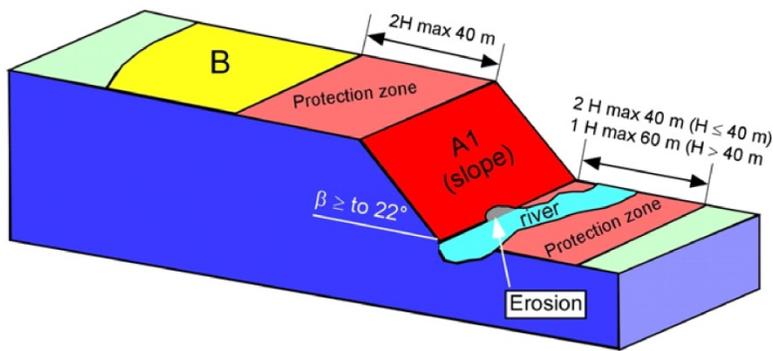


Figure 8. Example of protection zones in sensitive clay (Bilodeau et al., 2005, symbols are defined in Figure 7).

With the above described considerations based on hundreds of case histories, it is possible to produce constraint maps showing constraint zones that include the slope itself and protection zones above and below the slope of various widths according to the soil type, slope height and the potential type of landslide (e.g. Demers et al., 2008).

The Quebec hazard mapping and assessment procedures have been developed to be directly used by planners at the municipal level so that the end product maps are at a scale of 1: 2,000 or 1:5,000 (Demers et al., 2008; Robitaille et al., 2002).

Risk assessment has been considered for sensitive clay (Locat and Leroueil, 1997; Leroueil and Locat, 1998), but applications are very limited and its development is still in its infancy.

Thibault et al. (2008) present the first quantitative approach to risk evaluation and risk management related to large retrogressive landslides in sensitive clay. The approach is based on the susceptibility map that provides the areal extent of the slope prone to a first slide (e.g. Demers et al., 2008). The assumption is that a large retrogressive landslide will be initiated by a first slide. The next task analyzes the probability of a large retrogressive landslide, considering previous landslides along a river. This approach identifies parts of a river that can experience large retrogressive landslides. Currently, the tools for such risk assessments are still under review.

2.1.5 Management and Mitigation

Thibault et al. (2008) has summarized mitigation related to large retrogressive landslides in sensitive clay; whereas Demers et al. (2008) summarized the administrative aspects. Figure 9 is a flow chart of the approach to manage risks in an area that has been previously investigated and for which susceptibility and constraint maps exist. Figure 9 also indicates that, as the risk increases, mitigation may be necessary to reduce the risk to acceptable levels by either removing the elements at risk or reducing the hazard by some form of remediation.

According to Thibault et al. (2008), the approach considers three actions. The first action is linked to communicating the risk to the various stakeholders, including authorities and residents, so that they are aware of the situation, the measures to be applied and the respective roles. For example, residents are informed about how to be vigilant and to look for features such as tension cracks and erosion features. The second action looks at managing the risk by preparing monitoring plans. The third action considers further actions needed when the risk level requires immediate mitigation.

Landslide hazard and risk assessments in sensitive clay in Quebec are quickly evolving and landslide professionals should consult with the Section des mouvements de terrain, Ministère des Transports du Québec for current practice.

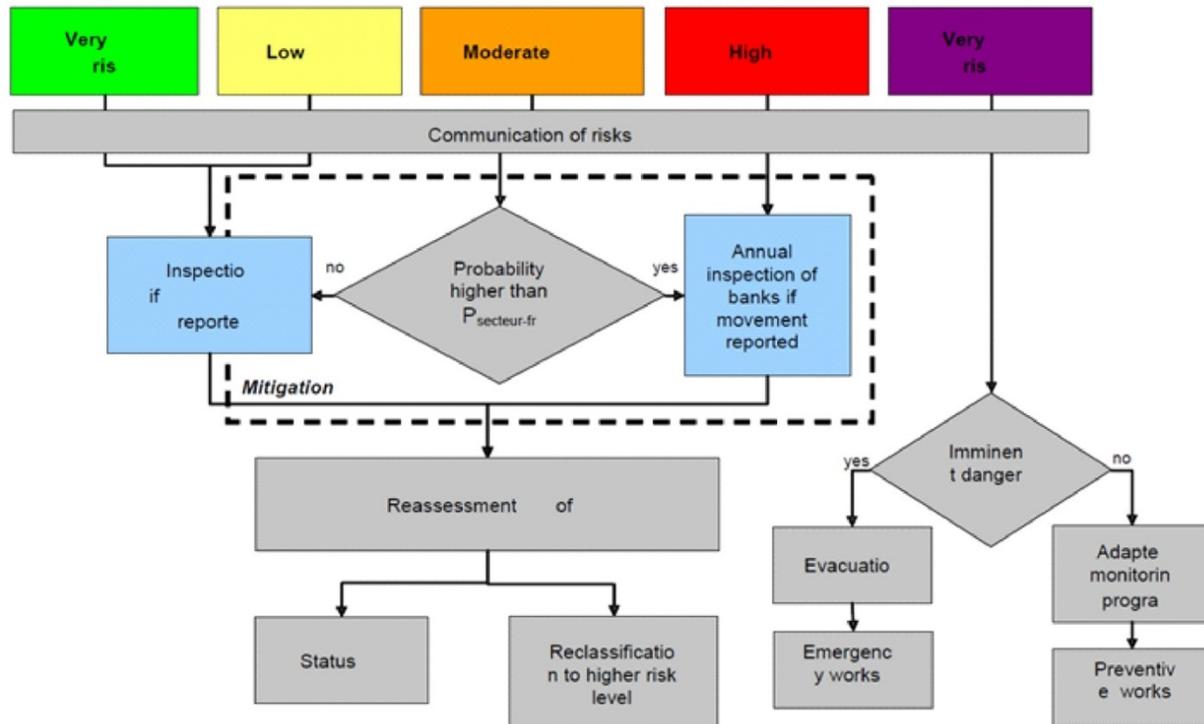


Figure 9. Flow chart showing the approach proposed to manage risks from large retrogressive landslides in sensitive clay (Thibault et al., 2008).

2.1.6 Examples

In Canada many landslides in sensitive clay have been studied. A selection of examples of thoroughly studied and well-documented landslides, some of which have already been mentioned, are listed in Table 3.

2.2 Glaciolacustrine and Lacustrine Clay and Silt Slides and Flows

2.2.1 Occurrence and Identification

Landslides in glaciolacustrine deposits are widespread along river valleys of the Interior Plains and in excavations from the Rocky Mountains to Lake Winnipeg. They also occur in BC river valleys, and in the lowlands of eastern Canada, outside the extent of glaciomarine soils. Although there are many similarities in the landslide activity of these regions, there are also substantial differences depending on their geological and physiographic settings. Not coincidentally, the methodologies used in their analyses differ.

The geomorphology of Canada is dominated by the effects of periods of glaciation that covered much of the country (Fulton, 1995). At their maximum, the Laurentide and Cordilleran ice sheets were several kilometres thick. During glacial retreat, this ice stagnated in places east of the Cordillera, covering the landscape with a mantle of ablation till. Very extensive shallow lakes

and associated deposits of glaciolacustrine clay and silt were the result. These deposits were eventually dissected by meltwater channels and present-day rivers.

Table 3. Examples of well-documented landslides in sensitive clay.

Province Location	Year	Type of Landslide			Type of Investigation			Principal Reference/Remarks
		Sl	Fl	Sp	M	G	S	
Quebec								
St. Jude	2010			x	x	x	x	Locat et al. (2012b)
St. Jean-Vianney	1971		x					Potvin et al. (2001)
St. Valliers	1968	x						Lefebvre and LaRochelle (1974)
St. Barnabé	2007			x				Locat et al. (2008)
Nicolet	1955		x					Hurtubise & Rochette (1956)
various sites		x				x	x	Lefebvre et al. (1992); earthquake triggered
Ontario								
South River Nation	1971	x			x			Eden et al. (1971)
Lemieux	1983	x			x			Evans and Brooks (1994)
British Columbia								
Mink Creek	1993/ 1994		x		x	x		Geertsema and Torrance (2005)
Khyex River	2003		x		x			Schwab et al. (2004)

Legend **Sl**: slide; **Fl**: flow; **Sp**: spread; **M**: geomorphological investigation; **G**: geotechnical investigation; **S**: stability estimation

In the mountains, the retreating ice sheets were reduced to valley glaciers. Often these glaciers both over-excavated the valleys and left behind thick deposits of glacial drift. Further in the process of deglaciation, the valley glaciers sometimes forced meltwater to flow along overland channels, cut new valleys, and/or temporarily form proglacial lakes and deposits of clay and silt. Periodic ice advances over-consolidated these glaciolacustrine deposits and in some locations covered them by till.

This very simplified description of deglaciation in Western Canada explains the three main sources of landslides in glaciolacustrine clays and silts: i) landslides derived from normally-consolidated clay deposits that form the uppermost layer of the regional stratigraphy in Manitoba, Saskatchewan and Alberta; ii) landslides in over-consolidated clay and silt formed during interglacial periods in the Rocky Mountain foothills; and iii) landslides in clay and silt in the major valleys in the BC interior.

2.2.2 Characterization, Analysis and Examples

Most landslides in glaciolacustrine and lacustrine deposits are rotational and compound slides in clay and silt (Hutchinson, 1988; Hungr et al., 2014). Many are slow moving, although some extremely rapid landslides have been observed. The main causes of these landslides include river erosion, surface water infiltration (especially snowmelt), irrigation, poorly engineered construction, and rapid drawdown of reservoirs. Flows also occur in these deposits.

Winnipeg, MB - At its greatest extent, the Late Pleistocene Lake Agassiz covered more than 400,000 km², centered approximately on the City of Winnipeg. The resulting glaciolacustrine

clay deposits are now the source of landslides along the Red and Assiniboine Rivers and their tributaries in Winnipeg (Baracos and Graham, 1981). The clay is moderately to highly plastic, laminated and prone to swelling, as it contains smectite, illite and kaolinite minerals with varying proportions of silt (Baracos et al., 1980). Although normally consolidated, the clay has moderate and variable apparent over-consolidation due to desiccation. It is firm to stiff in consistency, fissured in surface horizons, and has a peak effective friction angle of about 20° and residual friction angles of 9° to 11°. The clay is underlain at about 15 m depth by till, overlying pervious limestone bedrock. The bedrock and till are known to have artesian porewater pressures.

Although the river banks in Winnipeg do not exceed 15 m in height, they experience frequent rotational slides (e.g. Figure 10). Baracos and Graham (1981) identified 40 individual landslide areas in downtown Winnipeg. The river banks are being undermined by erosion on the outside of the sinuous river meanders. Annual floods submerge the banks and create high porewater pressures that trigger landslides by rapid drawdown when the flood waters recede. Local stability analyses routinely use residual strength on circular or non-circular pre-sheared surfaces. Stable slopes are in the order of 1 (V) to 8 (H).



Figure 10. Typical rotational slide, with headscarps identified, in lacustrine clay along a Winnipeg, MB, river bank (photo A. James, used with permission).

Saskatchewan - In Saskatchewan, the glaciolacustrine clay has similar properties to that in Manitoba, but is often strongly laminated or varved. Deeper deposits and more deeply incised river valleys produce multiple retrogressive rotational slides on the outside of river meanders. An

example, near the City of Saskatoon, is described by Haug et al. (1977), who also present a method of analyzing the landslides, using limit equilibrium analysis applied to each retrogressive slide. Examples of multiple retrogressive rotational slides along the South Saskatchewan River, 170 m south of Saskatoon, are shown in Figure 11 (see also Plate 3-40, page 261 in Mollard and Janes, 1984).



Figure 11. Retrogressive, multiple, rotational slides in lacustrine clay in Saskatchewan; width of image depicts approximately 3 km across (Government of Canada airphoto A5511-68, 1968).

Peace River, BC - The Peace River Valley in north-eastern BC is typical of the major meltwater channels draining the eastern slopes of the Rocky Mountains. The valley is cut approximately 180 m into a plain, is underlain by till and Cretaceous shale and is overlain by the discontinuous Late Pleistocene and Early Holocene Lake Peace clay. The valley approximately follows a wider interglacial meltwater channel that was infilled by glacial drift during the last glacial period (Mathews, 1978) and accommodated a meltwater lake, Lake Mathews (Hartman, 2005). A sequence of over-consolidated interglacial clay and silt, overlain by till and Lake Peace clay, is exposed in many locations, where the present valley wall deviates from the old valley.

This region therefore has both lacustrine and glaciolacustrine deposits, both of which are prone to landsliding (Severin, 2004). The Lake Peace lacustrine clay, where undercut, contains numerous extensive scars of flows that resemble morphologically the landslide scars in the

sensitive clay of eastern Canada. Even though the beds are less than 40 m thick, individual landslides often cover areas of more than 20 ha (Figure 12). The mode of movement may be retrogressive multiple flowing similar to the sensitive flows described in Section 2.1. This behavior is surprising, because limited laboratory tests on Lake Peace clay indicate low sensitivity (VanEsch, 2012). A typical flow of more than 3 million m³, which occurred in 1990, was described by Bobrowsky et al. (1991) and VanEsch (2012). The interpretation of the Lake Peace flows, proposed by VanEsch (2012), is that they are mobilized by liquefaction of loose, low-plasticity silt layers interbedded with the clay.



Figure 12. A large flow in Lake Peace clay, north-eastern BC; landslide depletion zone is on top of a bedrock scarp. The scar is approximately 300 m wide and 600 m long (photo D. Moore, used with permission).

The over-consolidated interglacial glaciolacustrine clay and silt, lower in the stratigraphic sequence of the Peace River region, contain plastic layers which tend to attract the base of compound slides at various elevations. The May 1973 Attachie landslide along the Peace River is a remarkable landslide in terms of its behaviour (Fletcher et al., 2002; VanEsch, 2012). The valley wall at this location is cut into an infill of the pre-glacial valley. The lower third of the slope is eroded into stable shale. Above the bedrock, a thin layer of basal fluvial gravel is exposed, overlain by approximately 40 m of over-consolidated Lake Mathews interglacial clay and silt, about 15 m of till and 20 m of Lake Peace clay.

In the area of the Attachie landslide, the entire overburden column has long been subject to compound slides, seated on weak layers in the Lake Mathews deposits. Numerous scarps and tension cracks and grabens, visible on pre-1973 airphotos, indicate that the entire slope had

undergone ductile displacements on the order of several tens of metres in the distant past (Figure 13). In 1973, over 14 million m³ of soil from this disturbed slope, including both the interglacial clay and till became unstable (VanEsch, 2012). Eight million m³ descended over the bedrock scarp, crossed the 900 m wide floodplain of the Peace River in a matter of seconds and produced a 21 metre high displacement wave on the opposite bank (Figure 14). The river remained blocked for 6 hours by the flat, thinly spread-out landslide debris, before it cut a narrow channel (Figure 14 and Evans et al., 1996).



Figure 13. Pre-Attachie landslide airphoto, Peace River, BC (airphoto BC 7279-070 taken 1970).

The clay and silt involved in the Attachie landslide was over-consolidated, stiff and with low sensitivity comprising illite and kaolinite mineralogy. The till, forming about 50% of the landslide debris, was very dense and during the event broke into angular blocks resembling fragmented weak rock (Fletcher et al., 2002). The landslide may have been triggered by intense surface water infiltration, during a spring with unusually thick snow cover.

The volume of the landslide is remarkable and its extreme mobility is very difficult to explain. The soil was insensitive, weak and heavily deformed prior to the landslide, all conditions that would typically be expected to lead to ductile landslide behavior. The current explanation is that loose silty material accumulated in the extensive crack systems on the disturbed slope, softened and formed a mixture of brittle soil blocks, surrounded by a liquefied matrix (Fletcher et al., 2002). Based on its behavior, the landslide can be termed a flow, although it formed in material that would normally not be considered susceptible to this mode of movement. Overburden landslides with these characteristics are rare in the Peace River Valley and no comparable example is known.



Figure 14. Attachie landslide, BC; width of the image depicts approximately 1.8 km (airphoto BC 5529-075 taken 1973).

Although not hazardous to life, the slow-moving compound slides in the over-consolidated glaciolacustrine clay in the Peace River valley create a major constraint on development – an important area of oil, gas and hydroelectric resources. A classic example of such a slow moving landslide on the Beatton River was partially re-activated by road construction excavations in the 1990s (Polysou et al., 1998). The new road traverses the landslide over a length of several kilometres without problems, because it was mostly constructed so as to avoid increasing the load on the inactive body of the landslide. However, a bridge approach close to a tributary of the Beatton River necessitated a deeper cut (Figure 15). The landslide responded with slow displacements of several metres, mostly horizontal in direction. A very well-defined compound rupture surface was identified from inclinometer observations. The basal part of the rupture surface lies on a weak over-consolidated clay layer, pre-sheared to a residual friction of 9° . The landslide was stabilized by installing approximately 90, 1500 mm diameter steel piles, 20 to 30 m deep, filled with concrete. The piles intersected the pre-sheared sliding surface and stopped the sliding by lateral support. The cost of the stabilization was \$2.38 million (1998 dollars), and movements have been reduced to an insignificant rate (Polysou et al., 1998). The same pre-sheared weak surface forms the base of several smaller landslides in the vicinity of the same bridge, on both sides of the river.



Figure 15. Compound slide on the Beaton River, BC; landslide in the upper left corner is one of several in the area that appear to utilize the same weak surface (photo O. Hungr).

BC Interior - The main valleys of the BC interior are infilled by thick deposits of glacial drift. Typically, the central portions of these valleys are occupied today by rivers or narrow lakes. Massive terraces of glaciolacustrine silt, deposited in Late Pleistocene proglacial lakes, border the valleys. The silts are varved, unsaturated, and form high rock-like cliffs where eroded. Lum (1977) estimated that the cohesion of the silt is derived equally from negative porewater pressure of the unsaturated deposits, a small dry clay fraction, and calcitic mineral cement. The silt loses strength dramatically upon wetting (Evans and Buchanan, 1977) resulting in the formation of deep near vertical-sided gullies, as well as sinkholes and piping (pseudo-karst) channels. Landslides are relatively rare, with the most common type being topples of silt blocks, which are separated along vertical joints in the silt bluffs, and occasionally disintegrate and form extremely rapid dry flows. One fatality occurred in 1978 when a dry silt flow impacted a house in Naramata, near Penticton (Dunkley, 1992).

European settlers arrived in the BC interior with the construction of the CP Rail mainline in the 1880s. The silt terraces lining the valleys were soon recognized for their excellent agricultural potential with irrigation. Early irrigation systems used wooden flumes to transport water from upland creeks, sometimes over distances of many kilometres. The water was then freely applied to the terrace by what is called the 'ditch and furrow' irrigation method. As a result, between 1880 and 1930, more than a dozen very large deep-seated compound slides occurred in the South Thompson valley, south of Ashcroft (Stanton, 1898). The largest occurred in October 1880,

comprised about 15 million m³ and dammed the South Thompson River for 44 hours (Evans, 1986). One silt slide near Spence's Bridge in August 1905 crossed the river at high speed and killed 15 persons on the opposite bank (Evans, 1986).

Many of these large landslides damaged the CP Rail mainline, which generally follows the river near the toe of the valley slopes. In 1914, the CP Rail won a court injunction to permanently prohibit ditch and furrow irrigation on the silt terraces in the South Thompson River Valley. Very few new landslides of significance have occurred in this area since, although there have been several similar occurrences in the Okanagan Valley to the east.

In 1982, the Goddard landslide, one of the large landslides in the South Thompson River Valley that first occurred in 1886 and 1897, re-activated and moved approximately 20 m, destroying the CP Rail mainline (Porter et al., 2002). In a lawsuit brought by CP Rail under the 1914 injunction against a cattle farming company, who were irrigating the terrace above the Goddard landslide, the court determined that sprinkler irrigation, unlike ditch and furrow irrigation, is unlikely to cause substantial increases in porewater pressures.

Site investigations carried out in connection with the above lawsuit supplied detailed geotechnical data for the Goddard landslide (Eshragian et al., 2007). The compound landslide is seated on a plastic clay horizon within glaciolacustrine silt that is pre-sheared to a residual friction of 11°. Movements and retrogressions correlate both with the river level and with the piezometric level within the landslide. Eshragian et al. (2007) ascribed the re-activation of this landslide to toe erosion of the 90-year old landslide debris by the South Thompson River, combined with rapid drawdown caused by the lowering of the river water level after spring runoff.

2.2.3 Hazard and Risk Analysis and Assessment

Many of the valleys affected by landslides in glaciolacustrine and lacustrine clay and silt are excluded from development. However, they need to be crossed by roads, pipelines and bridge abutments or piers. There is no single method for designing such infrastructure, and each case represents a unique challenge and requires state-of-the art application of geotechnical skills.

Most slope stability analyses use limit equilibrium methods. Many landslides of this type are controlled by horizontal weak surfaces, such as high plasticity layers, that are pre-sheared by previous movements, valley rebound or glacier drag. Limit equilibrium methods must be able to model the presence of such discontinuities using non-circular sliding surfaces. The groundwater conditions are often complex, including multiple perched water tables and alternating unsaturated zones. An unresolved challenge relates to the recognition of the potential for extremely rapid failures, as described in the Peace River area elsewhere.

It is common along river valleys in the Interior Plains to find landslides in soil to co-exist with landslides in shale bedrock of similar character (see Section 2.7). Site investigations, analyses and assessments must consider both of these processes.

A common hazard assessment issue associated with valley slopes is the determination of setbacks for development above the crests of the valleys. Again, there is no standard procedure for conducting such assessments. It is necessary to combine limit equilibrium analyses and geomorphological observations of the slopes in the vicinity of the subject site (e.g. Cruden et al., 1989a). To the authors' knowledge, quantitative probabilistic delineation of setback lines has not yet been used in western Canada.

2.2.4 Management and Mitigation

The main risk reduction tool in connection with landslides in glaciolacustrine and lacustrine clay and silt is to avoid the unstable areas. Where this is not possible, a wide variety of site-specific slope stabilization measures have been applied. Stabilization measures include re-grading, placement of stabilizing berms and the construction of shear keys and stone columns. Drainage is often less effective, due to the low permeability of the soils involved. Stabilization measures add significantly to the cost of construction of many development projects.

2.3 Debris Avalanches

2.3.1 Occurrence and Identification

Debris avalanches occur on many mountain slopes in the Cordillera in western Canada, as well as in the Appalachian Mountains in eastern Canada. On a smaller scale, debris avalanches occur along eroded banks of rivers and lakes and on some excavated slopes throughout Canada. The characteristics of such landslides vary with location and a uniform methodology for their characterization does not exist.

A debris avalanche is typically a shallow, translational slide of debris material on a steep open slope during or shortly after heavy rainfall or snowmelt. After initial movement it becomes flow-like and can accelerate to an extremely high velocity (Hungr et al., 2014). Some debris avalanches enter existing steep drainage channels and become debris flows. Others continue to move over long distances without confinement, although they usually entrain material from the slope, aided by rapid undrained loading. In the Working Classification, debris avalanches are complex debris-slides debris flows.

Debris avalanches destroy houses and infrastructure by direct impact at the foot of steep slopes and also deliver enormous quantities of sediment to mountain streams that can result in debris flows and debris floods (See Section 2.4) and can cause destruction on fans and/or floodplains many kilometers from where the landslides initiated.

In Canada, thanks to glacial erosion, slopes in both the Cordillera and the Appalachians have typically been scoured and lack deep weathered soil profiles. Thus Canada is typically spared regional disasters on the scale observed in non-glaciated countries. The steep slopes are, however, typically covered by thin (0.5 to 1 m), discontinuous veneers of glacial drift and/or colluvium and organic material. Sliding of these veneers that overlie a compact basal till substrate or bedrock typically results in debris avalanches (e.g. Figure 16). Such landslides tend to be smaller and more widely distributed than those seen in weathered landscapes.

2.3.2 Characterization and Examples

The causes of debris avalanches include intense precipitation, snowmelt or combination of both. They can occur during earthquake events, if coincident with wet periods. A major cause and/or trigger of debris avalanches is human activity, especially forestry related road construction in steep terrain.

A detailed investigation of debris avalanche scars in Haida Gwaii (on the Queen Charlotte Islands, BC; Rollerson, unpublished, see Hungr et al., 2005), produced data regarding thickness of material removed from the slope by debris avalanches. The thicknesses averaged 0.5 m, resembled a Poisson distribution and had a range up to 2.5 m.



Figure 16. Debris avalanche scar on Black Mountain, West Vancouver, BC; right side of photo shows a colluvial/organic veneer; left side shows a glacially-eroded diorite surface (photo O. Hungr).

The character of debris avalanches in the Canadian Cordillera is influenced by climate and geology, although no systematic documentation exists. From the authors' experience and a few local landslide inventories, the Southern Coast Ranges exhibit smaller and less frequent events. Central and Northern Coast Ranges, and the western slopes of Vancouver Island, where there is substantially higher annual precipitation, exhibit larger events and more closely-spaced clusters of debris avalanches. The BC interior and the Rocky Mountains have fewer debris avalanche clusters, but produce large debris avalanches sourced from thicker glacial drift deposits perched on upper slopes. Examples of these different scenarios are reviewed below.

Southern Coast Ranges of BC - A summer rainstorm in July, 1983 triggered a cluster of debris avalanches and debris flows near Chilliwack (Evans and Lister, 1984; Figure 17.). The storm lasted only a few hours and was concentrated, so that no significant hourly precipitation was recorded at the Agassiz rain gauge, only 20 km from the centre of the landslide cluster. Slopes, however, within a 10 km radius of the storm centre experienced tens of debris avalanches and debris flows recognizable on airphotos. Most of these events began on open slopes, but were eventually channelized and travelled as debris flows to the valley floors. Both the Trans-Canada Highway and the CP Rail mainline were severed. The individual debris avalanche scars were typically considerably less than 0.5 ha in area and many initiated as fill failures on forestry roads

that were constructed approximately 20 years earlier. Consistent with the forest practices prior to 1987 none of the roads were deactivated after logging.



Figure 17. Cluster of debris avalanches and debris flows caused by a summer rainstorm east of Chilliwack, BC in 1983 (photo D.F. VanDine, used with permission).

Central and Northern Coast of BC - The wet slopes in these regions exhibit clusters of debris avalanches, that involve a veneer of organic and colluvial soils, typically less than 1 m thick, failing over areas of several hectares in area. A typical cluster was described by Guthrie and Evans (2004) in Loughborough Inlet on the mainland opposite the north end of Vancouver Island that was triggered by a November 2001 rainstorm. Debris avalanches, numbering 101, were recorded in a study area of 370 km². The individual landslides, ranging from 0.1 to 40 ha in area covered both virgin slopes and slopes that were clearcut logged decades earlier. Whereas the average landslide density over the study area is not very large, local densities were much greater and the denudation ratios on some slopes reached approximately 25%, by visual estimate. The single largest debris avalanche (shown on Figure 18) began in a series of steep gullies upslope of a previously-logged area and left a scar on the steep slope of approximately 20 ha (slope area). Assuming an average thickness of 0.5 m, the debris avalanche involved 10,000 m³ of material. It is likely that the adjacent creek channel was briefly dammed by the debris and a resulting debris flow or debris flood continued 2.6 km to the shoreline.

Fortunately, these coastal regions are largely uninhabited, so there are few fatalities. However, in July 1891, several debris avalanches killed 50 people, mostly workers at the Inverness (North Pacific) Cannery, near Port Edwards (Septer and Schwab, 1995). This is one of the ten most deadly landslide disasters in Canadian history (Evans, 2003). The slope above the now

abandoned cannery continues to produce sizeable debris avalanches. In the same region, in the City of Prince Rupert, three houses were buried by a debris avalanche in November 1957, with seven fatalities (Evans, 2003).



Figure 18. Largest debris avalanche adjacent to an unnamed tributary to Loughborough Inlet, BC; debris avalanche scar is 310 m wide at its widest point (Google Earth image).

