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

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CLASSIFICATION, DESCRIPTION, CAUSES AND INDIRECT EFFECTS

Note to Reader

This is the ninth in a series of Geological Survey of Canada Open Files that will be published over the year. 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 compiled, updated and published as a GSC Bulletin. The intent is to have each Open File in the series correspond to a chapter in the Bulletin.

Comments on this Open File or any of the Open Files in this series should be sent before the end of May 2013 to Dr. P. Bobrowsky at pbobrows@NRCan.gc.ca

1. INTRODUCTION

A classification of landslides should assist a landslide professional to observe and clearly describe a landslide. Early classifications of landslides include those by Heim (1932), Ladd (1935), Sharpe (1938), Zaruba and Mencl (1969) and Varnes (1958, 1978). In the early 1990s, the International Union of Geological Sciences Working Party on World Landslide Inventory (WP/WLI) developed a landslide classification system that was based on the widely-used classifications of Varnes (1958, 1978). The classification system was summarized in the Multilingual Landslide Glossary (WP/WLI, 1993a), and published in Dikau et al. (1996, Appendix 1) and Chapter 3 of the (US) Transportation Research Board's special report on landslides (Cruden and Varnes, 1996). A recent handbook on landslides (Highland and Bobrowsky, 2008) has made the WP/WLI classification system widely available.

The WP/WLI classification system is amenable to additions. A term can be added if useful, if in common use, and if not already widely used in a different sense in the landslide literature.

The classification system presented herein is based on the WP/WLI classification system with some minor additions and modifications. Readers should note that other landslide classification systems exist, for example, Hungr et al. (2001) proposed a classification system specific to flow-type landslides, and Hungr et al. (2012) proposed another landslide classification system based on Varnes (1978).

This contribution also includes a general discussion of landslide size, intensity, travel angles, causes and indirect effects.

2. GUIDELINES FOR CLASSIFICATION

A landslide is often simply referred to by the type of material modifying the word slide, for example, to differentiate a rock slide from a soil slide. In such usage, the word slide is generic (short form of landslide) and does not refer to a specific mode of movement. Similarly the generic word slide is frequently added to a geographic location to name a landslide, for example, the Frank Slide. Such references are not landslide classifications.

The WP/WLI landslide classification includes the following seven criteria (Table 1): state of activity, distribution of activity, style of activity, rate of movement, water condition, type of material and mode of movement, and a series of descriptors for each criterion. Such a classification system lends itself to a thorough description of a landslide, to the creation of a database from which two or more landslides can be easily compared and to guide further investigation of a particular landslide.

Table 1. Landslide classification criteria and descriptors.

State of activity	**Distribution of activity**	**Style of activity**	**Rate of movement**	**Water condition**	**Type of material**	**Mode of movement**
Preparatory	Moving	Single	Extremely slow	Dry	Rock	Fall
Marginal	Advancing	Successive	Very slow	Moist	Soil	Topple
Active	Retrogressing	Multiple	Slow	Wet	Debris	Slide
Reactivated	Widening	Composite	Moderate	Very Wet	Earth	Spread
Suspended	Enlarging	Complex	Rapid	Frozen	Sand	Flow
Inactive	Confined		Very rapid	Thawed	Silt	
Dormant	Diminishing		Extremely rapid		Clay	
Abandoned						
Repaired						
Stabilized						
Relict						

In its most basic form, a landslide classification includes a mode of movement descriptor from Table 1 and a type of material descriptor from Table 1. The classification can expand as more information about the landslide becomes available. The recommended sequence of expansion is from right to left in Table 1 and indicates a typical progression in the focus of a landslide study. The recommended sequence of recording the criteria descriptors is from left to right in Table 1. Often the context of a specific landslide study implies a particular value of one or more criteria and those criteria can be omitted if implied, or not relevant.

Subsequent movements of the landslide, in composite or complex landslides (see Section 3.5), can be described by repeating descriptors in Table 1, however, subsequent-movement descriptors that are the same as those for the first-movement can be omitted. For example, the Frank Slide, which began as a rock fall (first-movement) and continued as a debris flow (second-movement), can be classified as a complex (style of activity), extremely rapid (rate of movement), dry (water condition), rock fall-debris flow (first, then second type of material and mode of movement). The sequence of modes of movement can be separated by a hyphen. The Frank Slide as classified above, implies that the debris flow (second movement) was also both extremely rapid and dry because the same descriptors are used to describe the initial (first movement) rock fall.

In a publication, the full classification of a landslide need only be used once, and subsequent references can be shortened to the initial type of material and mode of movement, as in *rock fall*, in the case of the Frank Slide.

Sometimes type examples are used to describe a landslide or to compare landslides. Shreve (1968), for example, referred to the Frank Slide as a *Blackhawk-type slide*. This practice has its limitations because it is not informative to anyone who doesn’t know the original type example. If used, type examples should be of historic significance, have been studied in detail and the subject of a definitive publication, as well as be of continuing interest to landslide professionals.

3. CLASSIFICATION DESCRIPTORS

The following paragraphs briefly describe the criteria descriptors listed from right to left in Table 1.

3.1 Mode of Movement

The five modes of movement are kinematically distinct as shown in Figure 1 and described below.