Appalachian Mountains - Debris avalanches also occur in the Appalachian Mountains in eastern Canada, although not as frequently as in the Appalachian Mountains south of the Canadian border. The 1973 Harbour Breton, NL debris avalanche swept into homes adjacent to the seashore killing 4 people Evans (2003).

Other Types of Debris Avalanches - Not all debris avalanches are shallow and translational. Some initiate as deeper rotational slides and probably involve some liquefaction (Hungry et al., 2001). An example, a debris avalanche on Legate Creek near Smithers, BC began on a steep mountain slope 1,000 m above the valley floor as a rotational slide in talus undercut by earlier debris flows (Figure 19). The trigger was likely snowmelt. The slide began to flow, possibly liquefied, and approximately 100,000 m³ of debris entered a stream channel and travelled 2.8 km to cover BC Highway 16 to a depth of 10 m. The final volume of material involved was >210,000 m³ (BGC Engineering Inc., 2007). Superelevation in bends of the flow path and a dynamic analysis indicated that the flow reached velocities of more than 30 m/s (108 km/h). A motorist barely escaped injury when his vehicle collided with the debris. The resulting investigation is the first example of the use of a formal Quantitative Risk Analysis for a debris flow in Canada (M. Jakob, pers comm). The Camp Creek and Hummingbird Creek debris flows discussed in Section 2.4 are similar in character.



Figure 19. Initiation zone of the Legate Creek debris avalanche, Smithers, BC (photo M. Jakob, used with permission).

In the coal regions of BC, highly mobile debris avalanches occur in coal mine waste piles on steep slopes (Hung et al., 2002). The coal mines remove >100 million m^3 of sandstone and shale waste rock every year to access coal seams. Economics dictate that the waste be spoiled on mountain slopes by end dumping without re-sloping or compaction. Deep-seated debris avalanches frequently occur in the waste piles and often turn into extremely rapid flows. In the 1990s, up to 12 debris avalanches occurred each year, with events of up to 3 million m^3 of debris (Hung et al., 2002). Certain waste pile crests experienced more than 10 m of movement before failure occurred. The resulting debris avalanches flowed over open slopes for hundreds of metres and sometimes turned into channelized debris flows travelling several kilometres. The runout areas are typically closed to the public, although half a dozen fatalities have occurred over the last 50 years. Today, typically a full time system of displacement monitoring, using wire extensometers and surveying is used to warn mine personnel of impending events.

A typical spoil pile debris avalanche near Sparwood, in southern BC, is shown in Figure 20. The initial slide is visible on the face of the waste pile in the background of the photo. The failure, 700,000 m^3 in volume, consisted of a steep main scarp extending through the waste rock and a flatter sliding surface following the contact between the waste and the ground. It is likely that the rupture surface involved the ground because the basal layer of the waste piles characteristically consists of a concentration of the largest boulders and therefore tends to be

well-drained and frictional, whereas the ground includes an organic layer, colluvium and weaker glacial drift. Dawson et al. (1998) suggested that liquefaction of both the saturated waste material and the ground were possible.



Figure 20. Debris avalanche caused by the failure of 60,000 m³ of coal mining waste from a spoil pile near Sparwood, BC; the source scar is visible in the background (photo O. Hungr).

This landslide moved rapidly over slopes covered with peat and silty colluvium. The soils were saturated and covered with a thin blanket of snow. The landslide entrained soil to a depth of <0.5 m, cut down to frozen ground and flowed down a wide gully, reaching a velocity of approximately 16 m/s (60 km/h) at mid-reach. The final runout distance, visible in the foreground of Figure 20, was 2 km. Test pits showed that the waste material was moving on a mobile cushion of saturated soil with organics, some of which was extruded to the surface of the debris, seen as brown patches in Figure 20. The travel angle between the crest of the initial landslide and the toe of the deposit of this event was 14°, whereas regionally the minimum is 10° (H/L of 0.18 in Figure 21). Thus, other than debris flows, mine waste debris avalanches are among the most mobile of all extremely-rapid landslides.

2.3.3 Hazard and Risk Analysis, Assessment, Management and Mitigation

Susceptibility of slopes to debris avalanches in western Canada should be part of hazard assessments for all forestry activities including road building. The methodology of hazard assessment used is commonly the ‘subjective geomorphic method’ (RIC, 1996) or ‘Map Type 2; Mapping Method D’ as described in Jackson et al. (2012). In this method, landform polygons are delineated and mapped by airphoto interpretation, supplemented by a prescribed level of field checking (BC Ministry of Forests, 1995). Individual mappers have their own (subjective) systems of assigning susceptibility classes, based on parameters such as slope angle, slope shape, landform class and the presence of observed instability (e.g. Chatwin et al., 1994; RIC, 1995). Semi-quantitative methods of landslide susceptibility estimation, based on the infinite slope equation, have been developed in BC and the US Pacific Northwest (Hammond et al., 1992;

The above observations regarding the influence of logging are similar to an earlier inventory of landslides in the Southern Coast Ranges of BC. In that study O'Loughlin et al. (1972) found that the landslide density was magnified from 1 to 8 times in clearcut logged areas, whereas the denudation ratio increased 2 to 5 times. However, corresponding increases were 400 and 350 times on areas classified as 'road right-of-way'.

This Clayoquot Sound area gained notoriety in the 1980s for widespread clearcut logging and associated road building, and indirectly resulted in the introduction of the BC Forest Practices Code Act – legislation that changed forestry practices in the province. The Act introduced requirements to deactivate forestry roads by pulling back fills and re-establishing natural cross drainage. Currently, many forestry roads are completely 'deconstructed' upon completion of the forestry activities.

Debris avalanche risks are usually studied on a subjective basis, combining susceptibility mapping with an empirical or analytical runout model. The first application of a formal Quantitative Risk Assessment (QRA) method in BC was a study of debris avalanches from scarp slopes in a study area in the District of North Vancouver in 2006 (BGC Engineering Inc., 2006). In this study, a judgment-based spatial distribution of slope failure susceptibility was combined with an empirical range of travel angles, backed by a three-dimensional dynamic analysis of a typical debris avalanche using the method of McDougall and Hungr (2004).

Thus far in Canada, only passive mitigation of debris avalanche hazards has been practiced, typically by restricting the use of high risk areas. Other mitigative methods have been discussed as part of the previous sub-sections.

2.4 Debris Flows and Debris Floods

2.4.1 Occurrence and Identification

Debris flows and floods are widespread in steep mountain drainage channels in all parts of the Canadian Cordillera and the Appalachian Mountains.

A debris flow is a very rapid to extremely rapid surging flow of saturated non-plastic debris in a steep channel (Hungr et al., 2014). Alpine debris flows, have been known for more than 100 years (Stini, 1910), involve a complex chain of events. Movement typically begins as a debris slide or avalanche on a steep mountain side or a creek bank, or as a spontaneous movement of saturated bedload material in a steep, first-order stream channel, usually during a period of unusually high runoff. The initial landslide moves debris into a steep channel (typical gradients 10° to 45°). Continuing downslope as a flow, it entrains material from the stream bed and its banks, growing substantially in volume. In a typical debris flow, the initiating slide or avalanche forms only a fraction of the final volume, the remainder being entrained along the length of the channeled path. Eventually, much of the coarse debris deposits on a 'debris fan' and sediment-charged water continue farther downstream and into the river network as a debris flood.

Debris fans prone to debris flows and debris floods are recognized by the steep slope of the fan (e.g. Jackson et al., 1987), the morphometric characteristics of the watershed (Wilford et al., 2004) and by observing characteristic features such as boulder levees, boulder trains and large deposited clasts on the fan surface. The existence of erodible debris in the steep segments of the channel is an important factor.

2.4.2 Characterization and Examples

Debris flows - A key aspect of a debris flow is its surge-building process. As liquefied, unsorted debris material flows along a channel, the coarse fraction tends to concentrate near the front of the flow, forming a bouldery 'head'. Finer and more dilute material is retained behind the front, forming a characteristic 'surge'. This process magnifies the peak discharge, so that the peak discharge of a debris flow surge can be as much as 50 times the discharge of a hydrologic flood (VanDine, 1985). An individual debris flow can consist of a single surge, or several. The typical characteristics of a coastal BC debris flow are illustrated next.

Charles Creek is the most active debris flow-producing drainage that crosses the BC Highway 99 north of Vancouver, BC (Hungr and Wilson, in press). Figure 22 provides an overview of the drainage; its principal morphologic parameters are listed in Table 4. In this area of coastal BC, debris flows are characteristically triggered by heavy winter rainfalls, combined with sudden melting of the snowpack in the headwaters of the creek. The heavy runoff exacerbated by the low permeability of the glacier-scoured quartz diorite bedrock, results in high water discharges in the steep upper channels and destabilizes coarse granular colluvial and stream deposits (Figure 23). Some Charles Creek debris flows have been triggered by rock falls from cliffs in the headwaters, impacting talus deposits.

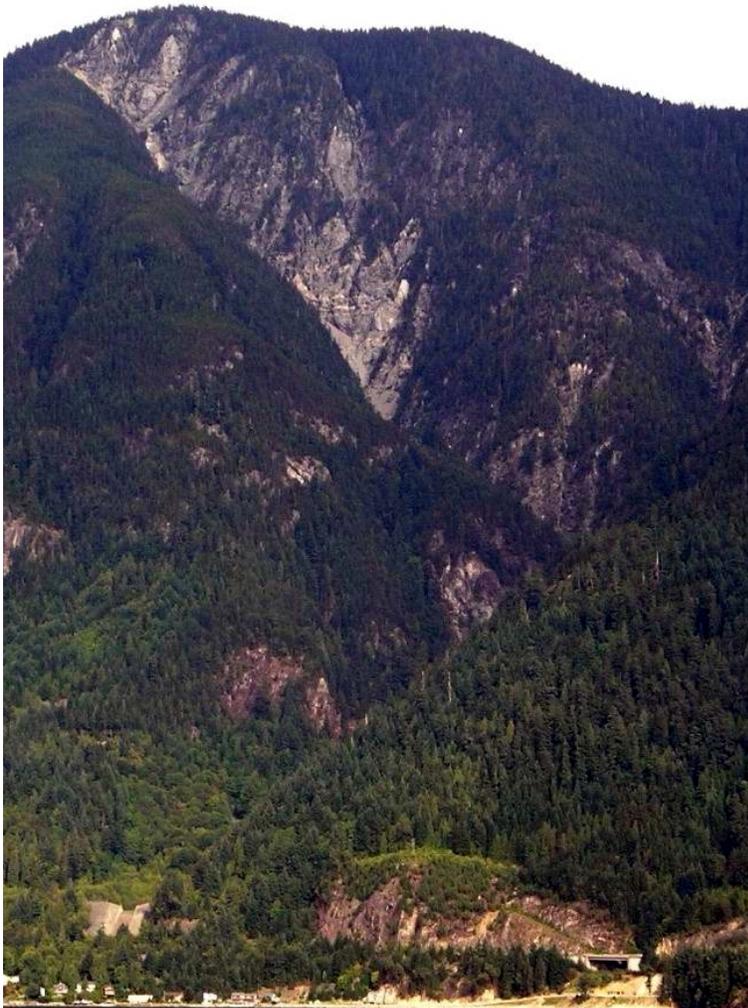


Figure 22. Overview of the Charles Creek drainage from Howe Sound, BC (photo O. Hungr).

The Charles Creek debris flows travel over two kilometers in confined, bedrock-lined channels, to deposit on both the subaerial debris fan and the much larger subaqueous debris flow fan in Howe Sound.

Table 4. Charles Creek, BC principal morphologic parameters (Thurber, 1983).

Geomorphic feature	Measurement
Drainage area	1.8 km ²
Main branch length	2,550 m
Total length (both tributaries)	3,526 m
Slope angle above fan (average)	27°
Vertical relief	1,325 m
Subaerial fan area	0.045 km ²
Fan slope angle (average)	16°
Estimated 200-year water flood	32 m ³ /s



Figure 23. Coarse granular colluvial and stream deposits in Charles Creek, BC (photo P. Wilson, used with permission).

Between 1969 and 2012, nine debris flows with volumes that ranged between 5,000 and 25,000 m³ were recorded (Septer and Blais-Stevens, 2007; Hungr and Wilson, in press). The December 1981 event consisted of a number of small surges that deposited most of its debris

beneath the BC Highway 99 bridge and caused an avulsion of the channel. The December 1983 event had only two surges, one of which was highly mobile. The 1983 debris flow damaged the highway bridge and swept a heavy pre-cast BC Rail bridge deck into Howe Sound. Three frames from a CBC video that recorded that event are shown in Figure 24. An analysis of this video indicated a discharge approximating $320 \text{ m}^3/\text{s}$ carrying boulders that were up to 4 m in diameter, and moving at approximately 10 m/s. For comparison, the peak discharge determined from a regional flood analysis of an extreme water flood on Charles Creek is approximately $32 \text{ m}^3/\text{s}$ (Thurber, 1983).



Figure 24. Three frames from a CBC video of the December 1983 Charles Creek debris flow.

A debris flow barrier and basin with a capacity of approximately $30,000 \text{ m}^3$ was constructed in 1986 to protect the highway, railway and houses located on the fan. Three times in recent years (2006, 2007 and 2010), the barrier retained debris flow events in the order of $20,000 \text{ m}^3$ (Figure 25).



Figure 25. Charles Creek debris flow barrier, showing fill line from the approximately $20,000 \text{ m}^3$ 2010 debris flow (photo O. Hungr).

Debris flows have occurred in all the mountain ranges of BC and Alberta since deglaciation. However, prior to 1980, there was little awareness of this phenomenon, despite numerous railway and highway disruptions and occasional fatalities (e.g. the Camp Creek debris flow of 1968, described by Nasmith, 1972 that flowed through a campsite near Revelstoke and killed 4 persons).

Attention to debris flows arose as a result of a cluster of events along BC Highway 99 in the early 1980s, including those on Charles Creek (Thurber, 1983). In October 1981, a major debris flow occurred on M Creek, 8 km north of Charles Creek and demolished a timber trestle bridge and a house. Five vehicles drove into the void left by the destroyed bridge and 9 people were killed as a result. Another debris flow-related death resulted from the December 1981 Charles Creek debris flow. In February 1983, two people died in a crushed house adjacent to Alberta Creek, 2 km north of Charles Creek. In total, 12 debris flow-related fatalities occurred and 5 houses and 6 bridges were destroyed in a relatively small geographic area within a 3 year period.

Debris flows in western Canada, however, are not limited to coastal areas. They are also common in the Rocky Mountains. For example, Jackson et al. (1990) describe a series of debris flows triggered by outbursts of melt water from a small glacier on Cathedral Mountain, BC, above the point where the CP Rail mainline and the Trans-Canada Highway cross the continental divide. Rocky Mountain debris flows typically involve finer-grained and more fluid debris, contrasting with the coarse, granular material of the Coast Ranges.

Several communities in BC have been affected by debris flows during recent decades (e.g. the Hummingbird Creek subdivision on Mara Lake, Jacob et al., 2000). It is, perhaps, fortunate that few debris flow-related fatalities have been reported from BC or Alberta since the spate of the BC Highway 99 debris flows of 1983.

Debris floods - Not all debris flows produce destructive high-discharge surges. Events that are transitional between debris flows and extreme water floods can transport large quantities of coarse sediment in steep mountain channels, but without the extreme magnification of peak discharge caused by full-scale surging and entrainment. These transitional events, referred to as debris floods (Hungr et al., 2001) are more frequent, but less damaging, than debris flows.

An example is the 1991 debris flood on Britannia Creek, north of Vancouver, BC along BC Highway 99, the effect of which is illustrated on Figure 26. In 1989, an old concrete buttress dam on the Britannia Creek was purposely demolished by blasting. The resulting water flood discharge of 255 m³/s, much larger than the extreme water flood, swept the stream channel and destabilized the channel and banks, but without producing large quantities of sediment. A large rainfall-related water flood in the summer of 1991 eroded the channel and resulted in a debris flood that brought approximately 33,000 m³ of debris onto the Britannia Creek alluvial fan. As is evident on Figure 26, the debris was deposited without large impact forces. The debris was limited to approximately 300 mm in diameter, in contrast to debris flow surges, that often carry boulders up to several metres in diameter.

For creeks in coastal BC Wilford et al. (2004) found that debris floods occur on streams with a Melton's ruggedness coefficient (drainage relief/square root of drainage area) of less than 0.6, or with a drainage length of more than 2.7 km. Britannia Creek falls into these criteria, in contrast with Charles Creek which is a known debris flow creek and whose Melton's ruggedness coefficient and length are 0.98 and 2.5 km, respectively.



Figure 26. Deposit of the 1991 debris flood on the fan of Britannia Creek, BC (photo K. Fletcher, used with permission).

2.4.3 Hazard and Risk Assessment

The first detailed, semi-quantitative hazard and risk assessment of debris flows in Canada was carried out in the early 1980s along BC Highway 99, north of Vancouver, BC (Thurber, 1983). The hazard posed by 26 small steep drainages prone to debris flows and floods was assessed, based on detailed history, condition of the channels, morphology of the fans and subjective judgment. A method of estimating the magnitude of future events was developed, as illustrated by the Charles Creek example above. Subsequent to the 1983 study, further debris flow occurrences have allowed the construction of a magnitude-frequency curve for Charles Creek (Hung and Wilson, in press).

A statistical method for estimating debris flow magnitude was developed by Fannin and Wise (2001) and an algorithm to predict debris flow occurrence based on climate observations was proposed by Jakob and Weatherly (2003). All such methodologies require careful calibration for specific site conditions.

A detailed Quantitative Risk Assessment of debris flows on the Cheekye Fan from a volcanic source on Mt. Garibaldi, near Squamish, BC, was completed in 2007, though it remains unpublished (BGC Engineering Inc., 2008). This study involved very detailed investigations including test pits and dating of debris fan deposits, LiDAR imaging, construction of a magnitude-frequency curve and runout analysis using a three-dimensional flow model.

2.4.4 Management and Mitigation

In response to the series of damaging debris flows of the early 1980s along BC Highway 99, described earlier, the BC provincial government commissioned the design of three debris

retention basins (one on Charles Creek) and one guiding channel (Hungre et al., 1987). As a result, a methodology for dealing with debris flow protection was developed (for example Hungre et al., 1984 and 1987; VanDine, 1985). Most examples of Canadian debris flow and debris flood mitigation involve debris retention basins or training berms to control the flow on the debris fans. One structure, an avalanche shed at Mt. Stephen in the Rocky Mountains (Hungre et al., 1987), has successfully protected the CP Rail mainline from frequent debris flows for the past 20 years. Stabilization measures on upper slopes, such as erosion sills or check dams, have not been extensively used in Canada.

Despite on-going protection efforts, the Trans-Canada Highway between Vancouver and the BC interior is periodically disrupted by debris flows. Some of these have resulted from failures of poorly-constructed forestry roads dating from the 1960s and 1970s. Changing forest practices in the 1990s has resulted in decreased debris flow activity in many areas.

2.5 Earth Flows

2.5.1 Occurrence and Identification

Earth flows occur at a variety of scales in the BC interior and in the valleys of the Rocky Mountain foothills. They are defined as slow to rapid, flow-like movements of plastic, clayey soils (Hungre et al., 2014).

Earth flows often occur in thick accumulations of weathered clayey colluvium. Morphologically and kinematically, they resemble valley glaciers. Their movement is usually extremely slow to slow and they can remain in a dormant state for hundreds of years. During periods of surges, which move along the length of the flow as kinematic waves, they can attain rapid velocities, up to metres per day or, much less frequently, metres per minute. Essentially, earth flows connect 'source areas', where clayey debris is produced by sliding or erosion of weak rocks, to an erosional sink, usually the channel of a river. Such landslides are widespread in many parts of the world but have so far received limited attention by landslide professionals.

2.5.2 Characterization and Examples

A series of large earth flows have been described in a belt of Cretaceous and Tertiary sedimentary and volcanic rocks along the western margin of the BC interior, centered on the Fraser River Valley, at approximately 1,200 m asl. Bovis (1985) recognized over a dozen large earth flows in this area with estimated volumes of 100,000 to 10 million m³, most of which appear inactive in the semi-arid climate in the rain shadow of the Coast Ranges.

The earth flows lie on average slopes of 5° to 17° and consist of mixed clayey soil derived from shale and siltstone, interbedded with weathered rhyolitic tuff, lava and ash containing fragments and boulders. The soil is smectitic in its mineralogy, with clay content ranging from 20% to 70%. The slope gradient of an earth flow is typically related to the clay content of the soil, with the most plastic example, the Hat Creek earth flow near Ashcroft, BC, having a 5° slope.

Bovis (1985) measured a mean velocity of 0.4 m/year in one example. The velocity rate was constant with location across the 90 m wide flow, indicating that most of the shearing was occurring on narrow shear planes at the margins, a characteristic feature of earth flow motion.

Figure 27 shows the Tunnel earth flow, a larger example, located on the left bank of the Fraser River, 65 km upstream of Lytton, BC. This 8-12 million m³ earth flow connects a series of forested scarps and gullies near the edge of the Interior Plateau with the Fraser River. The earth

flow does not reach the river channel, but rather its main lobe terminates on the slope approximately 50 m above the bedrock incised river. Clay rich landslide debris, approximately 2 m thick and containing boulders, spills from the terminus of the earth flow to the river over horizontally-bedded glaciofluvial terrace deposits. Although the river is no longer eroding the toe of the landslide, the earth flow material has low strength and local periodic re-activation has occurred during the last four decades, damaging the rail track and a provincial road. The re-activated movement is translational and relatively shallow, involving not more than 5% of the total volume of the earth flow. The rate of movement is measured in cm per year (BC Ministry of Transportation and Infrastructure, pers. comm.).



Figure 27. Tunnel earth flow above the Fraser River, upstream of Lytton, BC. The earth flow occupies most of the field of view on the right side of the photo. A local reactivation in recent years, near the centre of the photo, damaged both the highway and railway (photo O. Hungr).

The Drynoch earth flow is the best documented of the BC interior examples (VanDine, 1980 and 1983). This 17 million m³ earth flow reaches the South Thompson River and has been active for thousands of years (Figure 28). Both the CP Rail mainline and the Trans-Canada Highway cross its path and contend with movements of the order of 3 m/year, occurring at a depth of less than 18 m. Considering an average flow cross-section of 300 m wide and 10 m thick, the reported movement indicates that the earth flow can transport almost one million m³ of material per century from the source area to the river.



Figure 28. Drynoch earth flow, BC; width of the image depicts approximately 4 km (Google Earth image).

Earth flows are widespread on the valley walls of rivers that cross the Rocky Mountain foothills. Often an entire side of the valley can be covered by an earth flow complex derived from landslides and weathering of the steeper scarps in the upper part of the slope. This situation is shown in Figure 29 in the Liard Plateau region of north-eastern BC. The slope, a thick shale sequence with sandstone beds, has been eroded by the Liard River. Differential weathering and erosion has produced a step-like topography. The steep shale scarps produce clayey debris that drapes over the bedrock topography in the form of a continuous blanket – an earth flow complex. A segment of this blanket, to the left of centre of the photo, has recently re-activated (surged) and caused a local constriction of the river channel. This illustrates the role of the earth flow as a transporting agent.

Significant earth flow surges have been observed in northern BC, west of Fort Nelson (Geertsema et al., 2010). For example, the Muskwa earth flow surged in the late 1970s as a result of a rotational rock slide in shale on its upper slopes, and involved an estimated 2 to 3 million m³ of material. This rock slide mobilized an earth flow of 15 million m³ in clay-rich diamicton that extended more than 3 km downslope on an average 3.5° slope gradient. Because of its remoteness, few technical details exist. The area has sporadic permafrost that may play a role in the high mobility of the earth flows in this region (Geertsema and Schwab, 2006).

2.5.3. Hazard and Risk Assessment and Mitigation

Earth flow hazards have not been studied quantitatively in Canada. Where intermittent earth flow movements endanger roads or railways, such as at the Drynoch earth flow (Figure 28), periodic

realignment and maintenance of the infrastructure is required. For one recent case, a small portion of a major earth flow reactivated and caused minor disruption to a rural road and railway. At this location, stabilization using jet-grouted columns is being used (BC Ministry of Transportation and Infrastructure, pers comm).



Figure 29. Earth flow complex in the Liard River valley, BC; a surging segment of the complex can be seen left of the photo centre (photo O. Hungr).

One large earth flow lay unrecognized on a bedrock flank near the confluence of the Fraser and Chilliwack rivers in the lower mainland of BC. The Marble Hill subdivision was constructed on the toe of the earth flow in the 1990s. In the winter of 1997, possibly as a result of a persistent snow pack and the resulting enhanced infiltration, the Marble Hill earth flow moved slowly for approximately 10 cm, on a shear surface approximately 60 m deep. Most of the subdivision houses were displaced, but undamaged. A few suffered structural damage due to differential movements. To avoid liability, the BC Government expropriated a number of new houses at a cost of several tens of millions of dollars.

The toe of this earth flow was probably once eroded by the Fraser River. The river channel has, however, been displaced to the opposite side of the floodplain (possibly by the massive, mid-Holocene Cheam rock avalanche approximately 10 km to the east). Prior to 1997, the earth flow was subject only to minor, intermittent movements and was not identified as a major landslide. A recent LiDAR image can be interpreted as showing a flow-like feature that is quite distinct in morphology from an alluvial fan or debris fan. Unfortunately, most technical data concerning this example is not publically available.

2.6 Rock Slides in Weak Tertiary and Cretaceous Bedrock

2.6.1 Occurrence and Identification

Widespread rock slope instability occurs in Cretaceous bedrock valleys in the Interior Plains and the Rocky Mountain foothills. Smaller areas involving weathered Tertiary bedrock of the interior and northern BC are also subject to rock slides. Most of these landslides are slow, rotational or compound slides (Hutchinson, 1988; Hungr et al., 2014), caused by weak rock masses disturbed by stress relief along valley walls and facilitated by the presence of weak horizontal surfaces within the bedrock.

The sedimentary platform of the Interior Plains is more than 1,000 km wide. It is one of the largest expanses of undeformed, weak sedimentary bedrock in the world. It is composed mainly of marine shale and to a lesser extent of continental sandstone of Mesozoic to Tertiary age. The thick and sub-horizontally bedded stratigraphic sequence was deeply incised by Pleistocene meltwater channels, as a widening gap opened at the end of glaciation between the continental ice sheet, receding to the east, and Cordilleran ice sheet, retreating more slowly to the west. Some of these channels were infilled by glacial drift during ice re-advances and many were re-excavated during the final ice retreat. These channels are presently occupied by contemporary rivers, such as the Liard, Peace, Athabasca, Saskatchewan, and Red Deer. Along most of their lengths, these valleys are bordered by bedrock landslides, landslides in glaciolacustrine and lacustrine clay and silt and landslides containing both bedrock and overburden (Mollard, 1977 and Section 2.2. in this contribution).

2.6.2 Characteristics and Examples

A comprehensive inventory of bedrock landslides in these valleys does not exist but would number in the thousands. However, some local inventories and descriptions do exist. The basic character of these bedrock landslides is described by Thomson and Morgenstern (1974). The bedrock is typically sandstone, siltstone, claystone and shale with scattered seams of coal and smectitic clay and is mostly of marine origin, grading to massive continental sandstone near the top of the sequence. The beds typically dip a few degrees to the east, with some steeper dip angles closer to the mountains. The valleys are narrow, steep-sided and incised into bedrock to depths of 60 to 120 m. There are very few faults or other tectonic features, however, the relatively rapid early post-glacial excavation of the valleys resulted in widespread stress relief and a set of local micro-tectonic features, known collectively as ‘valley rebound features’ (Matheson and Thomson, 1973).

The shale contains smectitic clay, both as an admixture in certain beds and in the form of bedding-parallel bentonite seams, probably the remains of Cretaceous ash falls. This composition has a controlling influence on the shear strength of the rock masses and on the mechanism of sliding that is determined by the presence of weak sub-horizontal layers at many levels within the stratigraphic sequence. The valley rebound was accompanied by upward flexing of the unloaded strata beneath the valley floor. The flexural slip pre-sheared the weak horizons adjacent to the valley walls and prepared the slopes for landslides. The pre-sheared surfaces may have residual friction values ranging from 5 to 11° (Matheson and Thomson, 1973).

Although rotational slides do occur, in most cases the slides are compound. A typical example is the 100,000 m³, 2003 Keillor Road landslide in Edmonton, AB (Figure 30). It occurred in Cretaceous shale overlain by glacial drift (Soe Moe et al., 2009). The rupture surface consists of a steep main scarp, sometimes curved, that is connected to a basal surface seated in one of the weak

sub-horizontal layers in the stratigraphy. Much of the sliding movement involves translation along the weak surface and some authors have referred to these slides as translational. However, as noted by Hutchinson (1988), there is an important difference between the compound and translational failure mechanisms. The former is driven only by the instability of the active block at the head of the landslide and the stability neutral point is at the intersection of the two main segments of the rupture surface. The landslide is self-stabilizing, as subsidence of the active block reduces the driving forces moving the passive block forward.

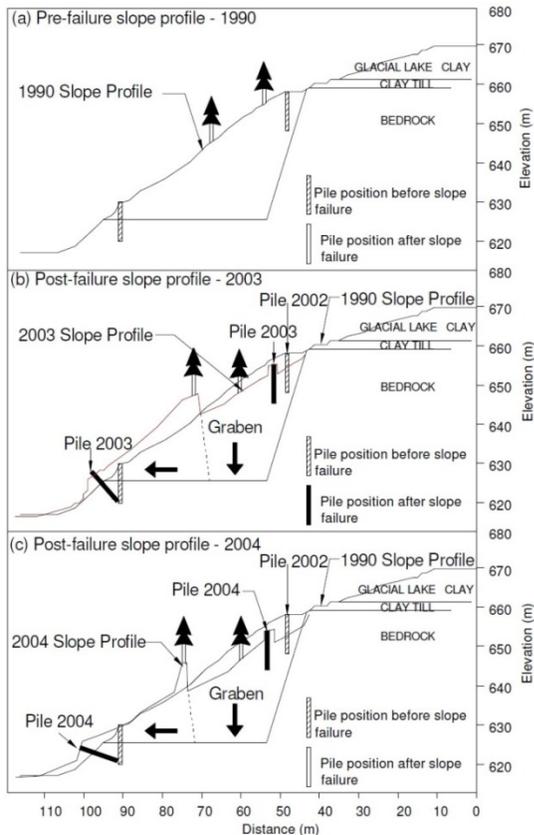


Figure 30. Schematic of the development of the Keillor Road compound slide in Edmonton, AB; the main scarp may not be as steep and linear as shown here, but may curve to a lower angle within the shale layer; such details are often difficult to document without extensive drilling investigation (Soe-Moe et al., 2009).

The compound mechanism can develop at several depths within the slope, giving rise to multiple compound slides. The type of compound sliding observed in the Cretaceous bedrock is similar to that in the overlying over-consolidated glaciolacustrine clay, described in Section 2.2. As a result, many deeper sections of the valleys in Alberta and eastern BC exhibit multiple successive compound slides both in bedrock and overburden. It is often difficult to distinguish the bedrock level by observing the morphology of such slopes (Figure 31).

Scatter River, BC - Some of the most remarkable features involving landslides in Cretaceous bedrock are found on the Scatter River, a minor tributary of the Liard River, in north-eastern BC (Gerath and Hungr, 1983). A tributary creek approximately 10 km from the confluence occupies a wide valley, excavated by early post-glacial meltwater in the Lower Cretaceous shale of the Liard Formation, overlain by a massive sandstone unit. The left side of the meltwater channel

exhibits rotational slides. The opposite side has failed as compound slides, consisting of steep main scarps, well-defined grabens, horst blocks and disturbed blocks descending towards the canyon occupied by the undersized creek.



Figure 31. Multiple compound slides on the northern bank of the Pine River, BC; the bedrock-overburden interface is at mid-height of the slope (photo O. Hungr).

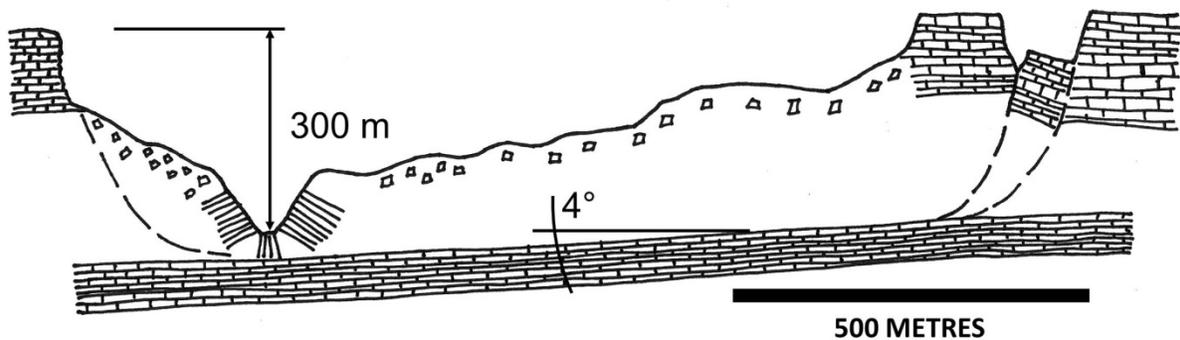


Figure 32. Schematic interpretation of the asymmetric landsliding on the two sides of Ship Creek, tributary to Scatter River, BC (Gerath and Hungr, 1983).

A cross-section of the valley, derived from surface topography, surface mapping and limited stability analyses is shown as Figure 32. The rupture surface of the compound slide follows a weak surface situated near the base of the Cretaceous bedrock sequence, at a depth approximately 300 m beneath the top of the plateau. The sub-horizontal attitude of the basal weak surface is indicated by the displacement of the horst block ('the Ship'), which moved away from the main scarp in a sub-horizontal displacement of tens of metres, with only very minor subsidence. Although the regional structure consists almost exclusively of undeformed, sub-horizontal beds, the two sides of the canyon expose strata inclined 45° away from the stream, and rock exposures in the creek bed contain vertical beds. This area is interpreted as a pressure zone, where the toes of the landslides from the opposite sides of the valley meet and support each other. Further movement is facilitated by the incision of the creek into this pressure zone. However, because the present stream is very small compared to the meltwater that flowed through this valley in early post glacial times, present movements are extremely slow.

A limit equilibrium analysis was carried out to explain the striking asymmetry of the valley. The Cretaceous bedrock strata have a regional dip of approximately 4° . An analysis of the right side of the valley, using a piezometric surface close to the ground surface, indicates that movement of the compound sliding body is possible provided that a pre-sheared weak surface exists, with a residual friction angle of 8° . The steep opposite side does not have the benefit of the regional dip and fails by simple rotational sliding.

Spectacular sliding features on a large scale occupy the entire length of the creek and the lower Scatter River (Figure 33).

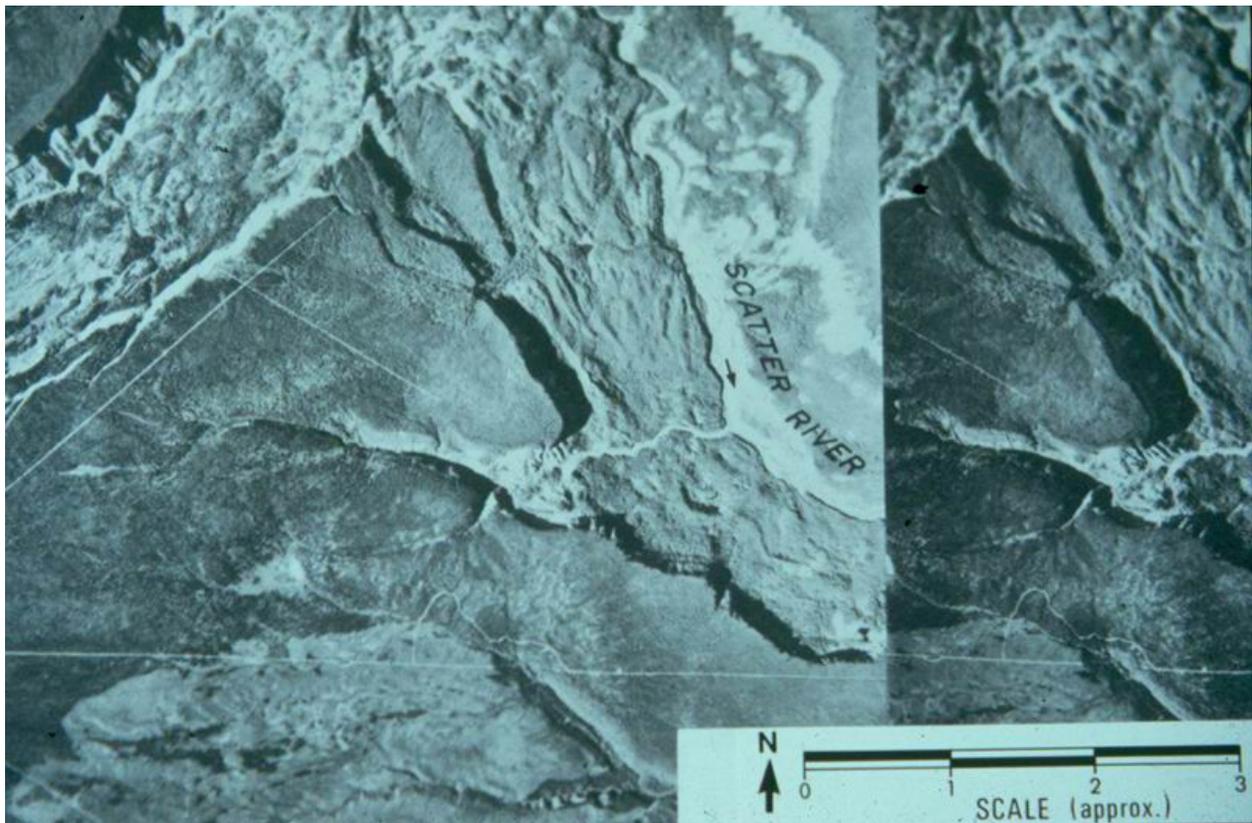


Figure 33. Stereo airphoto pair of landslides at the confluence of the Scatter River and Ship Creek (upper left corner of the image); the back-tilted landslide block above the centre of the image is 1.3 km long and 0.5 km wide (Gerath and Hungr, 1983).

2.6.3 Hazard Assessment

Thomson and Morgenstern (1974) described several inventories of landslides in shale along rivers of southern Alberta. In one example, involving a 435 km long reach of the Red Deer River, 137 individual landslides were identified (0.31 cases per km of valley), ranging from 0.2 to 1.5 km² in plan area.

Severin (2004) completed an inventory of landslides in river valleys of the Charlie Lake map sheet, including the Peace River and its tributaries, in north-eastern BC. The initial analysis used 1:60,000 scale airphotos and involved 1,292 km of valley length. The individual landslides were outlined on the airphotos, classified and transferred to topographic maps. The initial study identified 1,610 individual landslides (1.25/km of valley), with average plan area from 0.4 to 0.6 km². Of these landslides, 61% were classified as inactive (dormant), and 39% moderately to very active. The active group, identified by widespread signs of on-going movement, numbered 237 (15%).

A little less than half of these landslides were interpreted as slides in shale bedrock, whereas a somewhat larger number involved only glacial drift. This distinction, however, is difficult to make at this scale (1:60,000) of investigation because of the similarity of style and mechanism of landsliding in the two materials. Severin updated his inventory in 2010 using LiDAR images of the area. The LiDAR image allowed better identification of individual slide bodies within landslide complexes, so that the landslide counts increased substantially from the first version of the inventory (J. Severin, pers. comm.).

2.6.4 Mitigation

The few examples discussed indicate that bedrock and overburden landslides are extremely common in the Tertiary and Cretaceous terrain of the Interior Plains. This presents significant constraints to the infrastructure located in the valleys. Nearly every road or pipeline presents a number of difficult challenges. As a result, considerable expertise concerning site investigation, slope stability analysis and design is required.

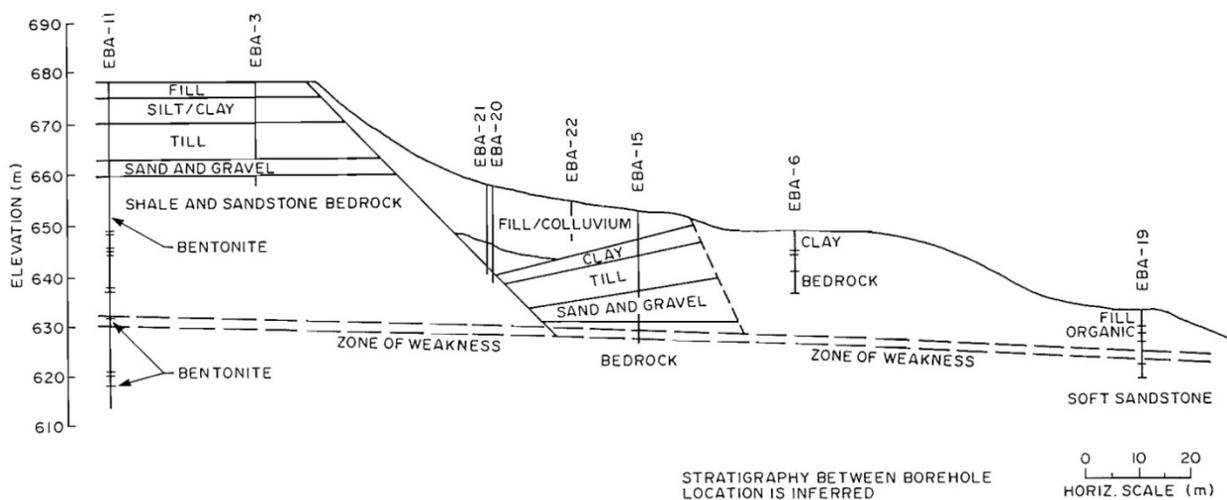


Figure 34. Cross-section of the Grierson Hill landslide (Chan and Morgenstern, 1987).

An interesting example of mitigation is the design and construction of the Edmonton Convention Centre, situated on a stabilized compound landslide in Cretaceous shale and overburden (the Grierson Hill landslide, Edmonton, AB, Morgenstern, 1982). Figure 34 shows a cross-section of the inactive landslide that exhibits typical features of compound slides. The main scarp is a steep shear surface cutting through glacial drift. The basal portion of the rupture surface follows a sub-horizontal pre-sheared bentonite seam in the bedrock, with a residual friction angle of 7°. The morphology of the landslide, although subdued by erosion, exhibits the characteristic active graben block, fronted by a passive horst. Although inactive, the landslide area was initially prohibited from development. In a bold design concept, however, the landslide was stabilized by unloading its head and the active block, then excavating a 25 m high vertical face into the intact soil sequence behind the main scarp. This was stabilized by permanent, pressure-grouted cable anchors, up to 25 m long. Analysis of progressive deformation of the Edmonton Convention Centre excavation was carried out using an elasto-plastic stress-deformation model that predicted movements of the excavation would remain within tolerable limits (Chan and Morgenstern, 1987).

2.7 Rock Slides and Topples in Strong Bedrock, and Mountain Slope Deformation

2.7.1 Occurrence and Identification

There are steep natural slopes in many parts of Canada and rock slides are common. The Canadian Cordillera represents one of the largest contiguous mountain regions in the world and large rock slides are common. Bedrock landslides in Canada include rapid or slow, large translational and compound slides, as well as flexural and block topples. Mountain slope deformation, some of which is precursory to rock avalanches, is also widespread. One of the major causes of rock slope instability, especially in the Cordillera, is debuttressing due to valley glacier erosion.

Natural rock slides do not pose high human risks in Canada as they do elsewhere in the world, due to the low population density of this country. However, hazardous events do occur. For example, in 1956, a rock slide demolished two-thirds of the 400,000 kW Schoellkopf Hydroelectric Station on the American side of the Niagara Gorge. Spectacular images of the event can be found on the Internet. The rock slide in dolomite was estimated to contain 20,000 m³ of material and was essentially a natural cliff collapse, probably toppling of a slab of rock separated along vertical stress-relief joints. It is quite possible that the rock slide was triggered by porewater pressure increase in the joints due to changes of drainage caused by canals constructed at the crest of the gorge wall. The damage was estimated at \$25 million 1956 US dollars and one person was killed (<http://astheysawit.com>).

2.7.2 Examples and Hazard and Risk Management

Transportation - There are numerous Canadian examples of rock slides along transportation routes. Some of these in natural steep cliffs, some are failures of cut slopes and many involve natural slopes that have been modified to some extent by human activity. The Porteau Bluffs, situated along BC Highway 99 between Vancouver and Squamish, have gained notoriety for planar rock slides along inclined stress-relief joints in quartz diorite of the Coast Plutonic Complex. It is a natural cliff, shaped by glaciers, but in the mid-1950s it was undercut by blasting during the construction of the Pacific Great Eastern railway and BC Highway 99. In a series of stabilization projects implemented over the past 60 years, specific sections of the cliff have been

stabilized by rock bolts and by removal of loose rock by ‘trim blasting’ (Blais-Stevens and Hungr, 2008). However, large masses of rock, separated by a family of stress relief joints, dipping at 55°, remain unreinforced and rely on the discontinuity of the joints for their stability. A large planar rock slide in the 1960s appears on the cover of the 2nd edition of the text, Rock Slope Engineering (Hoek and Bray, 1977). In July 2008, a very similar rock slide near the same location closed both the railway and the highway for several days (Figure 35).



Figure 35. Rock slide at Porteau Bluffs, between Vancouver and Squamish, BC; photo, taken following the stabilization of the slope, shows the planar rupture surface, defined by a stress relief joint (photo O. Hungr).

Many potential rock slides along transportation routes are stabilized. For example, a 145,000 m³ rock slide of weathered and sheared granite was triggered by a deep excavation during the twinning of BC Highway 97, near Summerland, BC. The rock slide initially opened a wide crack accompanied by 1 m displacement of the unstable block. Repeated surveys and a wire extensometer monitoring system were undertaken to ensure worker safety while the landslide was stabilized by unloading its head (Bean and Hungr, 2011). The effects of the unloading were quantified using three-dimensional limit equilibrium analysis.

BC Hydro - BC Hydro operates 42 dams with over 3000 km of reservoir shorelines – many formed in mountainous terrain. The possibility of a slope failing, impacting a reservoir and causing a landslide-generated wave must be considered. As a result, BC Hydro has carried out many detailed site investigation programs to assess the stability of specific locations bordering the reservoirs. Several major slopes have been stabilized, and for the past 50 years, BC Hydro has had a program of systematic reservoir slope inspections, including continuous displacement

monitoring of several critical sites. The Downie landslide, where a billion m³ of metamorphic rock was recorded to be moving at rates of up to 10 mm/year towards BC Hydro's Revelstoke reservoir, was stabilized by excavating a large drainage adit and drilling 'fans' of drainage holes beneath the rupture surface (Piteau et al., 1978).

The 130 million m³ Dutchman's Ridge landslide, also in metamorphic rock, was identified during the design stage of BC Hydro's Mica dam in the 1960s. The landslide is located 1.5 km across the reservoir from the crest of the rock fill. An extensive mapping, drilling and instrumentation program was carried out. The rock slide, in schistose bedrock, is moving on a thin zone of sheared clay-rich rock that is interpreted as a tectonic fault dipping towards the reservoir. The movement rates prior to reservoir impoundment were negligible. With impoundment, they accelerated up to 6 mm/year. A drainage system with an adit and drill holes was installed and reduced the piezometric pressure head on the sliding surface by up to 90 m at certain locations. The resulting movement rates decreased to 1.4 mm/year. The estimated total cost of the stabilization was approximately \$25 million in 1980 dollars (Moore and Imrie, 1992).

A large topple near Chilliwack, BC was likely de-stabilized by the construction of a BC Hydro power tunnel and incline at shallow depths beneath the slope surface in 1952. Active movements of a rock mass containing approximately 20 million m³ of steeply-jointed and sheared diorite were recognized in 1989 (Moore et al., 1992). The slope exhibits ancient anti-slope scarps, indicative of previous toppling displacements. The slope was stabilized in 1990 by abandoning and draining the 1950s power tunnel and incline as well as excavating new ones at a greater depth. With this modification, power tunnel leakage ceased and the tunnel became an effective drain for the slope. This landslide can be seen in the centre of Figure 17.



Figure 36. Example of mountain slope deformation ("sacking" directly right of the centre of the photo), on Mission Ridge, near Lillooet, BC (photo C. Esposito, used with permission).

In 1977, during excavation for the abutments for Revelstoke dam, BC Hydro identified several large potential failures of tectonically weakened gneiss that threatened the dam facilities. The largest of these, a 70° slope 60 m high, was stabilized by installing 60 tensioned cable anchors, up to 50 m in length, with a total capacity of over 16,000 tonnes, in addition to an extensive drainage system (Moore and Imrie, 1982).

BC Hydro, and other authorities in western Canada who are responsible for infrastructure safety, should consider the existence of widespread deformation features on mountain ridges throughout the Cordillera. Figure 36 shows slope sagging features on a ridge near Lillooet, BC. These features are an example of double, compound, listric slope sagging, as defined by Hutchinson (1988). BC Hydro has monitoring systems on two deformed ridges of similar description, but so far no significant movement has been registered.

Mining - Canadian open pit mines have also experienced rock slope instability. Both pits of the Highland Valley Copper Mine, near Kamloops, BC, have a long history of slow movements. The most significant deformation affects the south-east wall of Lornex pit, which has reached a depth of 600 m (Newcomen et al., 2008). The pit is excavated in altered and sheared Jurassic diorite. Flexural toppling along pervasive near-vertical joint sets deforms the benched excavation walls, producing a series of anti-slope scarps that obliquely cross the benches of the pit. A graben structure is forming at the top of the slope. The movements respond to rain and snowmelt infiltration during the spring and have, on several occasions, produced ‘pulses’ of movement, up to 25 mm/day. However, an extensive program of dewatering using horizontal drill holes has kept the movement rates at a tolerable limit and mine excavation is continuing under the protection of full-time monitoring.



Figure 37. Tension crack systems behind the South Peak of Turtle Mountain, Frank, AB, that are being monitored by the Alberta Geological Survey (photo O. Hungr).

The 1903 Frank landslide (see Section 2.9.2) caused an extensive crack system on the ridge of Turtle Mountain, Alberta (Figure 37). The cracks were first described and measured in the 1930s. Currently, they are the subject of an extensive, state-of-the-art monitoring program by the Alberta Geological Survey. The program comprises differential global positioning surveys, extensometers, geophones, and InSAR observations. Even though the movements are extremely slow, a risk management plan has been prepared to protect the population and infrastructure on the floor of the Crowsnest River Valley, approximately 900 m downslope of the ridge (Froese et al., 2009).



Figure 38. The site of a fatal rock fall on BC Highway 99, south of Squamish (Photo O.Hungr).

2.8 Rock Falls

2.8.1 Occurrence and Identification

Rock falls occur in all parts of Canada, on natural cliffs, excavation faces above transportation routes and in open pit mines. A typical large rock fall on a highway in BC is shown on Figure 38. Given the vast extent of highways and railways that are bordered by rock cuts, it is surprising that Hungr and Evans (1989) could only find published records of 9 deaths caused by rock falls (this number has since increased by about 18 additional cases). Reported deaths caused by rock falls on houses account for another 5 cases.

Frequency of rock falls has been documented by summarizing rock fall maintenance observations by the BC Ministry of Transportation and Infrastructure and the railway companies (Hungr et al., 1999). Figure 39 shows a magnitude-cumulative frequency (MCF) curve for a sector of BC Highway 99 between Vancouver and Whistler, where the highway is bordered by 10 km of rock cuts greater than 10 m. Dividing the data from Figure 39 by 10, the frequency of rock falls $>1 \text{ m}^3$ /km of rock cut is less than 1 per year, whereas an event of 100 m^3 is 10 times less frequent (1 in 10 years per km of rock cut). A risk analysis based on these data showed estimated risk to highway users is in the same order as the observed mortality rate in the same highway sector (Hungr et al., 1999). These frequencies appear to be an order of magnitude greater than those observed by Gardner (1983) on natural limestone cliffs in the Rocky Mountains. The inclination of the MCF curve derived by Gardner (1983) is also somewhat flatter than the curve from the coast of BC, indicating that limestone cliffs produce a relatively larger proportion of large magnitude rock falls.

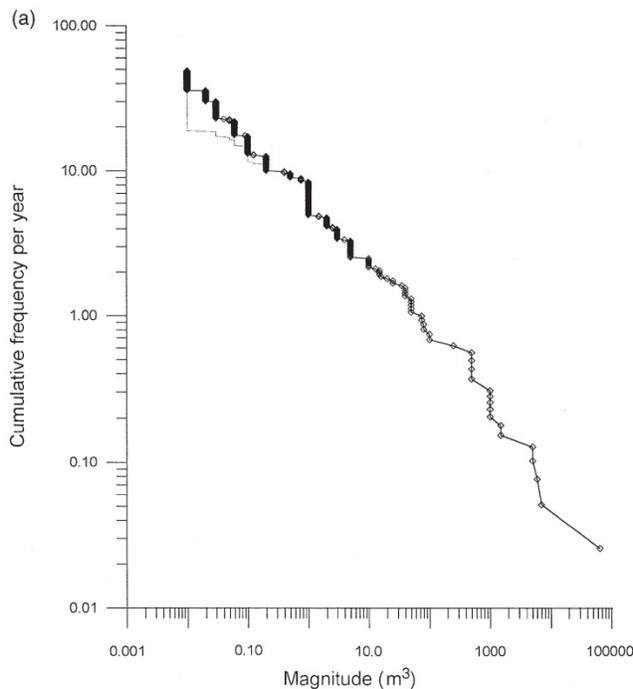


Figure 39. Magnitude-cumulative frequency curve for rock falls along a sector of BC Highway 99, between Vancouver and Whistler (Hungr et al., 1999).

A striking example of a rock fall involving a residence occurred in November 1983 in the community of Sunnybrae, near Salmon Arm, BC (Hungr and Evans, 1989). A single, wheel-shaped boulder, approximately 6 x 6 x 2 m in size and weighing approximately 100 tonnes, separated along a stress-relief joint from the lower part of a natural limestone cliff and rolled downslope approximately 700 m before impacting a house (Figure 40). Two residents were killed; a third survived. Rock falls occur so rarely at this site that very few talus deposits were noted. The house site remains inhabited today.



Figure 40. Source area and general path of the fatal rock fall of 2003 at Sunnybrae, near Salmon Arm, BC; the boulder path is the vertical cleared track through the trees, directly above the chimney; the boulder bounded over the cliff in the centre of the photo, changed direction and demolished a home to the right of the photo (photo O. Hungr).

2.8.2 Hazard and Risk Assessment

To optimize available funds, Canadian transportation agencies (provincial highway departments and railway companies) typically use the ‘ALARP’ (as low as reasonably practical) approach (Porter and Morgenstern, 2013) to manage rock fall risks. Although most Canadian transportation agencies use adaptations of the Oregon rock fall hazard rating system (Pierson et al., 1990), some Canadian-specific systems have also been developed (Abbott et al., 1998).

In 1993, BC Ministry of Transportation and Infrastructure allocated approximately \$3.5 million (1993 dollars) per year for maintenance of rock cuts subject to rock falls. This amount is spent for scaling, trimming and stabilization, and is guided by a qualitative risk-based priority system. Third parties suffering damage by rock falls are compensated through litigation, with individual court settlements having reached several million dollars. Bunce et al. (1997) carried out a detailed risk analysis at a location on BC Highway 99 where a court settlement was awarded, and concluded that the actual risks to the travelling public from rock falls are small, compared to the risk of traffic accidents.

2.8.3 Analysis, Management and Mitigation

Rock fall mitigation methods used in Canada include slope stabilization by shotcrete, mesh, rock anchors, and scaling, protective ditches, barriers and cable fences. Many of these methods, and the approach to their design, are described by Wyllie and Mah (2004).

2.9 Rock Avalanches

2.9.1 Occurrence and Identification

The most spectacular of all landslide types, rock avalanches, occur as a result of large failures of mountain slopes. The Canadian Cordillera contains over 1 million km² of mountainous terrain. Many large rock slides in this physiographic region turn into highly mobile streams of fragmented rock, known as rock avalanches.

2.9.2 Characterization and Examples

An example of a rock avalanche is the Frank landslide in Alberta, where 36 million m³ of limestone descended from Turtle Mountain in April 1903 and travelled as a flow for more than 3 km in less than 2 minutes (Figure 41). The mountain was likely destabilized by river erosion near the base of the slope (Cruden and Martin, 2007). In demolishing a part of the town of Frank, the rock avalanche became the most deadly landslide in Canadian history, with approximately 70 victims (Evans, 2003).

There have been numerous large prehistoric rock avalanches in many mountain ranges of the Cordillera. For example, an inventory by Cruden, (1985) reports 129 post-glacial rock avalanches in the folded calcareous rocks of the Rocky Mountains in Alberta, an area approximately 60,000 km². Assuming the post-glacial period to be about 10,000 years, this is an average frequency of more than one natural event per century. As indicated by Cruden (1982), at least one historic landslide has taken place in this area – the 1933 Brazeau Lake rock avalanche, with a volume of 4 million m³. The Frank landslide has been considered a result of human activity.



Figure 41. Panoramic view from the crown of the Frank landslide, AB; the toe is 3.3 km (horizontal) distance and 800 m below where the photo was taken; the remnant town of Frank, AB is to the left (photo O. Hungr).

The 2010 Capricorn Creek rock avalanche, which descended from the western flank of the Mt. Meager volcano, near Pemberton, BC, is the most significant recent landslide in North America (Guthrie et al., 2012). In August 2010, the western flank of the 2,680 m high Mt. Meager collapsed, and released approximately 48 million m³ of fragmented lava and tephra into the valley of Capricorn Creek at the foot of Capricorn Glacier. The landslide debris flowed down the valley at extremely high speeds, superelevating around bends. The superelevation geometry indicates a maximum speed of more than 60 m/s (216 km/h). On entering the Meager Creek Valley, the debris climbed the opposite valley slope to a height of 100 m, then divided into two streams, one travelling 3 km upstream along Meager Creek, the other moving an equal distance downstream and spreading widely over the Meager Creek fan and the floodplain of the Lillooet River (Figure 42). The landslide debris created two landslide dams, one on Meager Creek and the second on the Lillooet River and a brief flooding alert was given for areas downstream. Fortunately, the high mobility of the landslide debris, caused by the liquefaction of valley deposits and the dilution of the debris, resulted in low wide dams, so that their eventual breach involved only limited discharge (Guthrie et al., 2012).

The Capricorn Creek rock avalanche may have occurred due to the recent retreat of the Capricorn Glacier. No specific trigger has been proposed; there was no pre-cursory earthquake (Guthrie et al., 2012).

A back-analysis of the Capricorn Creek rock avalanche, using the dynamic model DAN3D (McDougall and Hungr, 2004) resulted in a realistic simulation of most aspects of the landslide behaviour. The analysis assumed initial frictional sliding followed by flow in the Capricorn Creek Valley using the Voellmy rheological model. However, in order to simulate the long runout of the landslide in the lower valley and where the landslide entered Meager Creek, it was necessary to reduce the Voellmy rheological parameters to extremely low values. Downstream of this point, the debris behaved like a turbulent fluid, with a very small frictional component. This is explained as a result of liquefaction of loose, saturated volcanic debris that comprises the valley fills.



Figure 42. Orthophoto of the 2010 Capricorn Creek rock avalanche (image courtesy R. Guthrie, used with permission).

Table 5. Historical rock avalanches in southern BC with volumes exceeding one million m³

Year	Event	Volume (10 ⁶ m ³)	Reference
Non-volcanic terrain			
1964	Hope	48	Evans (2003)
1959	Pandemonium Creek	5	Evans (2001)
1970	Kennedy Lake	4	S.G. Evans (pers. comm.)
1997	Mt. Munday	3	Evans and Clague (1999)
1956	Tim Williams Glacier	3	Evans and Clague (1999)
1993	Kshwan glacier	3	Evans and Clague (1999)
1946	Mt. Colonel Foster	1	Evans (2001)
Quaternary volcanics			
1853	The Barrier, Mt. Garibaldi	62	Moore and Mathews (1978)
2010	Mt. Meager	45	Guthrie et al. (2012)
1975	Devastation Peak, Mt. Meager	13	Evans and Clague (1999)
1964	Dusty Creek, Mt. Cayley	5	Clague and Souther (1981)

In southern BC there have been numerous prehistoric rock avalanches, however, a comprehensive inventory has not been compiled. An incomplete list of large historical rock avalanches is included in Table 5. Only one, the 1946 Mt. Colonel Foster rock avalanche, is confirmed to have been triggered by an earthquake (Evans, 2001). The Coast Mountains of BC have a slightly greater incidence of large rock avalanches than the Rocky Mountains, possibly as a result of more intense glaciation.

The Mackenzie Mountains, an extension of the Rocky Mountains in the Northwest Territories, contain many examples of large prehistoric rock avalanches (Eisbacher, 1979). Only one historical event in that region has been recorded, the 5 to 7 million m³ North Nahanni rock avalanche, in the Mackenzie Mountains, NWT, triggered by the 1985 North Nahanni earthquake (Evans et al., 1987; Figure 43).



Figure 43. North Nahanni rock avalanche, Mackenzie Mountains, NWT; note the long travel distance of saturated soil that was liquefied by the impact of the rock avalanche (photo O. Hungr).

As noted by Evans and Clague (1999), rock avalanches seem to be associated with deglaciation. A specific example is the July 2007 Mount Steele rock and ice avalanche in the St. Elias Mountains, YT (Lipovsky et al., 2008). This rock avalanche involved several tens of million m³ of material, mostly ice, although the rupture surface was in sheared dioritic bedrock (Figure 44). The landslide travelled 6 km over the surface of the Steele Glacier and climbed a ridge to a height of 275 m. The trigger is uncertain but is not related to an earthquake, although both the main landslide, as well as a smaller preliminary icefall, generated measurable seismic signals.

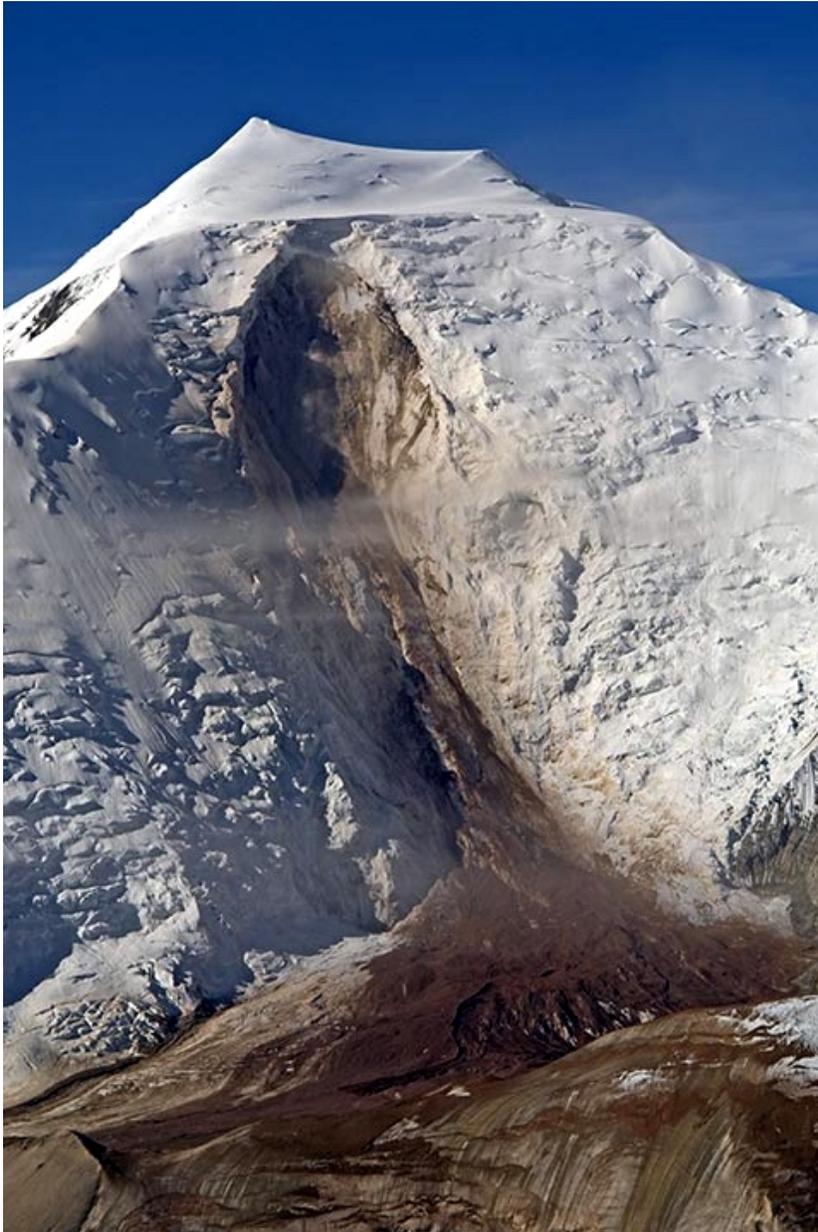


Figure 44. Mount Steele rock and ice avalanche, YT (photo P. Lipovsky, used with permission).

2.9.3 Hazard and Risk Assessment and Mitigation

Several large rock slides, potentially capable of generating rock avalanches in western Canada have either been stabilized by drainage, or are being monitored to provide a warning of slope failure. In addition to the large-scale mountain slope stabilization and monitoring projects by BC Hydro, described in Section 2.7, BC Hydro is also monitoring other sites, for example Santa Claus Mountain near Lillooet, BC (Moore and Imrie, 1992). An extensive monitoring system is being maintained by the Alberta Geological Survey on the South Peak of Turtle Mountain, Alberta, adjacent to the source of the 1903 Frank landslide (Froese et al., 2009). A detailed hazard assessment, including 3D dynamic modelling of rock avalanche runout has been completed on the same site (Pedrazzini et al., 2012).

It is of interest that an explicit warning of a major landslide involving Mt. Meager, and a potential flood hazard downstream on Lillooet River and in the Town of Pemberton was issued only two years before the 2010 Capricorn Creek rock avalanche (Friele et al., 2008).

2.10 Landslides in Permafrost Terrain

2.10.1 Occurrence and Identification

A large portion of Canada lies within the ‘permafrost zone’ where the ground temperature is at or below 0°C for a minimum of two consecutive years. In northern Canada, permafrost is typically continuous, but moving southward there is transition, initially, into the ‘discontinuous permafrost zone’, then into the ‘non-permafrost zone’. The various permafrost zones are classified somewhat differently by different researchers (see Heginbottom, 2002).

Because of annual temperature variations, the near-surface permafrost layer can exist above 0°C for part of the year, resulting in melting of the ground ice. This layer, the ‘active layer’, is delineated by measuring ground temperature versus depth over a minimum of two years. The resulting depth-temperature profile is called a ‘trumpet curve’ (Figure 45).

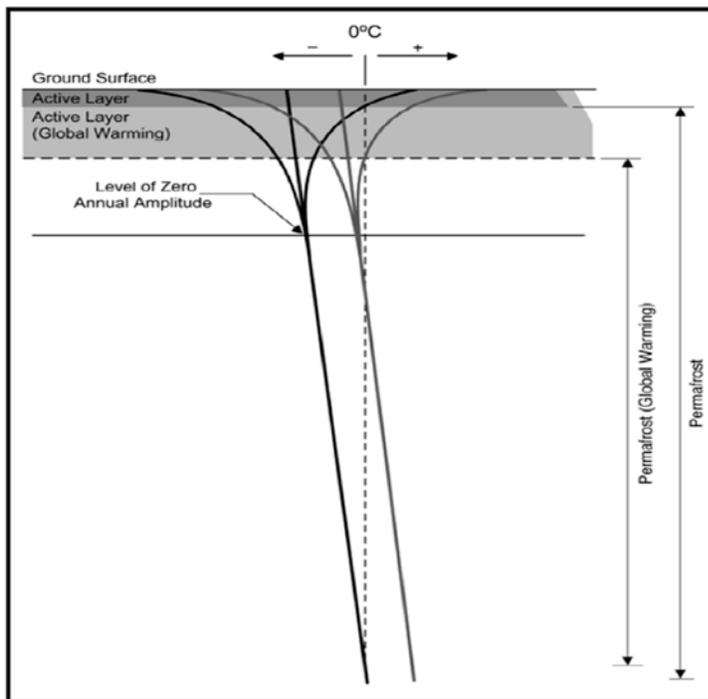


Figure 45. Example ‘trumpet curve’ of ground temperature profiles used to define the active layer; also shows an illustration of the effect of a global warming on the active layer (Weitzner et al. 2011).

Permafrost is not limited to a material (e.g. soil or rock); it is a condition of the material. The effect of thawing on the strength properties of soil is described by McRoberts and Morgenstern (1974). For rock masses, the main effect is related to the thawing of the ice contained in the fractures, with the resulting loss of strength and potential pressurization of the fractures (Arnold et al., 2005; Rist, 2007; Springman and Arenson, 2008). In both cases landslides can result.

Permafrost-related landslides are the result of disturbances to the active layer such as direct exposure of ground ice to the atmosphere or water, a change in runoff and groundwater flow patterns (Lipovsky and Huscroft, 2006), forest or tundra fires (e.g. Huscroft et al., 2004), river erosion and/or increasingly, the warming trend of the climate (Ford and Pearce, 2010). The effect of warming is shown on the trumpet curve on Figure 45 by an increase in the thickness of the active layer and an overall reduction in the thickness of permafrost layer (Weitzner et al., 2011). In the Mackenzie River Valley, NWT, Wang et al. (2009) found that retrogression of a vertical permafrost face was up to 20 m/y and was independent of the orientation of the face.

Because permafrost is only defined in terms of temperature of the ground, permafrost-related landslides types are similar to those found elsewhere. Therefore, this sub-section concentrates on landslides exacerbated by climate warming. The effect of climate change on permafrost has been studied for many years at various sites in Canada (Smith et al., 2005).

Permafrost-related landslides can start as slow movements up to 0.7 m/year (Savigny and Morgenstern, 1986a and 1986b), but can evolve into more rapid retrogressive flows (either debris flows or earth flows), all within the active layer. Examples of such flows are shown in Figure 46. McRoberts and Morgenstern (1974), while mapping landslides in permafrost in the Mackenzie River Valley, subdivided permafrost-related flows into three types: solifluction, skin, and bimodal flows. Harris and Lewkowicz (2000) distinguished between flow and slide-dominated permafrost-related landslides: the former termed 'skin flows' and the latter termed 'active-layer detachment landslides'. Landslide development in permafrost terrain, once initiated, can continue for many years.



Figure 46. Retrogressive thaw flow, YT (Lipovsky and Huscroft, 2006).

2.10.2 Characterization

Landslides in permafrost are mostly influenced by melting of the ice and the resulting significant reduction in the shear strength of the material. Therefore, the primary factors to consider in permafrost-related landslides are the presence and amount of ice in the ground, and the nature of the soil or rock in which the ice is present. Various techniques have been developed to detect and measure permafrost including, drilling, georadar and seismic cone penetration (Table 6; Leblanc et al. 2004). In some situations, for example patterned ground formed by ice-wedge polygons, the presence of permafrost is evident (Figure 47). Murton and French (1994) provide a classification of cryostructures and cryotextures related to frozen ground. More recently, various techniques including satellite monitoring (Singhroy et al., 2007) and LiDAR has been used to identify the extent of permafrost by developing a terrain model coupled with a climate model (Lewkowicz and Bonnaventure, 2008).



Figure 47. Pattern ground in dry sphagnum peat in the Hudson Bay lowlands, Brown polygons indicate massive ice wedges that extend down 2 or 3 m from the surface. (photo Natural Resources Canada).

Table 6. Methods of detection of permafrost (after Heginbottom, 2002).

	Direct observations	Indirect or remote observations
Geological methods	Borings and excavations; laboratory testing of samples	Air climate data; terrain typing; landscape analysis; vegetation mapping; etc.
Geophysical methods	Ground temperature measurements; thermal properties measurements	Seismic, electro-magnetic or ground radar profiling and sounding; geothermal modelling

McRoberts and Morgenstern (1974), Segó and Morgenstern (1983), and Savigny and Morgenstern (1986b), provide details of the geotechnical characteristics of ice-rich clay – the origin of most of the permafrost-related flows in Canada. Under some conditions, the liquidity index of the soil can be significantly above 1, providing a remolded strength sufficient for flow to take place (Wang et al., 2009).

2.10.3 Analysis and Modeling

McRoberts and Morgenstern (1974) first analysed thaw flows in permafrost terrain. They considered that in most cases, slope stability can be approximated by considering an infinite slope analysis. Thawing slopes were analyzed by introducing a ‘thaw-consolidation model’ that allowed for an estimation of excess porewater pressures required to reduce the factor of safety of the slope to close or below 1. Harris and Lewkowitz (2000) and Harris et al. (2001) agree with McRoberts and Morgenstern (1974), but suggest that *in situ* porewater pressure measurements near the failure plane are required for an effective stress approach for the stability analysis. If the material behaves like a fluid, then Harris et al. (2001) suggest the approach of stability analysis proposed by Vallejo (1980) or a numerical flow modeling technique like BING (Imran et al., 2001) could be used.

2.10.4 Hazard and Risk Assessment

Mass movements, including landslides, related to permafrost degradation are summarized in Table 7. Albeit developed for mountainous areas the matrix is applicable to all types of terrain.

Table 7. Matrix of potential landslide and related phenomena associated to permafrost degradation (after Harris et al., 2001)

Slope class (degrees)	Bedrock			Sediment	
	Non-competent lithologies (shale, soft mudstone, etc.)	Competent well-jointed lithologies	Competent massive lithologies	Fine-grained (silt, clay, some tills)	Coarse-grained (scree, gravel, sand)
>75	Rock fall	Rock fall	Occasional rock fall	--	--
30-74	Debris flows and slides (including deep-seated failures)	Rock slides, debris flows	--	Debris flows	Debris flows
15-29	Slides, thaw subsidence	Rock slides	--	Slide/ mudflow	Accelerated permafrost creep (rock glaciers)
<15	Thaw settlement	--	--	Thaw subsidence, solifluction, mudslides on steeper slopes	Accelerated permafrost creep
0	Thaw settlement	--	--	Thaw settlement	--

The first step in a hazard assessment is to map the extent of permafrost. This effort has been on-going in parts of Canada since the early 1970s (e.g. Rutter et al., 1973). The development of

terrain models and access to remote sensing technology has helped develop hazard mapping, in particular where related to ice-rich permafrost (e.g. Lipovsky and Huscroft, 2006; Lyle and Hutchinson, 2006).

Lewkowicz and Harris (2005) attempted to estimate the frequency and magnitude of active-layer detachment landslides both in the Mackenzie River Valley, NWT and on Ellesmere Island, Nunavut, and concluded that with climate warming and a reduced cloud cover, an increase in the potential number of permafrost-related landslides is expected. Huscroft et al. (2004) used a global circulation model to estimate temperature and precipitation changes in the Yukon and found that by year 2050, there is a strong possibility that precipitation may increase by 25% and average yearly temperature may increase up to 4° C. Springman and Arenson (2008), however, noted that there are still many uncertainties in predicting long term permafrost geotechnical properties in the context of climate change.

The elements at risk in permafrost terrain are similar to those found elsewhere. Harris et al. (2001) proposed an integrated approach for assessing the hazard and risk (Figure 48). Ford and Smith (2004) proposed a framework for assessing the vulnerability and risk of northern communities associated with the climate change. For pipelines, Porter et al. (2004) evaluated the risk associated with various hazards, including thawing of permafrost, using a probabilistic approach. At the regional scale, Weitzner et al. (2011) provided an estimate of the risk associated with climate change.

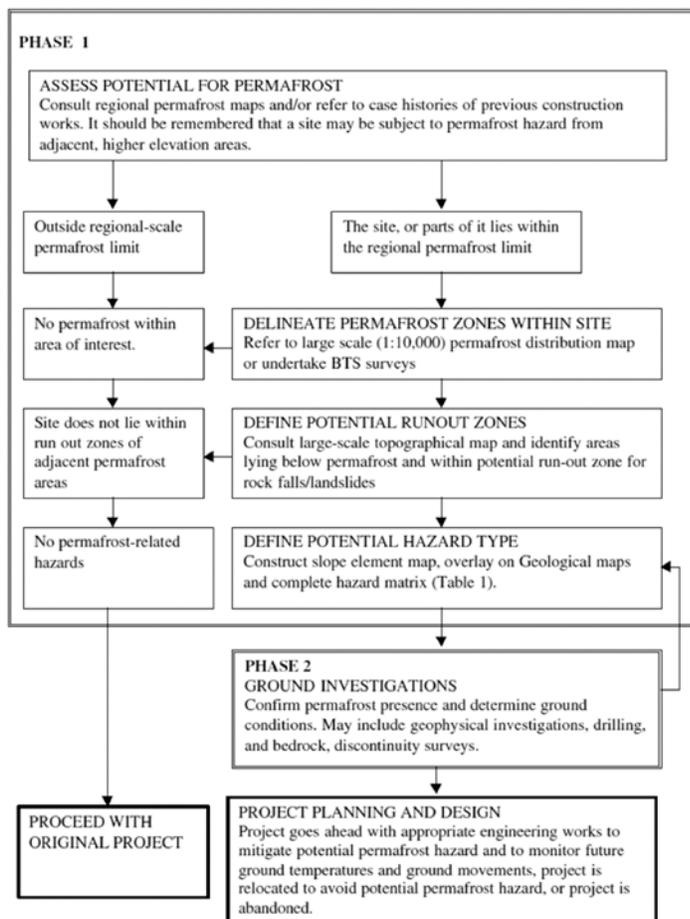


Figure 48. Flow chart illustrating integrated approach to assessing landslide hazards and risks in permafrost terrain (Harris et al., 2001).

2.10.5 Management and Mitigation

For landslides in permafrost terrain, the primary mitigation methods are to prevent the negative effects of temperature changes, or to avoid areas where such changes cannot be prevented (Harris et al., 2001).

2.11 Coastal Landslides

2.11.1 Occurrence and Identification

Canada's marine coastlines and fresh water shorelines total many thousands of kilometres, comprise a wide variety of geological materials and climatic environments, and represent dynamic environments shaped by erosional and depositional processes. Landslides in these environments (collectively referred to as coastal landslides) can originate subaerially or subaqueously. Submarine landslides are further discussed in Section 2.12.

Coastlines and shorelines are also exposed to tsunamis originating from earthquakes (also known as 'seiches') and subaerially landslide-generated waves (also known as 'surge waves', 'impulse waves' or 'displacement waves'; Rabinovitch et al., 2003), and subject to landslides triggered by processes not associated with coastal processes, such as earthquakes and strength degradation (Locat, 2011).



Figure 49. Havre St. Pierre landslide slide in sensitive clay along the north shore of the Gulf of St. Lawrence, QU (Bernarchez and Dubois, 2004).

The following discussion is limited to landslides along coastlines and shorelines where the primary causes are wave-dominated erosion and/or ablation of permafrost. For example, a coastal landslide in sensitive clays along the Gulf of St. Lawrence, QC (Figure 49; Bernatchez and Dubois, 2004); a rock slide in the Baie des Chaleurs, QC (Cloutier et al., 2012), a retrogressive thaw landslide on Herschel Island, NWT (Lantuit and Pollard, 2008); and a landslide along the Lake Erie bluffs in Ontario (Figure 50; Quigley et al., 1977). The rate of erosion or ablation of permafrost depends upon the associated geology and groundwater conditions, the fetch (length of body of water over which wind can blow), dominant wind directions, duration, and strength; water level fluctuations; and temperatures, and duration of ice cover (Reid et al., 1988; Penner et al., 1992; Bernatchez et al., 2011).

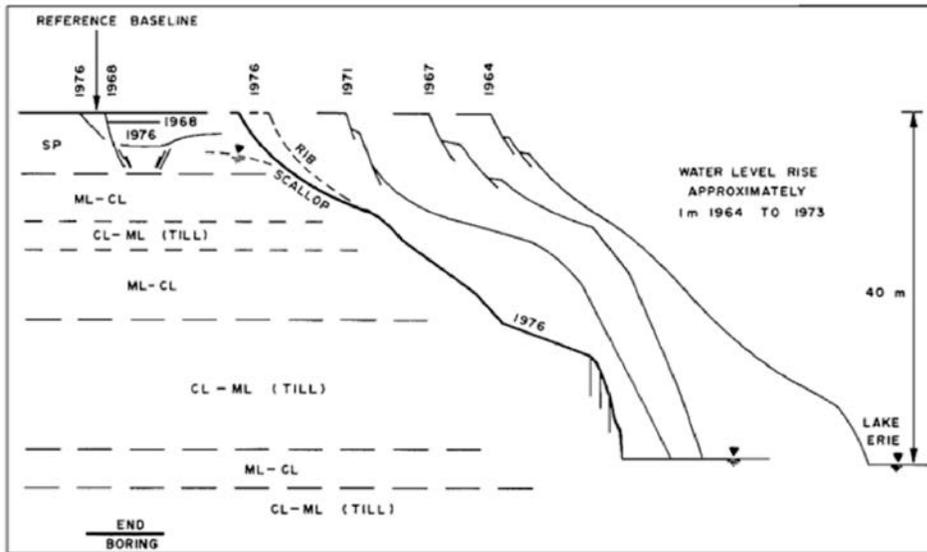


Figure 50. Shoreline retreat along the bluffs of Lake Erie, ON (Quigley et al., 1977).

In addition to the landslide causes common to other environments (Cruden and VanDine, 2013, Table 9), the effect of climate change on sea level must also be considered with respect to re-activation and/or increased erosion along marine coastlines. Figure 51 provides an overview of the sensitivity of the coastal zones of Canada to sea level rise and includes consideration of current glacio-tectonic adjustments of these zones. Typical effects of sea level changes are illustrated in Figure 52. According to Shaw et al. (1998), coastlines potentially affected by sea level rise include portions of the Atlantic, Pacific and the Beaufort Sea, to which Bernatchez and Dubois (2004) add the coastlines of the Gulf of St. Lawrence, QC. A summary of the processes related to bluff (cliff) erosion caused by sea level rise and climate change is shown in Figure 53.

2.11.2 Characterization, Analysis, Modeling and Hazard Mapping

All types of landslides occur along coastlines and shorelines and therefore the standard techniques of landslide characterization can be used. In recent years, both airborne and terrestrial LiDAR (Bernatchez et al., 2011), shoal LiDAR (Sallenger et al., 2003; Cottin et al., 2009) and multi-beam bathymetry in shallow waters have been successfully used to characterize coastline and shoreline morphology, identify active areas of erosion and predict future rates of erosion (e.g. Bernatchez and Dubois, 2004).

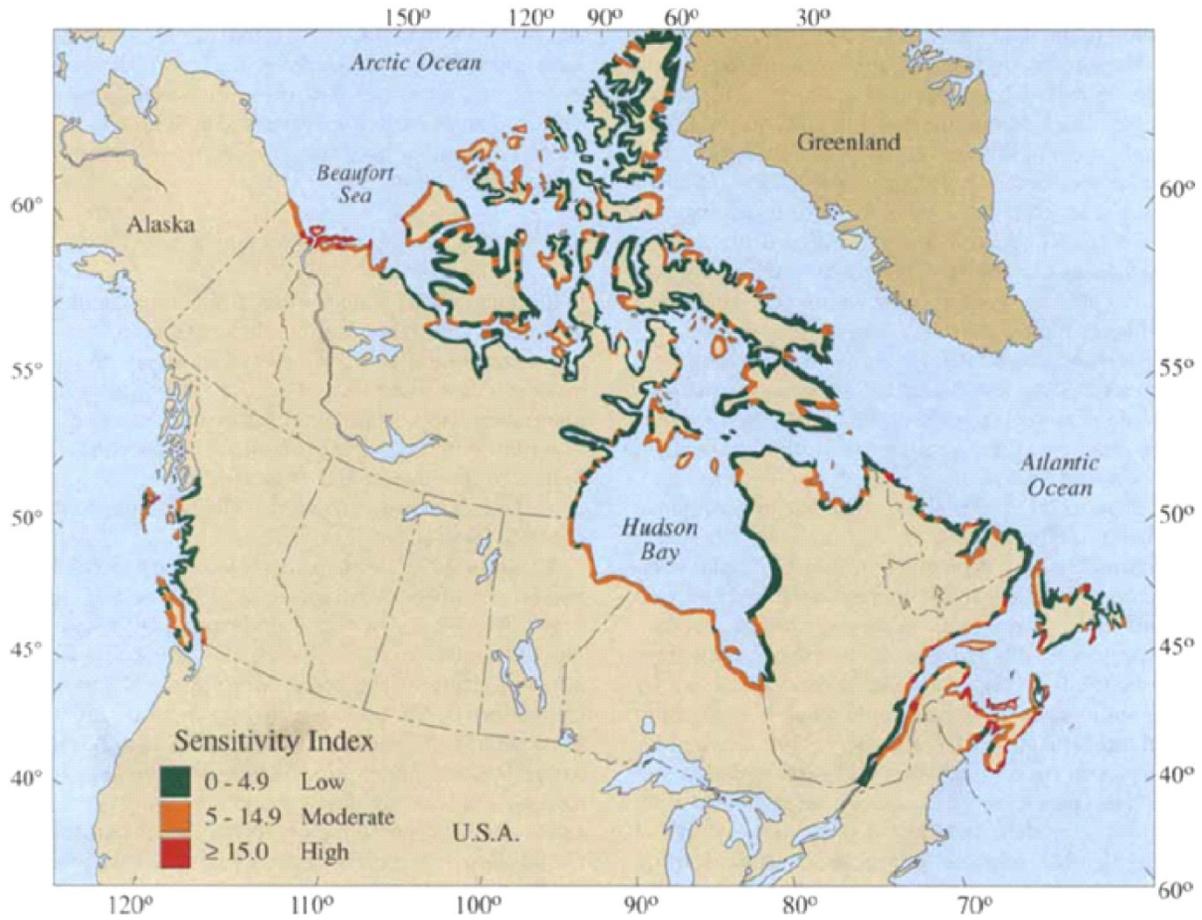


Figure 51. Sensitivity of Canadian coastlines to sea level rise (Natural Resources Canada).

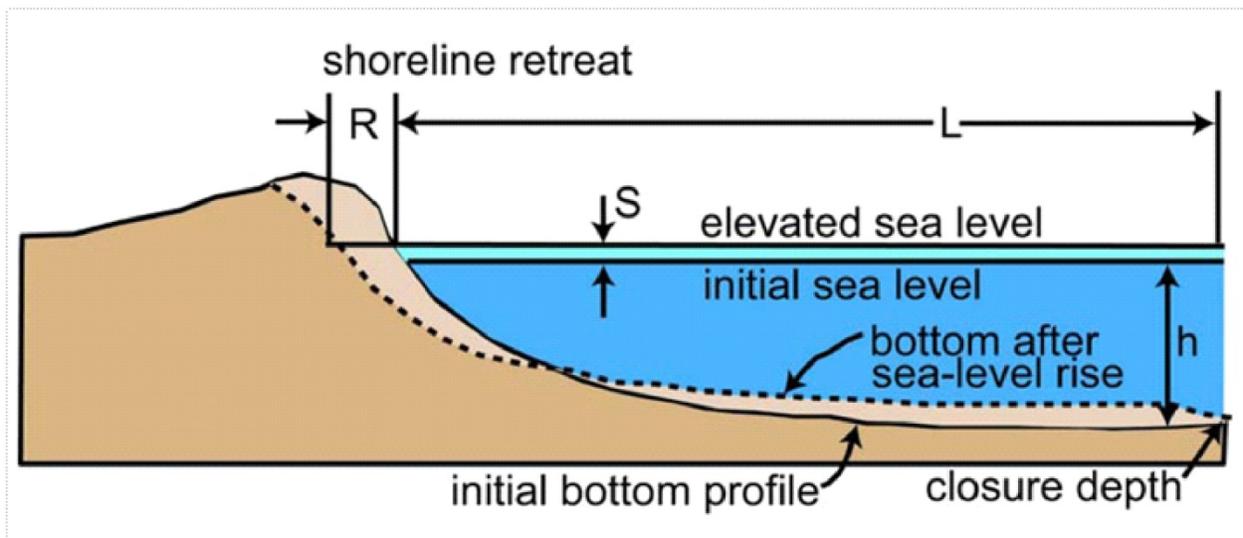


Figure 52. Schematic of the effect of sea level rise on shoreline erosion (Fitzgerald et al., 2008).

Shoreline erosion affects the geometry of the slope where undercutting the toe of shoreline bluffs and downcutting of the substrate in the near shore zone can trigger new landslides by oversteepening of bluff slopes. Based on the geology of the slope and erodibility of shoreline materials, various standard techniques can be used to analyze and model the rate of shoreline erosion. Results of shoreline erosion modeling are then input into slope stability models. The analysis of bluff recession rates should consider factors such as the geological stratigraphy of the bluff and composition of beach materials, historical erosion rates, hydrodynamic factors, wind conditions, land use and water resource management practices (in the case of regulated water bodies such as reservoirs), sea level rise and climate change (Figure 53).

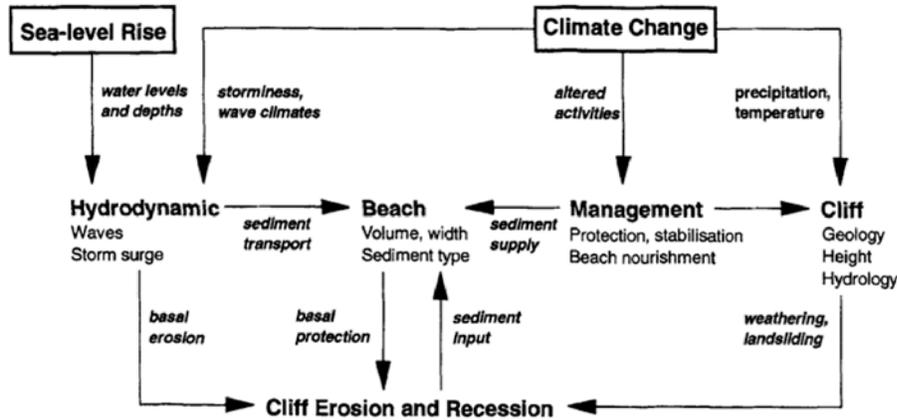


Figure 53. Summary of factors influencing cliff erosion (Bray and Hooke, 1997).

Two common approaches for assessing coastline and shoreline erosion rates, and their potential effect on slope stability, are: i) empirical methods that use a determination of historical bluff recession rates to estimate future rates of recession; and ii) deterministic or numerical models that predict future recession rates from a consideration of key input parameters in physically based models (Penner et al., 1992; Torgunrud et al., 2012; Nairn and Southgate, 1993; Southgate and Nairn, 1993). The latter have been successfully used in the past two decades in Manitoba, Saskatchewan and BC. BC Hydro regularly reviews land use development applications on its reservoir shorelines and conducts its own detailed assessments. A procedure developed by BC Hydro for evaluating operational effects on reservoir shorelines, from a range of processes including erosion, landsliding and landslide-generated waves, is described in Lawrence et al. (2009).

Fall et al. (2006) proposed an integrated approach to map coastal landslides that takes into account the results from both field and laboratory investigations. In most cases mapping and the subsequent analysis provides estimates of the rates of coastal regression, which can vary from low in rock (e.g. 0.04 m/year in sedimentary bedrock in the Gaspé, QC; Trenhaile et al., 2006), to approximately 1 m/year or more in glacial sediments (e.g. 1.5 m/y in Gulf of St. Lawrence, QC; Bernatchez and Dubois, 2008), to 0.3 to 3.0 m/year along the Lake Erie bluffs, ON (Gélinas and Quigley, 1973) to more than 20 m/year in ice-rich permafrost zones in Arctic coastal regions (Solomon, 2005) and in parts of BC. Mollard (1986) reported bluff recession rates ranging from 0.25 to 1 m/y in a large number of western Canadian lakes and reservoirs. In these lakes and reservoirs, recession rates typically reach up to several metres per year in the first few years following impoundment of a new reservoir as the shoreline adjusts to the new water level regime,

but then decreases to lower long-term rates over time (Penner et al., 1992; Penner and Boals, 2000).

There is a need to develop a predictive model of coastal erosion and landslides that takes into account the effects of climate change on sea level rise (Lee et al., 2001, 2002; Hall et al., 2002; Collins et al., 2007; Quinn et al., 2010).

2.11.3 Hazard and Risk Assessment

In Canada, there is no generally accepted framework within which to carry out coastal erosion and/or landslide hazard and risk assessments, although an overview has been presented by Shaw et al. (1998). The vulnerability of the communities along portions of the Arctic coastline to slope instability has been evaluated by Ford et al. (2006). In the UK, a detailed approach has been developed for bluff instability and erosion management (McInnes and Moore, 2011). Their approach is similar to that used for typical landslide hazard and risk assessments but also considers the analysis and monitoring of erosion rates. Another good source of information is the work by the USGS on erosion and instability issues along the Great Lakes shorelines (Hampton and Griggs, 2004).

Landslide-generated waves are another aspect of coastal landslides. A recent example is the 2007 Chehalis Lake rock slide in the southwestern BC which triggered a displacement wave up to 38 m (Brideau et al., 2012; Roberts et al., 2011; Lawrence et al., 2013; Figure 54). The hazards and risks can be assessed using a variety of methods. Historical information can provide data on the location and extent of past landslides and associated waves, however, the short period of modern settlement and sparse population density along parts of Canada's coasts typically limit the available historical information.



Figure 54. Chehalis Lake rock slide, BC (photo BC Ministry of Forests).

First Nations commonly have oral accounts of floods, some of which relate to landslide-generated waves. For example, Bornhold et al. (2007) documented oral stories of a First Nations village in Knight Inlet, BC, that was destroyed in the late 1500s by a landslide-generated wave caused by the collapse of a nearby mountainside into the inlet. High-resolution multibeam SONAR surveys can be used to identify landslide deposits on the seafloor, which can provide an indication of the background level of a hazard in an inlet or lake. For example, van Zeyl (2009) found several conical landslide deposits on the floor of Knight Inlet beneath steep fjords bordered by bluffs hundreds of metres high, whereas no similar features were identified in Howe Sound, a neighbouring inlet.

Landslide-generated wave deposits are sometimes preserved in low-energy areas within inlets or lakes, and can provide information on the number and age of past event. These deposits generally thin landward and contain shells that can be dated using radiometric methods. Such deposits have been used to infer ancient events along the west coast of Vancouver Island, BC (Clague et al., 2000).

Hydrodynamic modelling can be used to estimate the attributes of waves generated by landslides. Analytical methods can provide rapid wave height estimates. Numerical and physical models require much more detailed inputs, such as detailed bathymetry and landslide parameters, but can be used to estimate wave heights, travel times, impact forces, and wave run-up, which can be used to quantify the hazard for engineering design and land-use planning. Although numerical modeling that simulates the propagation of landslide-generated waves is becoming more common, laboratory scale experiments and empirical correlations are still used. Models and examples can be found in the work of Rabinovitch et al. (2003); Fine et al (2008); Heller (2008); Poncet et al. (2009), and Leonard et al. (2012).

2.11.6 Management and Mitigation

Management of land use along coastlines and shorelines can be complex due to the various elements at risk (e.g. residential development, industry, and related infrastructures) and the various natural processes. Landslides are not the only natural processes that need to be considered. The primary methods to reduce the risk posed by wave-erosion induced coastal landslides are by avoiding development in areas of significant erosion and/or instability and by reducing wave action on the slope geometry. The latter approach is often used in areas where land values and development pressures are high. Many examples of engineering solutions for reducing wave erosion and slope stabilization are provided by Hampton and Griggs (2004). The mitigation of sea level change will be a societal venture of global perspective.

2.12 Submarine Landslides

2.12.1 Occurrence and Identification

Canada has three coastlines, the Atlantic, Pacific and Arctic. The study of landslides in the marine environment, however, just began recently, thanks to the work of the Geological Survey of Canada and the Fisheries and Oceans Canada who initiated various seafloor mapping programs (Prior, 1993; Locat and Sansfaçon, 2000). Exploitation of offshore resources, development of communication and transportation corridors, fishing habitat protection and the protection of coastal communities and infrastructure have contributed to a growing interest in an improved

understanding of offshore geohazards, in particular seafloor landslides and their consequences (Nadim and Locat, 2005).

The most common classification of submarine landslides is the one proposed by Mulder and Cochonat (1996); (Figure 55). Slides, debris flows and turbidity currents are most common; debris avalanches are relatively rare.

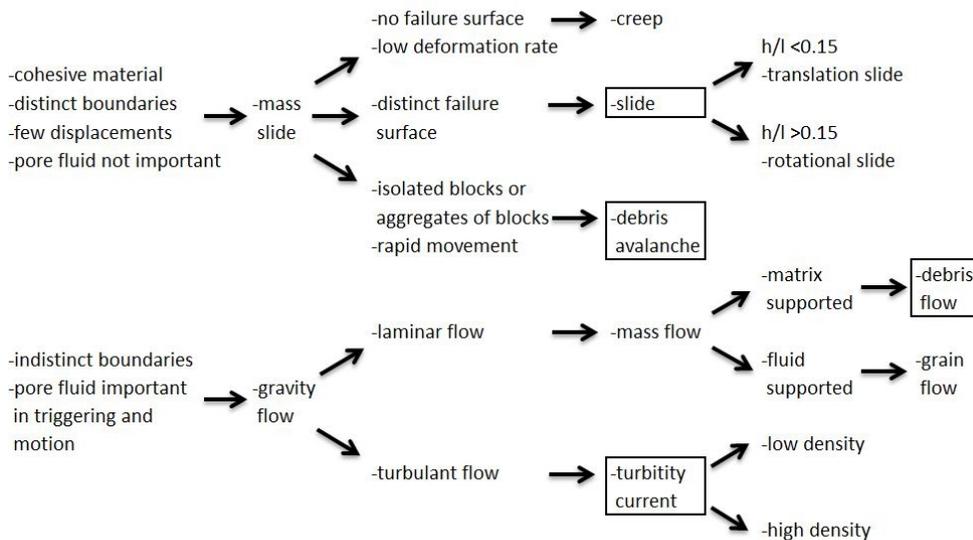


Figure 55. Classification of submarine landslides; main types are highlighted by a box (after Mulder and Cochonat, 1996).

Subaqueous landslides are found in lakes (Doughty et al. 2010), fjords (Prior et al., 1982; Levesque et al., 2006), estuaries (Campbell et al., 2008; Locat et al., 2012b) and the ocean (Piper and McCall, 2003). The well-known 1929 Grand Banks flow off the coast of Newfoundland generated a tsunami killing 29 people along the coast of the Burin Peninsula in that province. It had a volume of approximately 150 km^3 making it the largest recorded historic submarine landslide (Heezen and Ewing, 1952; Piper et al., 1988 and 1999; Mosher and Piper, 2007; Figure 56).

The inventory of submarine landslides is increasing as more of the seafloor is mapped (e.g. Piper and McCall 2003). Submarine landslides range widely in magnitude. They range from simple relatively small rotational slides, like the St. Siméon slide along the St. Lawrence River, QC (Figure 57) to the Grand Banks flow (Figure 56). The Betsiamites landslide complex on the north shore of the St. Lawrence River estuary, QC, was likely triggered by a large earthquake approximately 7,250 years ago and re-activated by another earthquake in 1663 (Cauchon-Voyer et al., 2008 and 2011). (Mosher et al., 2012) described an example of a major retrogressive landslide that occurred just off the Mackenzie River Delta, NWT. The 1946 Vancouver Island, BC earthquake triggered a few submarine landslides in the Strait of Georgia.

All causes or triggers of subaerial landslides are also applicable to submarine landslides, but in addition wave action and tidal variations (Atigh and Byrne, 2004), and the dissociation of gas hydrates (Grozic, 2010) have to be included. Contrary to most subaerial mass movements (except snow avalanches, Norem et al., 1990), subaqueous landslides have pore fluid characteristics similar to ambient fluid characteristics. This condition changes the behaviour of the flowing mass and likely accounts for long runout distances (up to 400 km).

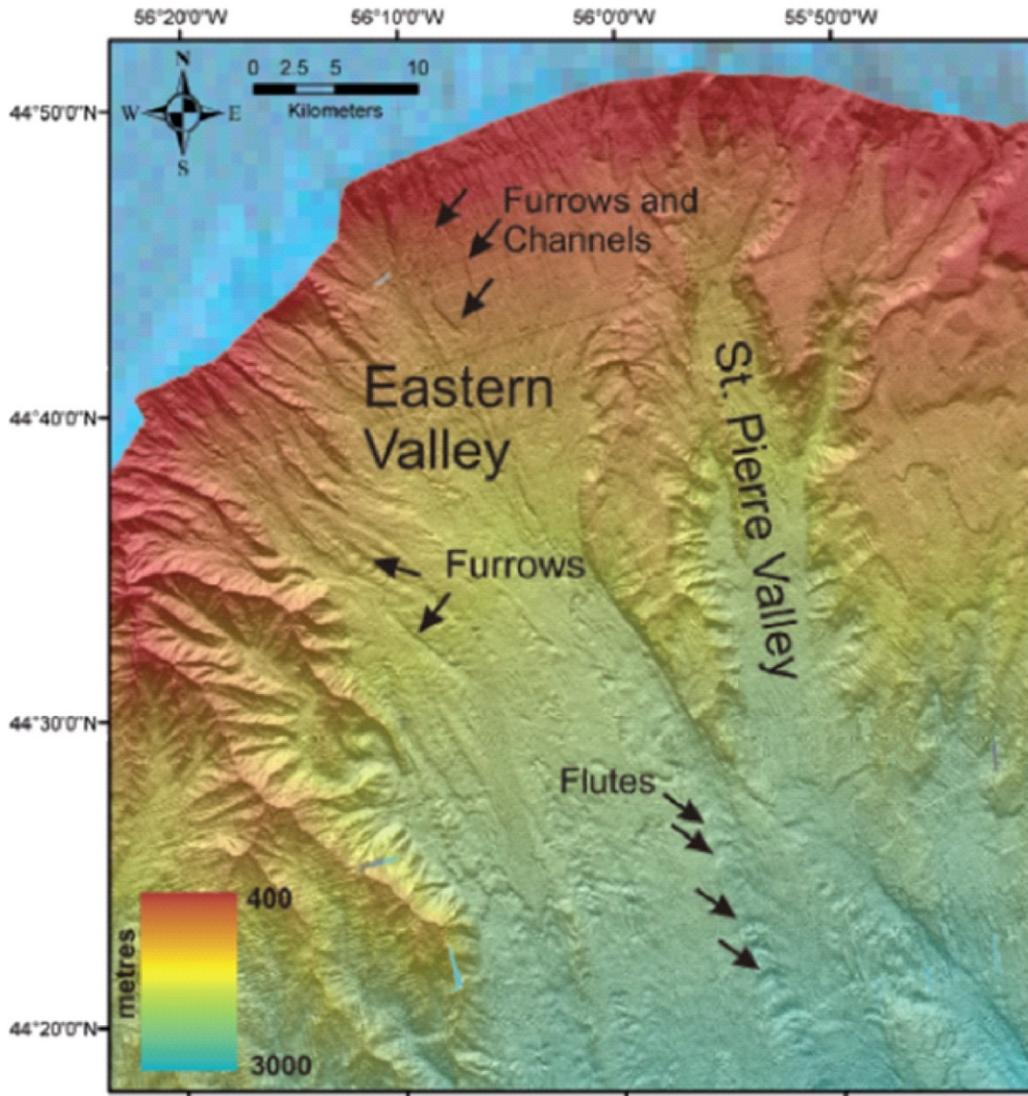


Figure 56. Grand Banks flow, NL, bathymetry showing the erosion characteristics of the valley; vertical exaggeration is 10 times.

It is interesting to note that most historical submarine landslides are first identified by either a tsunami or cable breaks (e.g. Nice and Grand Banks landslides). For comprehensive reviews of submarine landslides, refer to Locat and Lee (2002); Masson et al. (2006); and Lee et al. (2007).

2.12.2 Characterization

The recognition of landslides in the subaqueous environment requires different tools than on land. The main tools include: sonar (multibeam or interferometric) and seismic (2D or 3D). Refer to Locat and Lee (2009) for more details. The former provides information on the morphology (Clarke et al., 1996) and the latter provides information on the stratigraphy (often called seismo-stratigraphy). Contrary to the terrestrial environment, in the subaqueous environment it is relatively easy to obtain a detailed outline of the geometry of the landslide (e.g. debris flow or turbidite, e.g. Figures 57 and 58).

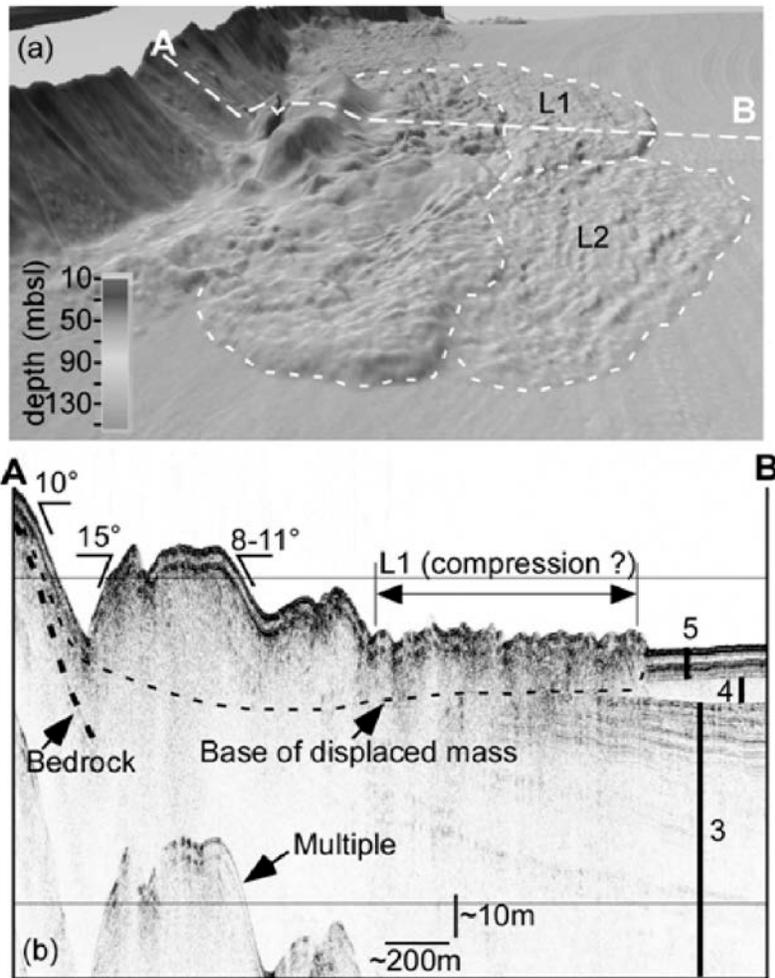


Figure 57. St. Siméon flow, QC (a) oblique view along the northern flank and (b) seismic cross section showing the thickness of the debris over the marine deposits (Locat et al., 2012a).

Although terrestrial airphotos have been available since at least 1925, seafloor mapping techniques, such as swath bathymetry (Prior, 1993; Clarke et al., 1996) can provide a ‘terrain’ model of similar quality to an airphoto. Cauchon-Voyer et al. (2011) provide a good example of combining multibeam sonar and 2D seismic for the Betsiamites landslide complex.

Whenever possible, core samples are obtained to validate the interpretation and to determine the geotechnical properties of the sediments. However, it is very difficult to obtain good quality core samples in the subaqueous environment, even more so when gassy sediments are involved (Sultan et al., 2004; Grozic, 2010). When gassy sediment samples are brought to the surface, the gas in solution in the pore fluid is expelled resulting in consequent remolding of the sample. Therefore soil mechanics principles and indirect methods must be used to determine the properties of the sediment. In rare cases, *in situ* measurements are made to determine both the soil strength and porewater pressures conditions (e.g. Kvaldstad et al., 2005; Sultan et al., 2010). Recently, subaqueous piezocone surveys, down to a depth of 30 m below sea floor, have been carried out, but not in Canada (Sultan et al., 2010). A drop cone penetrometer has been used in Canada, but limited to the Fraser River Delta, in BC (Christian et al., 1997). An example of the technology used for *in situ* porewater pressure measurements and seismic activity for part of the Fraser River Delta is shown in Figure 58.

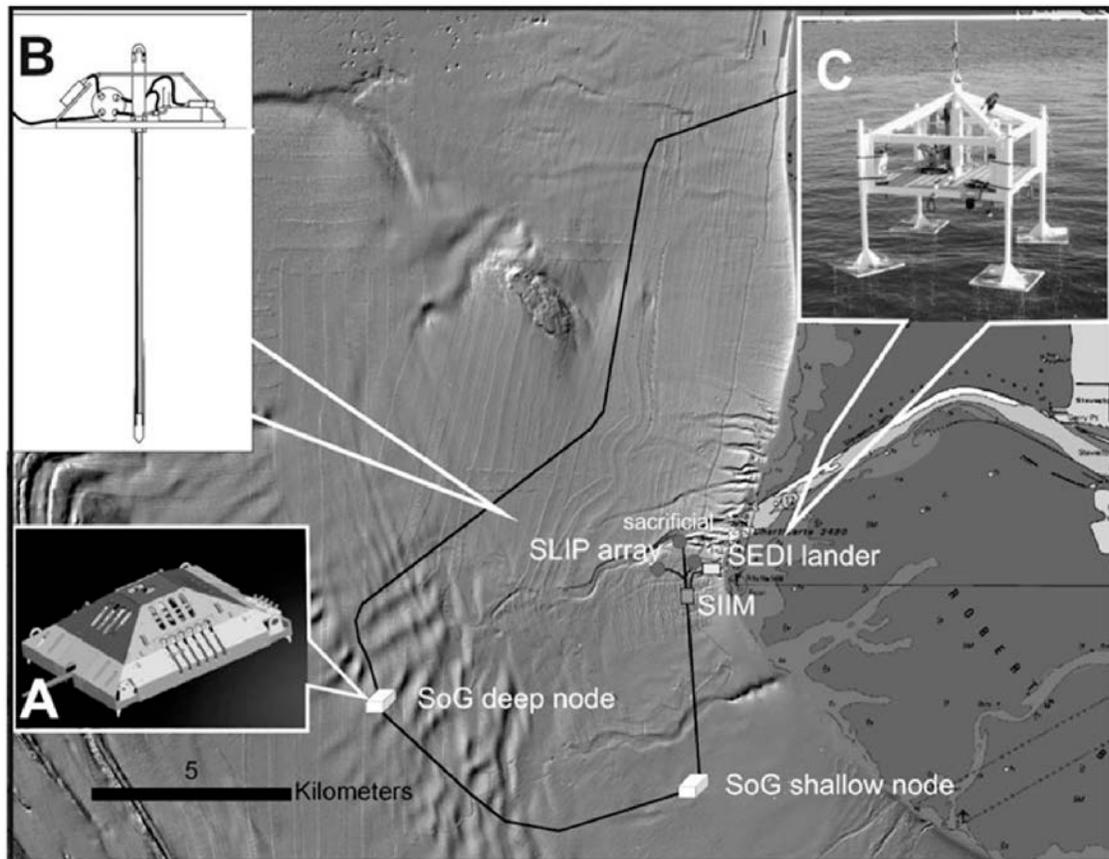


Figure 58. Schematic of VENUS (Victoria Experimental Network Under the Sea) installation in the Strait of Georgia, BC; the cable (black line) connects two nodes (A) to a shore station transmitting DC power and data; instruments can be plugged into the nodes; (SIIM) is a science instrument interface module; SLIP array (B) consists of four seismometers and piezometers; SEDI lander (C) is instrumented with devices to measure sediment fluxes and near-bed sediment transport (refer to Hill et al., 2008 for details).

2.12.3 Analysis and Modeling

For analysis and modeling in the subaqueous environment, Locat (2001) took into account active slope processes for the area of interest (Figure 59). The number of submarine landslides that have been back analyzed is limited, but include landslides in the Kitimat Inlet (Johns et al., 1985) and from the Fraser River Delta (Luternauer and Finn, 1983; Christian et al., 1997; Atigh and Byrne, 2004), both in BC, and the Saguenay Fjord, in Québec (Urgeles et al., 2002). Major studies are expected as part of the NEPTUNE (North East Time-series Undersea Networked Experiments) and VENUS (Victoria Experimental Network Under the Sea) ocean observatory projects now underway along the Pacific coast.

Locat et al., 2003 present an example of the approach for back analysis of submarine landslides failures for the Pointe-du-Fort landslide in the Saguenay Fjord, QC (Figure 60). The approach is strongly based on morphological characteristics, simple limit equilibrium methods and mobility modeling. In this case, it was possible to obtain *in situ* measurements from the adjacent shoreline to help constrain the geotechnical data. This may be the only Canadian example where the submarine stability analysis provides a complete picture of an analysis from first failure to post-failure.

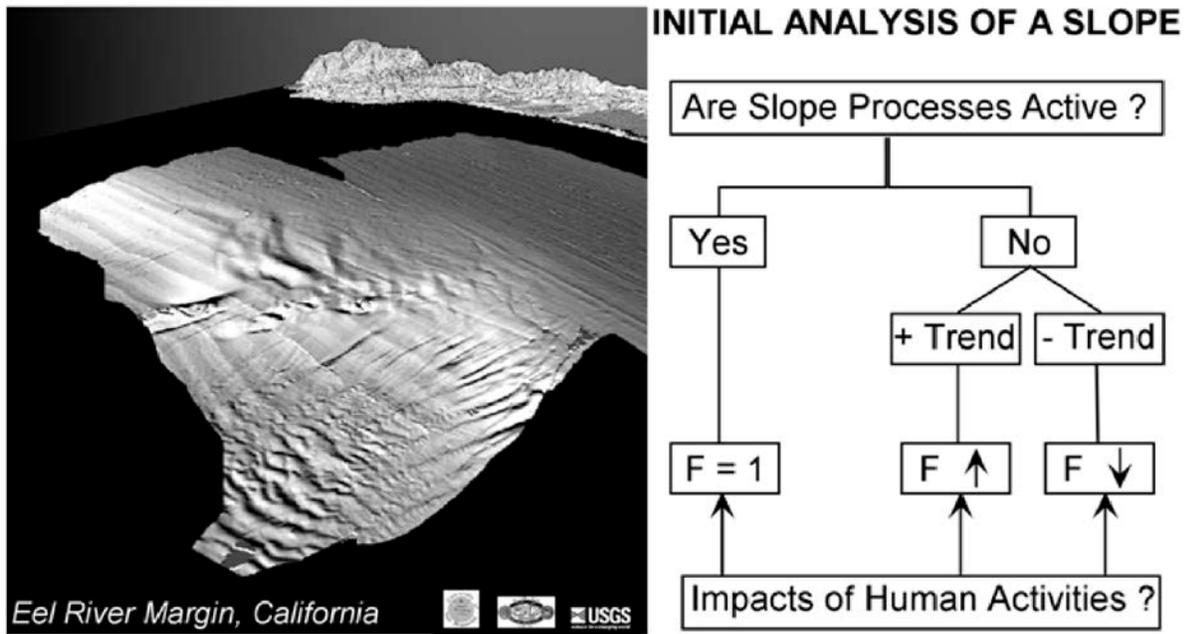


Figure 59. Initial analysis of the safety factor of a slope (F) illustrated with a multibeam 3D view of the Eel River Margin off Eureka, California (multibeam image is from USGS; refer to Locat, 2001 for details).

First failure analyses can use limit equilibrium methods and a Mohr-Coulomb failure criteria, and should consider the presence of the water column above the subaqueous sediment or rock. Where slopes are $<10^\circ$, an infinite slope model (Morgenstern, 1967) can be used (e.g. the loose Fraser River Delta sediments (Christian et al., 1997). For steeper slopes, a rotational model can be used (e.g. Pointe-du-Fort landslide; Locat et al., 2007). The Pointe-du-Fort slide was triggered by an earthquake, whereas the Fraser delta slides are mostly triggered by sediment overloading (Luternauer and Finn, 1983).

Post-failure analyses of submarine landslides include analyses of spreads and/or flows that can further develop into turbidity currents (Locat and Lee, 2002). Atigh and Bryne (2004) provide a detailed study of the initiation of flows on the front sets of the Fraser River Delta that were caused by tidal variations on the strength of gassy cohesionless sediments.

The post-failure behavior of clayey sediments, as in the case of the Pointe-du-Fort landslide, has been analyzed using 2D fluid mechanics software (BING, Imran et al., 2001) that models the material either as a Bingham, a Herschel-Bulkey or a Bi-Linear fluid. Locat and Demers (1988), and Locat (1997) showed that in such cases the liquidity index of the undisturbed sediment can be used as a proxy for estimating fluid yield strength and viscosity.

Modeling of underwater rock slides and avalanches has not yet been carried out in Canada, but has been modeled in the United States and Europe (e.g. Masson et al., 2006; Locat and Lee, 2009). Submarine rock falls have been modeled by Turmel and Locat (2011).

2.12.4 Hazard and Risk Assessment and Mapping

The most striking features of submarine landslides are that they can take place on slopes as low as 1° , can involve volumes of hundreds of cubic kilometres, and travel distances over hundreds of kilometres. These characteristics make submarine landslides complex processes for hazard and risk assessment (Nadim and Locat, 2005).

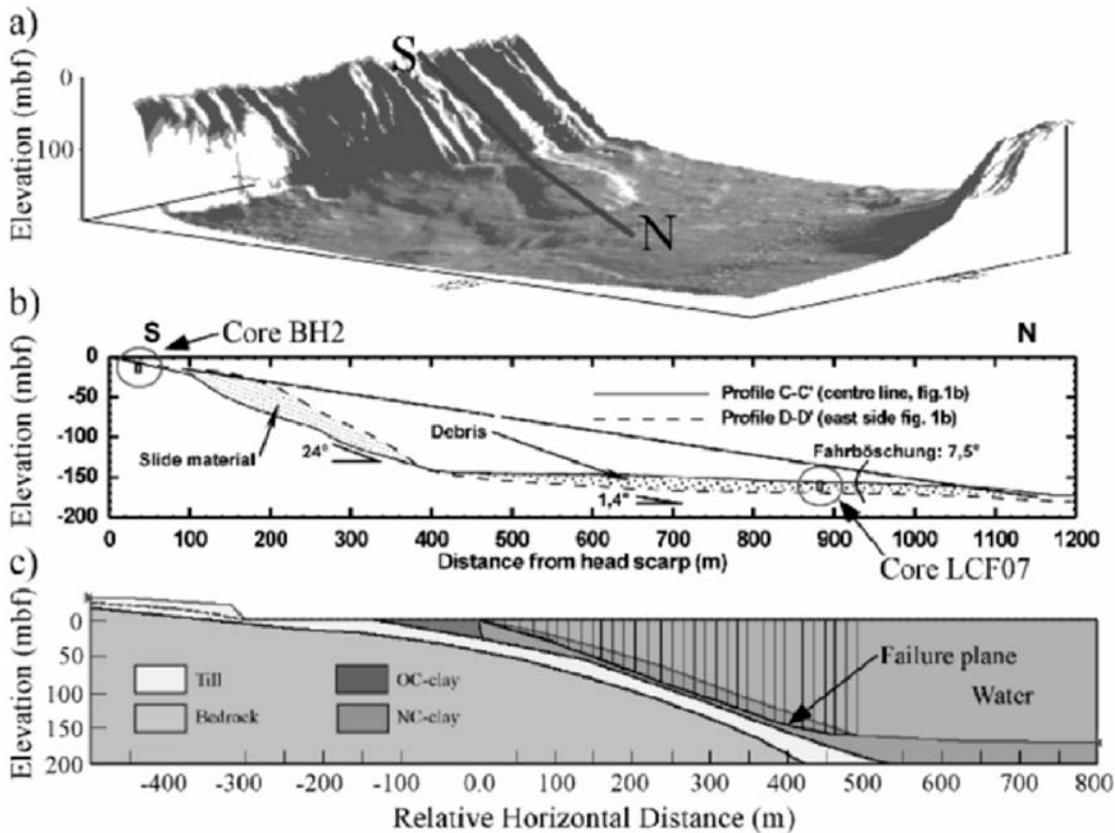


Figure 60. (a) 3D view of the Point-du-Forts landslide, QU; (b) geometric reconstruction of the pre-landslide slope, and (c) geological model used for slope stability analysis (refer to Locat et al., 2003 for details).

As mentioned above, the inventory of submarine landslides is growing. In some regions, like along the coast of Charlevoix, QC, approximately 50% of the submarine coastal zone is known to be covered by submarine landslides (Locat et al., 2012a). In the Saguenay Fjord, Levesque et al. (2006) concluded that submarine landslides were caused by earthquakes.

Nadim and Locat (2005; Figure 61) present an approach for the hazard assessment of submarine landslides based on investigations, characterization and analysis of the Saguenay Fjord. Magnitude (volume) can be estimated from morphology and seismic techniques, but the frequency requires the dating of the events. In the marine environment, direct observations are rare, therefore, dating methods have been developed that use sedimentation rates over a landslide surface or landslide debris, C14 dating of landslide debris, and stratigraphic and morphologic correlations (Levesque et al., 2006; Locat, 2011).

Fig. 62 presents a general framework for risk assessment for submarine landslides (Nadim and Locat, 2005). In Canada, when compared to subaerial landslides, the effect of submarine landslides on coastal and marine infrastructure is limited but still significant, when considering the number of documented cases. The most significant is the aforementioned 1929 Grand Banks flow that killed 29 people (Piper et al., 1999). On the Pacific coast in 1975, a low tide deltaic landslide in the Kitimat Inlet generated an 8.2 m tsunami that damaged coastal infrastructure 8 km away from the initiation area (Bornhold et al., 2001, 2007). The 1663 Charlevoix earthquake likely triggered a landslide that may have resulted in a local tsunami (Poncet et al., 2009).

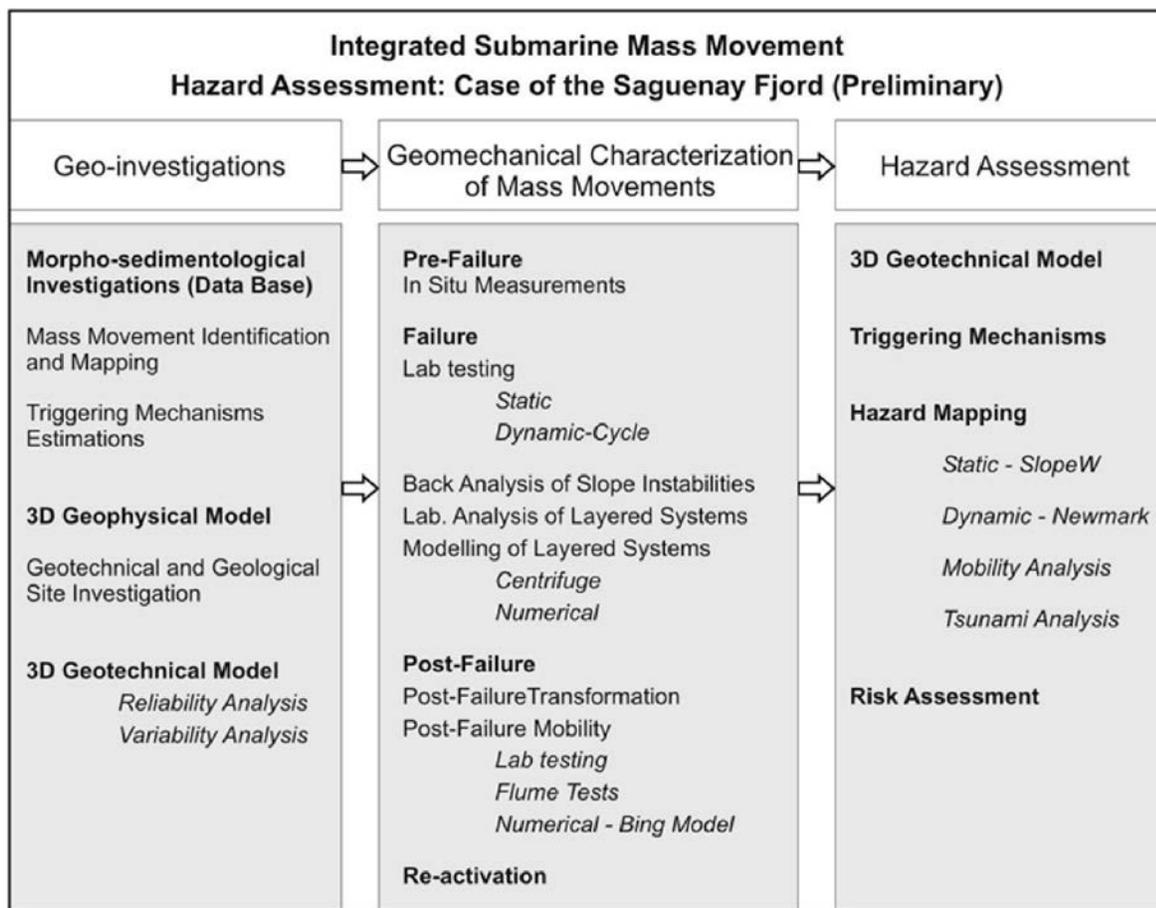


Figure 61. Approach for submarine landslide hazard assessment in the Saguenay Fjord region, QU (refer to Nadim and Locat, 2005 for details).

Leroueil et al. (2003) proposed a simplified risk assessment approach for the Saguenay Fjord, QC, in which the consequences of submarine landslides are limited to their potential to generate tsunamis. The examples of the Kitimat Inlet landslide, BC (Prior et al., 1982), and the Betsiamites landslide complex, QC (Cauchon-Voyer et al., 2008), show the potential for submarine landslides to reach the coast.

2.12.5 Management and Mitigation

Currently in Canada there are no comprehensive management or mitigation strategies with respect to submarine landslides. Only recently was an attempt made to evaluate the tsunami hazard (resulting from both earthquakes and landslides) along Canadian coastlines (Leonard et al., 2012). Up until this time, most efforts have been concentrated on mapping and understanding submarine landslides and their consequences. In the coastal zone where infrastructure may be at risk, analyzing the landslide potential and accounting for it in design can avoid problems like those encountered elsewhere (e.g. in 1979 at the Nice Airport (France), Dan et al., 2007; in 1994 in Skagway (Alaska), Kulikov et al., 1996).

For specific cases, for instance underwater pipelines, some studies have demonstrated how to link an understanding of submarine landslides to the design of mitigation measures taking into account drag forces (Zakeri et al., 2008). Mitigating the effects of submarine landslides are presented in Nielsen (2009).

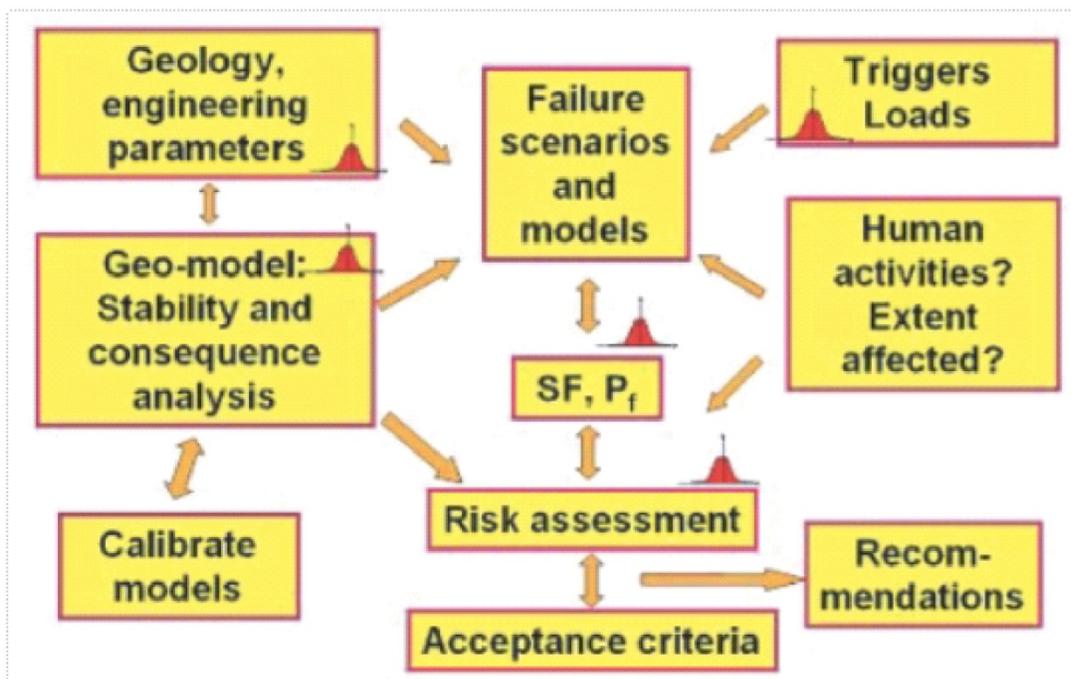


Figure 62: General framework for submarine landslide risk assessment; SF is factor of safety; P_f is probability of failure (refer to Nadim and Locat, 2005 for details).

3. CONCLUSION

A wide variety of landslide types occur in all regions of Canada. The resulting damaging effects and loss of life are not as severe as those experienced in some other countries, but they have been significant to local and regional economies and populations in this country. Landslide risks to life are highest in the Canadian Cordillera and the glaciomarine clay regions of the St. Lawrence Lowlands. This, however, is probably a consequence of the relative low population density in many parts of the country. As the population and infrastructure extend into more remote regions, the significance of landslides in Canada is certain to increase.

4. ACKNOWLEDGEMENTS

The authors have not sought direct assistance from colleagues in the preparation of this review. But obviously, most of the information contained herein has its source in the valuable contributions of many landslide professionals from all parts of Canada. Their indirect assistance is acknowledged in the list of references.

5. REFERENCES

- Abbott, B., Bruce, I., Savigny, W., Keegan, T., and Oboni, F., 1998, A methodology for the assessment of rockfall hazard and risk along linear transportation corridors. *in* Proceedings – 8th International Congress of the International Association for Engineering Geology and the Environment, (ed.) D.P. Moore and O. Hungr; Balkema, Netherlands; v. 2, p. 1195-1200.
- Adams, J. and Halchuk, S., 2003. Fourth generation seismic hazard maps of Canada; values for over 650 Canadian localities intended for the 2005 National Building Code of Canada; Geological Survey of Canada, Open File 4459, 155 p.

- Arnold, A., Thielen, A., and Springman, S., 2005. On the stability of active layers in alpine permafrost. *in* Proceedings – 11th International Conference and Field Trips on Landslides (ICFL), Trondheim, Norway; Taylor and Francis, p. 19-25.
- Atigh, E. and Byrne, P., 2004. Liquefaction flow of submarine slopes under partially undrained conditions; an effective stress approach; *Canadian Geotechnical Journal*, v. 41, no. 1, p. 154-165
- Baracos, A., Graham, J., and Domaschuk, L., 1980. Yielding and rupture in a lacustrine clay; *Canadian Geotechnical Journal*, v. 17, no. 4, p. 559-573.
- Baracos, A. and Graham, J., 1981. Landslide problems in Winnipeg; *Canadian Geotechnical Journal*, v. 18, no. 3, p. 390-401.
- BC Ministry of Forests, 1995. Mapping and assessing terrain stability guidebook. Forest Practices Code of British Columbia, B.C. Ministries of Forest and Environment, Victoria, 34 p.
- Bean, S. and Hungr, O., 2011. North Beach Rock Slide, Summerland, BC Movement Monitoring and Analysis. *in* Proceedings, Canadian Conference on Geotechnique and Natural Hazards, 5, Kelowna, B.C., 39 p.
- Bernatchez, P. and Dubois, J., 2004. Bilan des connaissances de la dynamique de l'érosion des cotes du Québec maritime laurentien; *Géographie physique et quaternaire*, v. 58, no. 1, p. 45-71.
- Bernatchez, P., Fraser, C., Lefavre, D. and Dugas, S., 2011. Integrating anthropogenic factors, geomorphological indicators and local knowledge in the analysis of coastal flooding and erosion hazards; *Ocean and Coastal Management*, v. 54, no. 8, p. 621-632.
- BGC Engineering Inc., 2006. Berkley Landslide Risk Management, Phase 1 Risk Assessment. Unpublished report to the District of North Vancouver, British Columbia, 30 p. (www.dnv.org – natural hazards programs and reports).
- BGC Engineering Inc., 2007. Unnamed creek – debris flow hazard and risk assessment. Unpublished report to the B.C. Ministry of Transportation and Highways, Prince George, BC.
- BGC Engineering Inc., 2008. Cheekeye River Debris Flow Risk Assessment. Unpublished report to Kerr Wood Leidal Associates, 32 p. plus appendices.
- Bilodeau, C., Genois, A., Demers, D., Potvin, J., Robitaille, D. and Dupuis, C., 2005. Cartographie des zones exposées aux glissements de terrain dans les dépôts meubles: Guide d'utilisation des cartes de zones de contraintes et d'application du cadre normatif; Publication du Gouvernement du Québec, Ministère de la Sécurité publique, 77 p.
- Blais-Stevens, A. and Hungr, O., 2008. Landslide hazards and their mitigation along the Sea to Sky Corridor, British Columbia. *in* Proceedings, Canadian Conference on Geohazards IV, From Causes to Management, (ed.) J. Locat, D. Perret, D. Turmel, D. Demers and S. Leroueil. Presse de l'Université Laval, 8 p.
- Bobrowsky, P., Catto, N. and Levson, V., 1991. Reconnaissance Quaternary Geological Investigations in Peace River, British Columbia - (93P, 94A). *in* B.C. Ministry of Energy, Mines and Petroleum Resources, Geological Fieldwork, 1990, Paper 1991-1, p. 345-358.
- Bornhold, B.D., Thomson, R.E., Rabinovich, A.B., Kulikov, E.A. and Fine, I.V., 2001. Risk of landslide-generated tsunamis for the coast of British Columbia and Alaska. *in* An Earth Odyssey, Proceedings of the 54th Canadian Geotechnical Society Conference, (ed.) M. Mahmoud, R. van Everdingen and J. Carss; Bitech Publishers Ltd., Richmond, BC, p. 1450-1454.
- Bornhold, B., Harper, J., McLaren, D. and Thomson, R., 2007. Destruction of the First Nations village of Kwalate by a rock avalanche-generated tsunami; *Atmosphere-Ocean*, v. 45, p. 123-128.

- Bovis, M., 1985. Earthflows in the Interior Plateau, Southwest British Columbia; *Canadian Geotechnical Journal*, v. 22, no. 3, p. 313-334.
- Bray, M. and Hooke, J., 1997. Prediction of Soft-Cliff Retreat with Accelerating Sea-Level Rise; *Journal of Coastal Research*, v. 13, no. 2, p. 453-466.
- Brideau, M., Sturzenegger, M., Stead, D., Jaboyedoff, M., Lawrence, M., Roberts, N., Ward, B., Millard, T. and Clague, J.J., 2012. Stability analysis of the 2007 Chehalis lake landslide based on long-range terrestrial photogrammetry and airborne lidar data; *Landslides*, v. 9, no. 1, p. 75-91.
- Bunce, C., Cruden, D. and Morgenstern, N., 1997. Assessment of the hazard from rock fall on a highway; *Canadian Geotechnical Journal*, v. 34, no. 3, p. 344-356.
- Campbell, D., Duchesne, M. and Bolduc, A., 2008. Geomorphological and geophysical evidence of Holocene seafloor instability on the southern slope of the Lower St. Lawrence Estuary, Québec. *in* Proceedings, Canadian Conference on Geohazards IV, From Causes to Management, (ed.) J. Locat, D. Perret, D. Turmel, D. Demers and S. Leroueil. Presse de l'Université Laval, p. 367-374.
- Canadian Geotechnical Society, 2006. Canadian Foundation Engineering Manual, 4th Edition, BiTech Publisher, 504 p.
- Carson, M., 1979. Le glissement de Rigaud (Québec) du 3 mai 1978: une interprétation du mode de rupture d'après la morphologie de la cicatrice ; *Géographie physique et quaternaire*, v. 33, no. 1, p. 63-92.
- Cauchon-Voyer, G., Locat, J., Leroueil, S., St-Onge, G. and Demers, D., 2011. Large-scale subaerial and submarine Holocene and recent mass movements in the Betsiamites area, Quebec, Canada; *Engineering Geology*, v. 121, no. 1-2, p. 28-45.
- Cauchon-Voyer, G., Locat, J. and St-Onge, G., 2008. Late Quaternary morpho-sedimentology and submarine mass movements of the Betsiamites area, Lower St. Lawrence Estuary, Quebec, Canada; *Marine Geology*, v. 251, no. 3-4, p. 233-252.
- Chagnon, J., 1968. Les coulees d'argile dans la province de Quebec; *Naturaliste Canadien- with English Abstract*, v. 95, no. 6, p. 1327-1343.
- Chan, D. and Morgenstern, N., 1987. Analysis of progressive deformation of the Edmonton Convention Centre excavation; *Canadian Geotechnical Journal*, v. 24, no. 3, p. 430-440.
- Chatwin, S., Howes, D., Schwab, J. and Swanston, D., 1994. A guide for management of landslide-prone terrain in the Pacific Northwest. B.C. Ministry of Forests, Land Management Handbook Number 18, 225 p.
- Christian, H., Mosher, D., Mulder, T., Barrie, J., and Courtney, R., 1997. Geomorphology and potential slope instability on the Fraser River delta foreslope, Vancouver, British Columbia; *Canadian Geotechnical Journal*, v. 34, no. 3, p. 432-446.
- Clague, J.J. and Souther, J., 1982. The Dusty Creek landslide on Mount Cayley, British Columbia; *Canadian Journal of Earth Sciences*, v. 19, no. 3, p. 524-539.
- Clague, J.J., Bobrowsky, P. and Hutchinson, I., 2000. A review of geological records of large tsunamis at Vancouver Island, British Columbia, and implications for hazard; *Quaternary Science Reviews*, v. 19, no. 9, p. 849-863.
- Clarke, J., Mayer, L. and Wells, D., 1996. Shallow-water imaging multibeam sonars; a new tool for investigating seafloor processes in the coastal zone and on the continental shelf; *Marine Geophysical Researches*, v. 18, no. 6, p. 607-629.
- Cloutier, C., Locat, J., Lord, P-E., Couture, R. and Jaboyedoff, M., 2012. Kinematic Considerations of the Gascons Rockslide, Québec (Gaspésie), Canada. *in* Landslides and Engineering Slopes: Protecting Society through Improved Understanding, Proceedings – 11th

- International Symposium on Landslides and 2nd North American Symposium on Landslides, Banff, Alberta, Balkema, Netherlands, v. 2, p. 1265-1271.
- Collins, B., Kayen, R. and Sitar, N., 2007. Process-based Empirical prediction of landslides in weakly lithified coastal cliffs, San Francisco, California, USA. *in* Landslides and Climate Change, Proceedings - International Conference on Landslides and Climate Change, Isle of Wight, UK, p. 175-184.
- Cottin, A., Forbes, D. and Long, B., 2009. Shallow seabed mapping and classification using waveform analysis and bathymetry from SHOALS LiDAR data; Canadian Journal of Remote Sensing, v. 35, no. 5, p. 422-434.
- Crozier, M., 2005. Multiple-occurrence regional landslide events in New Zealand; hazard management issues; Landslides, v. 2, no. 4, p. 247-256.
- Cruden, D.M., 1982, The Brazeau Lake slide, Jasper National Park, Alberta; Canadian Journal Of Earth Sciences, v. 19, no. 5, pp. 975-981.
- Cruden, D.M., 1985, Rock slope movements in the Canadian Cordillera; Canadian Geotechnical Journal, v. 22, no. 4, p. 528-540.
- Cruden, D. and Martin, C.D., 2007. Before the Frank Slide, Canadian Geotechnical Journal, v. 44, pp. 765-780.
- Cruden, D. and VanDine, D., 2013. Classification, description, causes and indirect effects; Canadian technical guidelines and best practices related to landslides; a national initiative for loss reduction; Geological Survey of Canada, Open-File Report Number 7359, 22 p.
- Cruden, D. and Varnes, D., 1996. Landslide types and processes – Chapter 3. *in* Landslides: Investigation and Mitigation, (ed.) A.K. Turner and R.L. Schuster; Special Report - Transportation Research Board, U.S. National Research Council, p. 36-75.
- Cruden, D., Tedder, K., and Thomson, S., 1989a. Setbacks from the crests of slopes along the North Saskatchewan River, Alberta; Canadian Geotechnical Journal, v. 26, no. 1, p. 64-70.
- Cruden, D., Bornhold, B., Chagnon, J., Evans, S., Heginbottom, J., Locat, J., Moran, K., Piper, D., Powell, R., Prior, D., Quigley, R. and Thomson, S., 1989b. Landslides; extent and economic significance in Canada. *in* Landslides: extent and economic significance, (ed.) E.E. Brabb and B.L. Harrod; Balkema, Rotterdam, Netherlands, p. 1-23.
- Dan, G., Sultan, N. and Savoye, B., 2007. The 1979 Nice harbour catastrophe revisited; trigger mechanism inferred from geotechnical measurements and numerical modelling; Marine Geology, v. 245, no. 1-4, p. 40-64.
- Dawson, R., Morgenstern, N. and Stokes, A., 1998. Liquefaction flowslides in Rocky Mountain coal mine waste dumps; Canadian Geotechnical Journal, v. 35, no. 2, p. 328-343.
- Demers, D. and Leroueil, S., 2002. Evaluation of preconsolidation pressure and the overconsolidation ratio from piezocone tests of clay deposits in Quebec; Canadian Geotechnical Journal, v. 39, no. 1, p. 174-192.
- Demers, D., Leroueil, S. and d'Astous, J., 1999. Investigation of a landslide in Maskinonge, Quebec; Canadian Geotechnical Journal, v. 36, no. 6, p. 1001-1014.
- Demers, D., Robitaille, D., Potvin, J., Bilodeau, C. and Dupuis, C., 2008. La gestion des risques de glissements de terrain dans les sols argileux au Québec. *in* Proceedings, Canadian Conference on Geohazards IV, From Causes to Management, (ed.) J. Locat, D. Perret, D. Turmel, D. Demers and S. Leroueil. Presse de l'Université Laval; Québec, p. 519-526.
- Doughty, M., Eyles, N. and Daurio, L., 2010. Earthquake-triggered slumps (1935 Timiskaming M6.2) in Lake Kipawa, Western Quebec Seismic zone, Canada. Sedimentary Geology, v. 228, no. 3-4, p.113-118.
- Dunkley, D., 1992. Management of Hazards on Glacial Lake Terrain in South-central British Columbia; Thesis (M.R.M), Simon Fraser University.

- Eden, W., Fletcher, E. and Mitchell, R., 1971. South Nation river landslide, 16 May 1971; Canadian Geotechnical Journal, v. 8, no. 3, p. 446-451.
- Eisbacher, G., 1979. Cliff collapse and rock avalanches (sturzstroms) in the Mackenzie Mountains, northwestern Canada; Canadian Geotechnical Journal, v. 16, no. 2, p. 309-334.
- Eshraghian, A., Martin, C. and Cruden, D., 2007. Complex earth slides in the Thompson River valley, Ashcroft, British Columbia; Environmental and Engineering Geoscience, v. 13, no. 2, p. 161-181.
- Evans, S.G., 1986. Landslide damming in the Cordillera of Western Canada. *in* Landslide Dams: processes, risk and mitigation, (ed.) R.L. Schuster, American Society of Civil Engineers, Geotechnical Special Publication, 3, p. 111-130.
- Evans, S.G., 2001. Landslides. *in* A synthesis of geological hazards in Canada, (ed.) G.R. Brooks, Geological Survey of Canada, Bulletin 548, p. 43-79.
- Evans, S.G., 2003. Characterizing landslide risks in Canada. *in* Proceedings 3rd Canadian Conference on Geotechnique and Natural Hazards, Canadian Geotechnical Society, Edmonton, Alberta, p. 35-50.
- Evans, S.G., Aitken, J., Wetmiller, R. and Horner, R., 1987. A rock avalanche triggered by the October 1985 North Nahanni earthquake, District of Mackenzie, N.W.T.; Canadian Journal of Earth Sciences, v. 24, no. 1, p. 176-184.
- Evans, S.G. and Brooks, G.R., 1994. An earthflow in sensitive Champlain Sea sediments at Lemieux, Ontario, June 20, 1993, and its impact on the South Nation River; Canadian Geotechnical Journal, v. 31, no. 3, p. 384-394.
- Evans, S.G. and Buchanan, R.G., 1977. Some aspects of natural slope stability in silt deposits near Kamloops, British Columbia. *in* Proceedings of the 29th Canadian Geotechnical Conference, Vancouver, British Columbia, Session 4, p. 1-32.
- Evans S.G. and Clague, J.J., 1999. Rock avalanches on glaciers in the Coast and St. Elias Mountains, British Columbia. *in* Proceedings of the 13th Annual Vancouver Geotechnical Society Symposium; BiTech Publishers, Richmond, B.C., p. 115-123.
- Evans, S.G. and Lister, D., 1984. The geomorphic effects of the July 1983 rainstorms in the southern Cordillera and their impact on transportation facilities; Current Research, Part B, Geological Survey Of Canada, Paper no. 84-1B, p. 223-235.
- Evans, S.G., Qu, X. and Enegren, E., 1996. The 1973 Attachie Slide, Peace River valley, near Fort St. John, British Columbia, Canada; a landslide with a high-velocity flowslide component in Pleistocene sediments. *in* Proceedings of the 7th International Symposium on Landslides, (ed.) K. Senneset, v. 2, p. 715-720.
- Evans, S.G. and Savigny, K.W., 1994. Landslides in the Vancouver-Fraser Valley-Whistler region. *in* Geology and geological hazards of the Vancouver region, southwestern British Columbia, (ed.) J.W.H. Monger, Geological Survey of Canada, Bulletin 481, p. 251-286.
- Fall, M., Azzam, R. and Noubactep, C., 2006. A multi-method approach to study the stability of natural slopes and landslide susceptibility mapping; Engineering Geology, v. 82, no. 4, p. 241-263.
- Fannin, R. and Wise, M., 2001. An empirical-statistical model for debris flow travel distance; Canadian Geotechnical Journal, v. 38, no. 5, p. 982-994.
- Fine, I., Cherniawsky, J., Rabinovich, A. and Stephenson, F., 2008. Numerical Modeling and Observations of Tsunami Waves in Alberni Inlet and Barkley Sound, British Columbia; Pure and Applied Geophysics, v. 165, p. 2019-2044.
- Fitzgerald, D., Fenster, M., Argow, B. and Buynevich, I., 2008. Coastal impacts due to sea-level rise; Annual Review of Earth and Planetary Sciences, v. 36, p. 601-647.

- Fletcher, L., Hungr, O. and Evans, S.G., 2002. Contrasting failure behaviour of two large landslides in clay and silt; *Canadian Geotechnical Journal*, v. 39, no. 1, p. 46-62.
- Ford, J. and Pearce, T., 2010. What we know, do not know, and need to know about climate change vulnerability in the Western Canadian Arctic; a systematic literature review; *Environmental Research Letters*, v. 5, no. 1, p. 1-9.
- Ford, J. and Smith, B., 2004. A framework for assessing the vulnerability of communities in the Canadian Arctic to risks associated with climate change; *Arctic*, v. 57, no. 4, p. 389-400.
- Ford, J., Smith, B. and Wandel, J., 2006. Vulnerability to climate change in the Arctic: A case study from Arctic Bay, Canada; *Global Environmental Change*, v. 16, no. 2, p. 145-160.
- Fortin-Rhéaume, A.-A., 2011. Étude de l'étalement latéral de 1988 et des autres glissements de terrain le long de la vallée à Brownsburg-Chatham, Québec. M.Sc. Thesis, Department of Civil Engineering, Laval University.
- Fransham, P. and Gadd, N., 1977. Geological and geomorphological controls of landslides in Ottawa Valley, Ontario; *Canadian Geotechnical Journal*, v. 14, no. 4, p. 531-539.
- Friele, P., Jakob, M. and Clague, J.J., 2008. Hazard and risk from large landslides from Mount Meager Volcano, British Columbia, Canada; *Georisk*, v. 2, no. 1, p. 48-64.
- Froese, C., Moreno, F., Jaboyedoff, M. and Cruden, D., 2009. 25 years of movement monitoring on South Peak, Turtle Mountain; understanding the hazard; *Canadian Geotechnical Journal*, v. 46, no. 3, p. 256-269.
- Fulton, R., 1995. Surficial materials of Canada-Matériaux superficiels du Canada; Geological Survey of Canada, "A" Series Map 1880A.
- Gardner, J.S., 1983. Rockfall frequency and distribution in the Highwood Pass Area, Canadian Rocky Mountains; *Zeitschrift fuer Geomorphologie*, v. 27, no. 3, p. 311-324.
- Geertsema, M. and Schwab, J., 2006. Challenges with Terrain Stability Mapping in Northern British Columbia; *Streamline Watershed Management Bulletin*, v. 10, no. 1, p.18-26.
- Geertsema, M. and Torrance, J.K., 2005. Quick clay from the Mink Creek landslide near Terrace, British Columbia: geotechnical properties, mineralogy and geochemistry. *Canadian Geotechnical Journal*, v. 42, p. 907-918.
- Geertsema, M., Schwab, J., Jordan, P., Millard, T.H. and Rollerson, T.P. 2010. Chapter 8 – Hillslope Processes – Chapter 8. *in* Compendium of forest hydrology and geomorphology in British Columbia, (ed.) R.G. Pike, T.E. Redding, R.D. Moore, R.D. Winkler and K.D. Bladon, B.C. Land Management Handbook 66, BC Forest Service, p. 213-273.
- Gélinas, P. and Quigley, R., 1973. The influence of geology on erosion rates along the north shore of Lake Erie. *in* Proceedings - Conference on Great Lakes Research, v. 16, p. 421-430.
- Gerath, R. and Hungr, O., 1983. Landslide terrain, Scatter River valley, northeastern British Columbia. *Geoscience Canada*, v. 10, no. 1, p. 30-32.
- Gouin, P., 2001. Historical earthquakes felt in Quebec (from 1534 to March 1925) as revealed by the local contemporary literature. Guérin Publisher, Montréal.
- Grozic, J.H., 2010. Interplay between gas hydrates and submarine slope failure', *Advances In Natural And Technological Hazards Research*, 28, pp. 11-30.
- Guthrie, R.R., 2013. Socio-economic significance, Canadian technical guidelines and best practices related to landslides; a national initiative for loss reduction. Geological Survey of Canada, Open File Report 7311, 19 p.
- Guthrie, R.R. and Evans, S.G., 2004. Magnitude and frequency of landslides triggered by a storm event, Loughborough Inlet, British Columbia. *Natural Hazards and Earth System Sciences [NHES]*, v. 4, no. 3, p. 475-483.
- Guthrie, R.R., Friele, P., Allstadt, K., Roberts, N., Evans, S.G., Delaney, K., Roche, D., Clague, J.J. and Jakob, M., 2012. The 6 August 2010 Mount Meager rock slide-debris flow, Coast

- Mountains, British Columbia; characteristics, dynamics, and implications for hazard and risk assessment; *Natural Hazards and Earth System Sciences [NHESS]*, v. 12, no. 5, p. 1277-1294.
- Hall, J., Meadowcroft, I., Lee, E. and van Gelder, P., 2002. Stochastic simulation of episodic soft coastal cliff recession; *Coastal Engineering*, v. 46, no. 3, p. 159-174.
- Hammond, C., Hall, D., Miller, S. and Swetik, P. 1992. Level 1 stability analysis (LISA), documentation for Version 2.0. General Technical Report INT-285. U.S. Department of Agriculture, Forest Services, Ogden, Utah.
- Hampton, M. and Griggs, G. 2004. Formation, evolution, and stability of coastal cliffs; status and trends; U. S. Geological Survey Professional Paper 1693, 123 p.
- Harris, C. and Lewkowicz, A., 2000. An analysis of the stability of thawing slopes, Ellesmere Island, Nunavut, Canada; *Canadian Geotechnical Journal*; v. 37, no. 2, p. 449-462.
- Harris, C., Davies, M. and Etzelmuller, B., 2001. The assessment of potential geotechnical hazards associated with mountain permafrost in a warming global climate; *Permafrost And Periglacial Processes*, v. 12, no. 1, p. 145-156.
- Haug, M., Sauer, E. and Fredlund, D., 1977. Retrogressive slope failures at Beaver Creek, south of Saskatoon, Saskatchewan, Canada; *Canadian Geotechnical Journal*, v. 14, no. 3, p. 288-301.
- Hartman, G., 2005. Quaternary stratigraphy and geologic history of the Charlie lake (NTS 94A) map Area, British Columbia. Unpublished MSc thesis, Simon Fraser University, 178 pages.
- Heezen, B. and Ewing, W. 1952. Turbidity currents and submarine slumps, and the 1929 Grand Banks [Newfoundland] earthquake; *American Journal of Science*, v. 250, no. 12, p. 849-873.
- Heginbottom, J., 2002. Permafrost mapping; a review; *Progress in Physical Geography*, v. 26, no. 4, p. 623-642.
- Heller, V., 2008. Landslide generated impulse waves; prediction of near field characteristics; *Mitteilungen Der Versuchsanstalt Fuer Wasserbau, Hydrologie Und Glaziologie Der Eidgenoessischen Technischen Hochschule Zuerich*, 204.
- Hill, P., Conway, K., Lintern, D., Meule, S., Picard, K. and Barrie, J., 2008. Sedimentary processes and sediment dispersal in the southern Strait of Georgia, BC, Canada; *Marine Environmental Research*, v. 66, suppl. 1, p. 539-548.
- Hungr, O., Morgan, G. and Kellerhals, R. 1984. Quantitative analysis of debris torrent hazards for design of remedial measures; *Canadian Geotechnical Journal*, v. 21, no. 4, p. 663-677.
- Hungr, O., Morgan, G., VanDine, D. and Lister, D. 1987. Debris flow defenses in British Columbia; *Reviews in Engineering Geology*, v. 7, p. 201-222.
- Hungr, O. and Evans, S.G., 1989. Engineering aspects of rockfall hazards in Canada; *Geological Survey of Canada, Open File 2061*, 102 p.
- Hungr, O., Evans, S.G. and Hazzard, J., 1999. Magnitude and frequency of rock falls and rock slides along the main transportation corridors of southwestern British Columbia; *Canadian Geotechnical Journal*, v. 36, no. 2, p. 224-238.
- Hungr, O., Evans, S.G., Bovis, M. and Hutchinson, J., 2001. A review of the classification of landslides of the flow type; *Environmental and Engineering Geoscience*, v. 7, no. 3, p. 221-238.
- Hungr, O., Dawson, R., Kent, A., Campbell, D. and Morgenstern, N.R., 2002. Rapid flow slides of coal-mine waste in British Columbia, Canada; *Geological Society of America Reviews in Engineering Geology*, v. 15, p. 191-208.
- Hungr, O., McDougall, S. and Bovis, M., 2005. Entrainment of material by debris flows-Chapter 7. *in Debris-Flow Hazards and Related Phenomena*, (ed.) M. Jakob and O. Hungr; Springer, Berlin, Germany, p. 135-158.

- Hungr, O., McDougall, S., Wise, M. and Cullen, M., 2008. Magnitude-frequency relationships of debris flows and debris avalanches in relation to slope relief; *Geomorphology*, v. 96, no. 3-4, p. 355-365.
- Hungr, O., Picarelli, L., and Leroueil, S., 2014. The Varnes classification of landslide types, an update. *Landslides*, v. 11, no. 2, p. 167-194.
- Hungr, O. and Wilson, P. (in press). Debris flows at Charles Creek, Howe Sound, British Columbia. *in Understanding Landslides through Case Histories*, (ed.) S. Leroueil and L. Picarelli, Springer Publishing, New York.
- Hurtubise, J. and Rochette, P.A., 1956. The Nicolet slide. *in Proceedings of the 37th Convention, Canadian Good Roads Association*, p. 143-155.
- Huscroft, C., Lipovsky, P. and Bond, J., 2004. Permafrost and landslide activity: case studies from southwestern Yukon Territory. *in Yukon Exploration and Geology 2003*, (ed.) D.S. Emond and L.L. Lewis, Yukon Geological Survey, p. 107-119.
- Hutchinson, J., 1988. General report; Morphological and geotechnical parameters of landslides in relation to geology and hydrogeology. *in Proceedings of the 5th International Symposium on Landslides*, p. 3-35.
- Imran, J., Parker, G., Locat, J. and Lee, H., 2001. 1D numerical model of muddy subaqueous and subaerial debris flows; *Journal of Hydraulic Engineering*, v. 127, no. 11, p. 959-968.
- Jaboyedoff, M., Demers, D., Locat, J., Locat, A., Locat, P., Oppikofer, T., Robitaille, D. and Turmel, D., 2009. Use of terrestrial laser scanning for the characterization of retrogressive landslides in sensitive clay and rotational slide; *Canadian Geotechnical Journal*, v. 46, no. 12, p. 1379-1390.
- Jackson, L.E., Jr., Kostaschuk, R.A. and MacDonald, G.M., 1987. Identification of debris flow hazard on alluvial fans in the Canadian Rocky Mountains. *in Debris Flows/Avalanches Processes*, (ed.) Costa, J.E., and G.F. Wiezorek, Geological Society of America, *Reviews in Engineering Geology*, v. VII, p. 115-124.
- Jackson, L.E., Hungr, O., Gardner, J. and MacKay, C., 1990. The Cathedral Mountain Debris Flows; *Bulletin International Association of Engineering Geology*, v. 40, p. 35-54.
- Jackson, L.E., Jr., Bobrowsky, P.T. and Bichler, A., 2012. Identification, Maps and Mapping - Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction. Geological Survey of Canada, Open File 7059, 33 p.
- Jakob, M., 2000. The impacts of logging on landslide activity at Clayoquot Sound, British Columbia; *Catena*, v. 38, no. 4, p. 279-300.
- Jakob, M., Anderson, D., Fuller, T., Hungr, O. and Ayotte, D., 2000. An Unusually Large Debris Flow at Hummingbird Creek, Mara Lake, British Columbia; *Canadian Geotechnical Journal* v. 37, no. 5, p. 1109-1125.
- Jakob M. and Weatherly H., 2003. A hydroclimatic threshold for landslide initiation on the north shore mountains of Vancouver, British Columbia; *Geomorphology*, v. 54, no. 3-4, p. 137-156.
- Johns, M., Prior, D., Bornhold, B., Coleman, J. and Bryant, W., 1985. Geotechnical aspects of a submarine slope failure, Kitimat Fjord, British Columbia; *Marine Geotechnology*, v. 6, p. 243-279.
- Kulikov, E.A., Rabinovich, A.B., Thomson, R.E. and Bornhold, B.D., 1996. The landslide tsunami of November 3, 1994, Skagway Harbor, Alaska; *Journal of Geophysical Research*, v. 101, p. 6609-6615.
- Kvalstad, T.J., Andresen, L., Forsberg, C.F., Berg, K., Bryn, P. and Wangen, M., 2005. The Storegga slide: evaluation of triggering sources and slide mechanics; *Marine and Petroleum Geology*, v. 22, no. 1-2, p. 245- 256.

- Lantuit, H. and Pollard, W.H., 2008. Fifty years of coastal erosion and retrogressive thaw slump activity on Herschel Island, southern Beaufort Sea, Yukon Territory, Canada; *Geomorphology*, v. 95, no. 1-2, p. 84-102.
- LaRochelle, P., Sarrailh, J., Tavenas, F., Roy, M. and Leroueil, S., 1981. Causes of sampling disturbance and design of a new sampler for sensitive soils; *Canadian Geotechnical Journal*, v. 18, no. 1, p. 52-66.
- Lawrence, M., Braund-Read, J. and Musgrave, B., 2009. Reservoir shorelines: a methodology for evaluating operational impacts. *in* GeoHalifax 2009 - Proceedings of the 62nd Canadian Geotechnical Society Conference and 10th Joint CGS/IAH-CNC Groundwater Conference, Halifax, Nova Scotia, Canada, p. 962-969.
- Lawrence, M.S., Roberts, N.J. and Clague, J.J., 2013. The 2007 Chehalis Lake landslide, British Columbia: A landslide-generated surge wave (tsunami) with implications for dam safety. *in* Proceedings of the 66th Canadian Geotechnical Society Conference, Montreal, Canada, Paper 626.
- Leblanc, A.M., Fortier, R., Allard, M., Cosma, C. and Buteau, S., 2004. Seismic cone penetration test and seismic tomography in permafrost; *Canadian Geotechnical Journal*, v. 41, no. 5, p. 796-813.
- Lebuis J., Robert J.M. and Rissmann P., 1983. Regional mapping of landslide hazard in Québec. Symposium on slopes on soft clays, Linköping, Suède, Report No.17, Swedish Geotechnical Institute, p. 205-262.
- Lee, E.M., Hall, J.W. and Meadowcroft, I.C., 2001. Coastal cliff recession: the use of probabilistic prediction methods; *Geomorphology*, v. 40, no. 3-4, p. 253-269.
- Lee, E.M., Meadowcroft, I.C., Hall, J.W. and Walkden, M., 2002. Coastal landslide activity: a probabilistic simulation model; *Bulletin of Engineering Geology and Environment*, v. 61, p. 347-355.
- Lee, H.J., Locat, J., Desgagnes, P., Parson, J., McAdoo, B., Orange, D., Puig, P., Wong, F., Dartnell, P. and Boulanger, E., 2007. Submarine Mass Movements. *in* Continental-margin Sedimentation: Transport to Sequence, (ed.) C. Nittrouer, J.A. Austin, M.E. Field, J.H. Kravitz, J.P.M. Syvitski and P.L. Wiberg, Special publication No. 37, International Association of Sedimentologists, p. 213-275.
- Lefebvre, G., 1981. Fourth Canadian Geotechnical Colloquium: Strength and slope stability in Canadian soft clay deposits; *Canadian Geotechnical Journal*, v. 18, p. 420-442.
- Lefebvre, G., 1996. Soft sensitive clays - Chapter 24. *in* Landslides: investigation and mitigation, (ed.) K. Turner and R.L. Schuster; Transportation Research Board, Special Report 247, p. 607-619.
- Lefebvre, G., Demers, D., Leroueil, S., Robitaille, D. and Thibault, C., 2008. Slope stability evaluation: more observation and less calculation. *in* Proceedings of the 4th Canadian Conference on Geohazards: From Causes to Management, (ed.) J. Locat, D. Perret, D. Turmel, D. Demers and S. Leroueil. Presse de l'Université Laval, Québec, p. 413-420.
- Lefebvre, G. and Lafleur, J., 1978. Influence des écoulements souterrain sur la stabilité des pentes naturelles d'argile. Department of Civil Engineering, University of Sherbrooke, Quebec, Canada, Report GEO-78-08.
- Lefebvre, G. and LaRochelle, P., 1974. The analysis of two slope failures in cemented Champlain clays; *Canadian Geotechnical Journal*, v. 2, p. 89-108.
- Lefebvre, G., Leboeuf, D., Horny, P. and Tanguay, L., 1992. Slope failures associated with the 1988 Saguenay earthquake, Quebec, Canada. *Canadian Geotechnical Journal*, v. 29, p. 117-130.

- Lefebvre, G. and Poulin, C. 1979. A new method of sampling in sensitive clay; *Canadian Geotechnical Journal*, v. 16, p. 226-233.
- Leonard, L.J., Rogers, G.C. and Mazzotti, S., 2012. A preliminary tsunami hazard assessment of the Canadian Coastline; Geological Survey of Canada, Open File 7201, 126 p.
- Leroueil, S. and Locat, J., 1998. Slope movements – geotechnical characterization, risk assessment and mitigation. *in* Proceedings of the 8th Congress of the International Association of Engineering Geology and the Environment, (ed.) D. Moore and O. Hungr, Vancouver, British Columbia, Canada, p. 933-944.
- Leroueil, S. Locat, J., Levesque, C. and Lee, H.J., 2003. Towards an approach for the assessment of risk associated with submarine mass movements. *in* Submarine Mass Movements and Their Consequences, (ed.) J. Locat and J.Mienert. Kluwer Academic publisher, p. 59-67.
- Leroueil, S., Perret, D. and Locat, J., 1996. Strain rate and structuring effects on the compressibility of a young clay. *in* Measuring and modeling time-dependent soil behavior, (ed.) T.C. Sheahan and V.N. Kaliakin; Geotechnical Special Publication 61, ASCE, New York, p. 137–150.
- Levesque, C.L., Locat, J. and Leroueil, S., 2006. Dating submarine mass movements triggered by earthquakes in the Upper Saguenay Fjord, Quebec, Canada; *Norwegian Journal of Geology*, v. 86, p. 231-242.
- Lévy, S., Jaboyedoff, M., Locat, J. and Demers D. 2012. Erosion and channel change as factors of landslides and valley formation in Champlain Sea Clays: The Chacoura River, Quebec, Canada; *Geomorphology*, v. 145-146, p. 12-18.
- Lewkowicz, A.G. and Bonnaventure, P.P., 2008. Interchangeability of mountain permafrost probability models, Northwest Canada; *Permafrost and Periglacial Processes*, v. 19, p. 49-62.
- Lewkowicz, A.G. and Harris, C., 2005. Frequency and magnitude of active-layer detachment failures in discontinuous and continuous permafrost, northern Canada; *Permafrost and Periglacial Processes*, v. 16, p. 115-130.
- Lipovsky, P. and Huscroft, C., 2006. A reconnaissance inventory of permafrost-related landslides in the Pelly River watershed, central Yukon. *in* Yukon Exploration and Geology 2006, (ed.) D.S. Emond, L.L. Lewis and L.H. Weston, Yukon Geological Survey, p. 181-195.
- Lipovsky, P.S., Evans, S.G., Clague, J.J., Hopkinson, C., Couture, R., Bobrowsky, P., Ekström, G., Demuth, D.M., Delaney, K.B., Roberts, N.K., Clarke, G. and Schaeffer, A., 2008. The July 2007 rock and ice avalanches at Mount Steele, St. Elias Mountains, Yukon, Canada; *Landslides*, v. 5, p. 449-455.
- Locat, A., 2012. Rupture progressive et étalements dans les argiles sensibles. PhD. Thesis, Department of Civil Engineering, Université Laval.
- Locat, A., Leroueil, S., Bernander, S., Demers, D., Locat, J. and Ouehb, L. 2008. Study of a lateral spread failure in an eastern Canada clay deposit in relation with progressive failure; the Saint-Barnabé-Nord slide. *in* Proceedings, Canadian Conference on Geohazards IV, From Causes to Management, (ed.) J. Locat, D. Perret, D. Turmel, D. Demers and S. Leroueil. Presse de l'Université Laval, p. 89-96.
- Locat, A., Leroueil, S., Bernander, S., Demers, D., Jostad, H.P. and Ouehb, L., 2011. Progressive failures in eastern Canadian and Scandinavian sensitive clays. *Canadian Geotechnical Journal*, v. 48, p. 1696-1712.
- Locat, J., 1995. On the development of microstructure in a collapsible soils, NATO Workshop. *in* Genesis and Properties of Collapsible Soils, (eds.) E. Derbyshire et al., Kluwer Academic Publishers, p. 93-128.

- Locat, J., 1997. Normalized rheological behaviour of fine muds and their low properties in a pseudoplastic regime. ASCE, First Conference on Debris Flows Hazards Mitigation, Mechanics, Prediction and Assessment, p. 260-269.
- Locat, J., 2001. Instabilities along Ocean Margins: A Geomorphological and Geotechnical Perspective. *Marine and Petroleum Geology*, v. 18, p. 503-512.
- Locat, J., 2011. Localisation et magnitude du séisme du 5 février 1663 (Charlevoix) revues à l'aide des mouvements de terrain. *Canadian Geotechnical Journal*, v. 48, p. 1266-1286.
- Locat, J. and Demers, D., 1988. Viscosity, yield stress, remolded strength, and liquidity index relationship for sensitive clays. *Canadian Geotechnical Journal*, v. 25, p. 799-806.
- Locat, J. and Leroueil, S., 1997. Landslide stages and risk assessment issues in sensitive clays and other soft sediments. *in* *Landslide Risk Assessment*, (eds.) D. Cruden and R. Fell, 1997, Balkema, p. 261-270.
- Locat, J. and Sanfaçon, R., 2000. Multibeam surveys: a major tool for geosciences. *Proceedings of the Canadian Hydrographics Conference, Montréal, 2000*, 11 p.
- Locat, J. and Lee, H.J., 2002. Submarine landslides: Advances and challenges. *Canadian Geotechnical Journal*, v. 39, p. 193-212.
- Locat, J. and Lee, H.J., 2009. Submarine Mass Movements and Their Consequences: An Overview. *in* *Landslides – Disaster Risk Reduction*, (eds.) K. Sassa and P. Canuti, Springer-Verlag, p. 115-142.
- Locat, P., Leroueil, S., Locat, J., and Duchesne, M.J., 2003. Characterisation of a submarine flow-slide at Pointe-du-Fort, Saguenay Fjord, Québec, Canada. *in* *Submarine mass Movements and Their Consequences*, (eds.) J. Locat and J. Mienert, Kluwer series on Natural and Technological Hazards, v. 19, p. 509-518.
- Locat, J., Tanaka, H., Tan, T.S., Dasari, G.R., and Lee, H., 2003. Natural soils: geotechnical behavior and geological knowledge. *in* *Characterisation and Engineering Properties of Natural Soils*, (eds.) Tan and ???, Balkema, v. 1, p. 3-28.
- Locat, J., Locat, P., Locat, A. and Leroueil, S., 2007. Linking geotechnical and rheological properties from failure to post failure: the Pointe-du-fort slide, Saguenay Fjord, Quebec. *in* *Submarine Mass Movement and Their Consequences*, (eds.) V. Lykousis, D. Sakellariou and J. Locat; Springer, p. 181-189.
- Locat, J., Turmel, D., Noël, F., Amiguer, C., Lajeunesse, P., St-Onge, G., and Terhzaz, L. 2012a. Exploring the contrasting signatures of submarine landslides along the North Channel of the St. Lawrence Middle Estuary (Charlevoix), Québec, Canada. *in* *Landslides and Engineered Slopes: Protecting Society through Improved Understanding*, (eds.) E. Eberhardt, C. Froese, K. Turner and S. Leroueil; Taylor & Francis Group, London; p. 1077-1083.
- Locat, J., Demers, D., Robitaille, D., Fournier, T., Noël, F., Leroueil, S., Locat, A., and Lefebvre, G. 2012b. The Saint-Jude landslide of May 10, 2010, Québec, Canada. *in* *Landslides and Engineered Slopes: Protecting Society through Improved Understanding*, (eds.) E. Eberhardt, C. Froese, K. Turner and S. Leroueil; Taylor & Francis Group, London; p. 635-640.
- Lum, K.Y., 1977. Stability of the Kamloops silt bluffs. M.A.Sc. thesis, Civil Engineering, University of B.C.
- Luternauer, J. and Finn, W.D.L., 1983. Stability of the Fraser River Delta front. *Canadian Geotechnical Journal*, v. 20, p. 603-616.
- Lyle, R. and Hutchinson, D.J., 2006. Influence of degrading permafrost on landsliding processes: Little Salmon Lake, Yukon Territory, Canada. 2006 ECI Conference on Geohazards, 10 p.
- McDougall, S. and Hungr, O., 2004. A model for the analysis of rapid landslide runout motion across three-dimensional terrain. *Canadian Geotechnical Journal*, v. 41, p. 1084-1097.

- McInnes, R.G. and Moore, R., 2011. Cliff instability and erosion management in Great Britain – A Good Practice guide. Halcrow Group Ltd, Birmingham, 88 p.
- McRoberts, E.C. and Morgenstern, N.R., 1974. The Stability of Thawing Slopes. *Canadian Geotechnical Journal*, v. 11, p. 447-469.
- Masson, D., Harbitz, C.B., Wynn, R.B., Pedersen, G., and Lovholt, F., 2006. Submarine landslides: processes, triggers and hazard prediction. *Philosophical Transactions Royal Society*, v. 364, p. 2009–2039.
- Matheson, D.S. and Thomson, S., 1973. Geological implications of valley rebound. *Canadian Journal of Earth Sciences*, v. 10, p. 961-978.
- Mathews, W.H., 1978. Quaternary stratigraphy and geomorphology of Charlie Lake (94A) map area, British Columbia. Geological Survey of Canada, Paper 76-20, 29 pages.
- Mollard, J.D., 1977. Regional landslide types in Canada. *in* *Landslides, Reviews in Engineering Geology*, (ed.) D.R. Coates; Geological Society of America; p. 29-56.
- Mollard, J.D. 1986. Shoreline erosion and slumping studies on prairie lakes and reservoirs. *in* *Proceedings Symposium on Cohesive Shores*, Burlington, Ontario, p. 277-291.
- Mollard, J.D. and Janes, J.R., 1984. Airphoto interpretation and the Canadian landscape. Energy, Mines and Resources Canada.
- Montgomery, D.R. and Dietrich W.E., 1994. A physically based model for the topographic control on shallow landsliding. *Water Resources Research*, v. 30, p. 1153-1171.
- Moore, D.P. and Mathews, W.H., 1978. The Rubble Creek rock slide, southwestern B.C. *Canadian Journal of Earth Sciences*, v. 15, p. 1039-1052.
- Moore, D.P. and Imrie, A.S., 1982. Rock slope stabilization at Revelstoke damsite. *in* *Proceedings of the 14th Congress of the International Commission on Large Dams*, Rio de Janeiro, v. 2, p. 365-384.
- Moore, D.P. and Imrie, A.S., 1992. Stabilization of Dutchman's Ridge. *in* *Proceedings of the 6th International Symposium on Landslides*, Christchurch, New Zealand, A.A. Balkema Publishers, v. 3, p. 1783-1788.
- Moore, D.P., Ripley, B.D., and Groves, K.L., 1992. Evaluation of mountain slope movements at Wahleach. *in* *Geotechnique and Natural Hazards*, BiTech Publishers, Vancouver, p. 99-107.
- Morgenstern, N.R. 1967. Submarine slumping and the initiation of turbidity currents. *in* *Marine Geotechnique*, (ed.) A.F. Richards; University of Illinois Press, Urbana, Ill., p. 189–210.
- Morgenstern, N.R., 1982. The analysis of wall supports to stabilize slopes. *in* *Proceedings of Application of Walls to Landslide Control Problems*, (ed.) R. Reeves, American Society of Civil Engineers, New York, p. 19-29.
- Mosher, D.C. and Piper, D.J.W., 2007. Analysis of multibeam seafloor imagery of the Laurentian Fan and the 1929 Grand Banks landslide area. *in* *Submarine Mass Movements and Their Consequences: Advances in Natural and Technological Hazards Research*, (eds.) V. Lykousis, D. Sakellariou, and J. Locat, Springer, The Netherlands, v. 27, p. 77-88.
- Mosher, D.C., Shimeld, J., Hutchinson, D., Lebedeva, I., and Chapman, B., 2012. Submarine Landslides in Arctic Sedimentation: Canada Basin. *in* *Submarine Mass Movements and Their Consequences*, 147 *Advances in Natural and Technological Hazards Research*, (eds.) Y. Yamada, K. Kawamura, K. Ikehara, Y. Ogawa, v. 31, p. 147-157.
- Mulder, T. and Cochonat, P., 1996. Classification of offshore mass movements. *Journal Sedimentary Research*, v. 66, p. 43–57.
- Murten, J.B. and French, H.M., 1994. Cryostructures in permafrost, Tuktoyaktuk coastlands, western arctic Canada. *Canadian Journal of Earth Sciences*, v. 31, p. 737-747.

- Nadim, F. and Locat, J., 2005. Risk assessment for submarine slides. *in* *Landslide Risk Assessment*, (eds.) O. Hungr, R. Fell, R. Couture and E. Eberhardt; Taylor and Francis, p. 321-333.
- Nairn, R.B. and Southgate, H.N., 1993. Deterministic profile modelling of nearshore processes. Part II. Sediment Transport and Beach Profile Development. *Journal of Coastal Engineering*, v. 19, p. 57-96.
- Nasmith, H., 1972. Engineering geology of the southern Cordillera of British Columbia. Field Excursion A08-C08, 14th International Geological Congress, Montreal.
- Newcomen, H.W., Maggs, C.S., and Shwydiuk, L., 2008. Managing Pit Slope Displacements: Highland Valley Copper's Lornex Pit Southwest Wall. *in* *Proceedings, Canadian Conference on Geohazards IV, From Causes to Management*, (ed.) J. Locat, D. Perret, D. Turmel, D. Demers and S. Leroueil. Presse de l'Université Laval, Quebec.
- Nielsen, W., 2009. Vulnerability of Subsea Telecommunication Cables: An Anglo American Perspective. Publications WFN Strategies.
- Norem, H., Locat, J., and Schieldrop, B. 1990. An approach to the physics and the modelling of submarine landslides. *Marine Geotechnology*, v. 9, p. 93-111.
- O'Loughlin, C.L., 1972. A preliminary study of landslides in the coast mountains of southwestern British Columbia. *in* *Mountain Geomorphology, Geomorphological Processes in the Canadian Cordillera*, (eds.) H.O. Slaymaker and H.J. McPherson. B.C. Geographical Series, Tantalus Research, Vancouver, British Columbia, v. 14, p. 101-111.
- Ouehb, L., 2007. Analyse du glissement de Saint-Liguori (1989) dans l'optique d'une rupture progressive. M.Sc. thesis, Département de génie civil, Université Laval, Québec, Qc, Canada.
- Pack, R.T., 1997. New developments in terrain stability mapping in B.C. *Proceedings of the 11th annual Vancouver Geotechnical Society Symposium - Forestry Geotechnique and resource engineering*, BiTech Publishers, Vancouver, p. 3-16.
- Pedrazzini, A., Froese, C.R., Jaboyedoff, M., Hungr, O., and Humair, F., 2012. Combining Digital Elevation Model analysis and run-out modelling to characterize hazard posed by a potentially unstable rock slope at Turtle Mountain, Alberta, Canada. *Engineering Geology*, v. 128, p. 76-94.
- Penner, L.A. and Boals, R.G., 2000. Numerical model for predicting shore erosion impacts around lakes and reservoirs. *in* *Proceedings of the Third Annual Canadian Dam Association Conference*, p. 75-84.
- Penner, L.A., Mollard, J. D., and Stokke, P., 1992. Modelling the shore erosion process for predicting bank recession rates around Canadian prairie and northern permafrost-affected lakes and reservoirs. *in* *Erosion: Causes to Cures, Short Course and Conference*, Regina, Saskatchewan.
- Pierson, L.A., Davis, S.A., and Van Vickle, R., 1990. The Rockfall Hazard Rating System: Implementation Manual. Technical Report FHWA-OR-EG-90-01, FHWA, U.S. Department of Transportation, 31 p.
- Piper, D.J.W., Shor, A.N., and Hughes Clarke, J.E., 1988. The 1929 Grand Banks earthquake, slump, and turbidity current. *in* *Geological Society of America Special Paper No. 229*, p. 77-92.
- Piper, D.J.W., Cochonat, P., and Morrison, M.L., 1999. The sequence of events around the epicenter of the 1929 Grand Banks earthquake: initiation of debris flows and turbidity current inferred from sidescan sonar. *Sedimentology*, v. 46, p. 79-97.
- Piper, D.J.W. and McCall, C., 2003. A synthesis of the distribution of submarine mass movements on the eastern Canadian Margin. *in* *Submarine Mass Movements and their Consequences*, (eds.) J. Locat and J. Mienert, Kluwer Publisher, p. 291-298.

- Piteau, D.R., Mylrea, F.H., and Blown, I.G., 1978. Downie Slide, Columbia River, British Columbia, Canada. *in* Rockslides and avalanches, (eds.) B. Voight, Amsterdam, Elsevier, v. 1, p. 365-392.
- Polysou, N.C., Coulter, T.S., and Sobkowicz, J.C., 1998. Design, construction and performance of a pile wall stabilizing a landslide. *in* Proceedings of the 51st Canadian Geotechnical Conference.
- Poncet, R., Campbell, D.C., Dias, F., Locat, J., and Mosher, D.C., 2009. A study of the tsunami effects of two landslides in the St. Lawrence estuary. *in* Submarine Mass Movements and their Consequences, Fourth International Symposium, Advances in Natural and Technological Hazards Research, (eds.) D.C. Mosher, C. Shipp, L. Moscardelli, C. Baxter, J. Chaytor, H. Lee, and R. Urgeles. Springer, The Netherlands, p. 755-764.
- Porter, M.J., Savigny, K.W., Keegan, T.R., Bunce, C.M., and MacKay, C., 2002. Controls on stability of the Thompson River landslides. *in* Proceedings of the 55th Canadian Geotechnical Conference: Ground and Water: Theory to Practice, Niagara Falls, Ontario. p. 1393–1400.
- Porter, M., Logue, C., Savigny, K.W., Esford, F., and Bruce, I., 2004. Estimating the influence of natural hazards on pipeline risk and system reliability. *in* Proceedings of the International Pipeline Conference, Calgary, Alberta, Paper IPC04-0238, 9 p.
- Porter, M. and Morgenstern, N.R., 2013. Landslide Risk Evaluation – Canadian Technical Guidelines and Best Practices related to Landslides: a national initiative for loss reduction. Geological Survey of Canada, Open File 7312, 21 p.
- Potvin, J., Pellerin, F., Demers, D., Robitaille, D., LaRochelle, P., and Chagnon, J.-Y., 2001. Revue et investigation complémentaire du site du glissement de Saint-jean-Vianney. *in* Proceedings of the Canadian Geotechnical Conference, an Earth Odyssey, Calgary, p. 792-800.
- Prior, D.B. 1993. Submarine landslides: the value of high resolution geophysical survey for engineering. *in* The Royal Academy of Engineering Conference on: Landslides Hazard Mitigation with Particular Reference to Developing Countries, p. 67-82.
- Prior, D.B., Bornhold, B.D., Coleman, J.M. and Bryant, W.R. 1982. Morphology of a submarine slide, Kitimat Arm, British Columbia: *Geology*, v. 10, p. 588-592.
- Quigley, R.M., Gélinas, P.J., Bou, W.T., and Packer, R.W., 1977. Cyclic erosion-instability relationships: Lake Erie north bluffs. *Canadian Geotechnical Journal*, v. 14, p. 310-323.
- Quinn, J.D., Rosser, N.J., Murphy, W., and Lawrence, J.A., 2010. Identifying the behavioural characteristics of clay cliffs using intensive monitoring and geotechnical numerical modelling. *Geomorphology*, v. 120, p. 107-122.
- Quinn, P.E., Hutchinson, D.J., Diederichs, M.S., and Rowe, R.K., 2011. Characteristics of large landslides in sensitive clay in relation to susceptibility, hazard, and risk. *Canadian Geotechnical Journal*, v. 48, p. 1212-1232.
- Rabinovich, A.B., Thomson, R.E., Bornhold, B.D., Fine, I.V., and Kulikov, E.A., 2003. Numerical modelling of tsunamis generated by hypothetical landslides in the Strait of Georgia, British Columbia. *Pure and Applied Geophysics*, v. 160, p. 1273-1313.
- Reid, J.F., Sandberg, B.S., and Millsop, M.D., 1988. Bank recession processes, rates and prediction, Lake Sakakawea, North Dakota, USA. *Geomorphology*, v. 1, p. 161-189.
- RIC, 1995. Resource Inventory Committee, Guidelines and Standards to Terrain Geology Mapping in B.C., Surficial Geology Task Group, Earth Sciences Task Force, Government of British Columbia.
- RIC, 1996. Resources Inventory Committee Terrain Stability Mapping in BC: A Review and Suggested Methods for Landslide Hazard and Risk Mapping; Slope Stability Task Group, Earth Sciences Task Force, Government of British Columbia.

- Rist, A. 2007. Hydrothermal processes within the active layer above alpine permafrost in steep scree slopes and their influence on stability. Ph.D. thesis. Swiss Federal Institute for Snow and Avalanche Research and University of Zurich, 168 p.
- Roberts, N.J., McKillop, R.J., Lawrence, M.S., Psutka, J.F., Clague, J.J., Brideau, M-A., and Ward, B.C., 2012. Impacts of the 2007 landslide-generated wave in Chehalis Lake, Canada. *in* Landslide Science and Practice, Proceedings of the Second World Landslide Forum, Rome, Italy, Springer-Verlag, New York.
- Robitaille, D., Demers, D., Potvin, J., and Pellerin, F., 2002. Mapping of landslides prone areas in the Saguenay region, Québec, Canada. *in* Instability Planning and Management, (eds.) Robin G. McInnes and J. Jakeway, Thomas Telford, Publisher, p. 161-168.
- Rutter, N.W., Boydell, A.N., Savigny, K.W., and van Everdingen, R.O., 1973. Terrain evaluation with respect to pipeline construction, McKenzie Transportation Corridor, southern part, lat. 60° to 14°. Task force on Northern oil Development, Report No. 73-36, 142 p.
- Saihi, F., Leroueil, S., LaRochelle, P., and French, I., 2002. Behaviour of the stiff and sensitive St. Jean-Vianney clay in intact, destructured, and remoulded conditions. *Canadian geotechnical Journal*, v. 39, p. 1075-1087.
- Sallenger, Jr. A.H., Krabill, W.B., Swift, R.N., Brock, J., List, Mark Hansen, J., Holman, R.A., Manizade, S., Sontag, J., Meredith, A., Morgan, K., Yunkel, J.K., Frederick, E.B., and Stockdo, H., 2003. Evaluation of Airborne Topographic Lidar for Quantifying Beach Changes. *Journal of Coastal Research*, v. 19, p. 125-133.
- Savigny, K.W. and Morgenstern, N.R., 1986a. Geotechnical conditions of slopes at a proposed pipeline crossing, Great Bear river valley, Northwest Territories. *Canadian Geotechnical Journal*, v. 23, p. 504-514.
- Savigny, K.W. and Morgenstern, N.R., 1986b. Creep behaviour of undisturbed clay permafrost. *Canadian Geotechnical Journal*, v. 23, p. 515-527.
- Schwab, J.W., Geertsema, M., and Blais-Stevens, A., 2004. The Khyex River landslide of November 28, 2003, Prince Rupert British Columbia. *Landslides*, v. 3, p. 243-246.
- Sego, D.C. and Morgenstern, N.R., 1983. Deformation of ice under low stresses. *Canadian Geotechnical Journal*, v. 20, p. 587-602.
- Septer, D. and Blais-Stevens, A., 2007. Flooding and Landslide Events Sea-to-Sky Transportation Corridor: A historic overview. Unpublished report, Geological Survey of Canada, Ottawa.
- Septer, D. and Schwab, J.W., 1995. Rainstorm and flood damage, northwest British Columbia, 1891-1991. B.C. Ministry of Forests, Land Management Handbook 31, 195 p.
- Severin, J., 2004. Landslides in the Charlie Lake Map Sheet, Fort St. John. M.A.Sc Thesis. The University of British Columbia.
- Shaw, J., Taylor, R.B., Solomon, S., Christian, H.A., and Forbes, D.L., 1998. Potential impacts of global sea-level rise on Canadian coasts. *Canadian Geographer*, v. 42, p. 365-379.
- Singhroy, V., Couture, R., Alasset, P.-J., and Ponce, V., 2007. InSAR monitoring of landslides on permafrost terrain in Canada. *IEEE*, p. 2542-2554.
- Smith, S.L., Burgess, M.M., Riseborough, D., and Nixon, F.M., 2005. Recent trends from Canadian permafrost thermal monitoring network sites. *Permafrost and Periglacial Processes*, v. 16, p. 19-30.
- Soe-Moe, K.W., Cruden, D.M., Martin, C.D., Lewycky, D., and Lach, P.R., 2009. Mechanisms and kinematics of three translational slides along the North Saskatchewan River Valley, Edmonton. *in* Proceedings of the 62nd Canadian Geotechnical Conference, Halifax.
- Solomon, S.M. 2005. Spatial and temporal variability of shoreline change in the Beaufort-Mackenzie region, Northwest Territories, Canada. *Geomarine Letters*, v. 25, p. 127-137.

- Southgate, H.N. and Nairn, R.B., 1993. Deterministic profile modelling of nearshore processes. Part I. Waves and Currents. *Journal of Coastal Engineering*, v. 19, p. 27-56.
- Springman, S.M. and Arenson, L.U., 2008. Recent advances in permafrost geotechnics. *in Proceedings of the 9th International conference on Permafrost*, p. 1685-1694.
- Stanton, R.B., 1898. The great land-slides on the Canadian Pacific Railway in British Columbia. Institution of Civil Engineers, Session 1897-1898, Part II, Section 1, Minutes of Proceedings.
- Sultan, N., Cochonat, P., Foucher, J.-P., and Mienert, J., 2004. Effect of gas hydrates melting on seafloor slope instability. *Marine Geology*, v. 213, p. 379-401.
- Sultan, N., Savoye, B., Jouet, G., Leunaud, D., Cochonat, P., Henry, P., Stogmann, S., and Kopf, A., 2010. Investigation of a possible submarine landslide at the Var delta front (Nice continental slope, southeast France). *Canadian Geotechnical Journal*, v. 47, p. 486-496.
- Stini, J., 1910. *Die Muren*. Verlag der Wagner'shen Universitätsbuchhandlung, Innsbruck. (Debris flows, English translation by M. Jakob and N. Skermer, 1997, EBA Engineering Consultants, Vancouver, Canada, 106 p.
- Tavenas, F., 1984. Landslides in Canadian sensitive clays – a state-of-the-art. *in Proceedings of the 4th International Symposium on Landslides*, Toronto, Ontario. University of Toronto Press, Toronto, Ontario, v. 1, p. 141-153.
- Tavenas, F., Chagnon, J.-Y., and LaRochelle, P., 1971. The Saint-Jean-Vianney Landslide: Observations and Eyewitnesses Accounts. *Canadian Geotechnical Journal*, v. 8, p. 463-478.
- Thibault, C., Potvin, J., and Demers, D., 2008. Development of a quantitative approach for evaluating and managing the risk associated with large retrogressive slides. *in Proceedings of the Canadian Geotechnical Conference, GeoEdmonton 2008*, Edmonton.
- Thomson, S. and Morgenstern, N.R., 1974. Landslides in argillaceous bedrock, Prairie provinces, Canada. *in Rockslides and avalanches*, (ed.) B. Voight, Amsterdam, Elsevier, v. 2, p. 515-530.
- Thurber Engineering Ltd., 1983. Debris torrent and flooding hazards, Highway 99, Howe Sound. Unpublished report to B.C. Department of Transportation and Highways, Victoria.
- Torgunrud, A.L., Cosford, J.I., Penner, L.A., and Ahmari, H., 2012. Validation of a GIS-based shore erosion model based on historical erosion rates in two northern Manitoba hydroelectric reservoirs. *in Proceedings of the Canadian Dam Association*.
- Trenhaile, A.S., Porter, N.J., and Kanyaya, J.I., 2006. Shore Platform Processes in Eastern Canada. *Géographie physique et Quaternaire*, v. 60, p. 19-30.
- Turmel, D. and Locat, J., 2011. Numerical modelling of underwater rockfall. *Canadian Geotechnical Journal*, v. 48, p. 16-25.
- Urgeles, R., Locat, J., Schmitt, T., and Hughes Clarke, J., 2002. The 1996 flood deposit in the Saguenay Fjord, Quebec, Canada: implications for sources of spatial and temporal backscatter variations. *Marine Geology*, v. 184, p. 41-60.
- Vallejo, L.E., 1980. A new approach to the stability analysis of thawing slopes. *Canadian Geotechnical Journal*, v. 17, p. 607-612.
- van Zeyl, D.P., 2009. Evaluation of subaerial landslide hazards in Knight Inlet and Howe Sound, British Columbia. Unpublished M.Sc. thesis, Dept. of Earth Sciences, Simon Fraser University, 199 p.
- VanEsch, K., 2012. Main landslide types in the Peace River Valley, north-eastern B.C. M.A. Sc. Thesis, University of British Columbia.
- VanDine, D.F., 1980. Engineering geology and geotechnical study of Drynoch landslide, British Columbia, Geological Survey of Canada, Paper 79-31, 34 p.
- VanDine, D.F., 1983. Drynoch landslide, British Columbia – A history. *Canadian Geotechnical Journal*, v. 20, p. 82-103.

- VanDine, D.F., 1985. Debris flows and debris torrents in the Southern Canadian Cordillera. *Canadian Geotechnical Journal*, v. 22, p. 44-68.
- Wang, B., Paudel, B. and Haoqiang, L. 2009. Retrogressive characteristics of landslides in fine-grained permafrost soils, Mackenzie Valley, Canada. *Landslides*, v. 6, p. 121-127.
- Weitzner, E., Lubbin, D., Richter-Menge, J., and Hinzman, L., 2011. Arctic environmental assessment and outlook report. Navy Arctic Roadmap, Action item 5.7, Task Force Climate Change/Oceanographer of the Navy, 25 p. (<http://greenfleet.dodlive.mil/files/2011/08/U.S.-Navy-Arctic-Environmental-Assessment.pdf>)
- Wilford, D.J., Sakals, M.E., Innes, M.E., Sidle, R.C., and Bergerud, W.A., 2004. Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. *Landslides*, v. 1, p. 61–66.
- Wyllie, D. and Mah, C., 2004. *Rock Slope Engineering, Civil and Mining*. Spon Press, Taylor and Francis, New York, 450 p.
- Zakeri, A., Hoeg, K., and Nadim, F., 2008. Submarine debris flow impact on pipelines – Part 1, Experimental investigation. *Coastal Engineering*, v. 55, p. 1209-1218.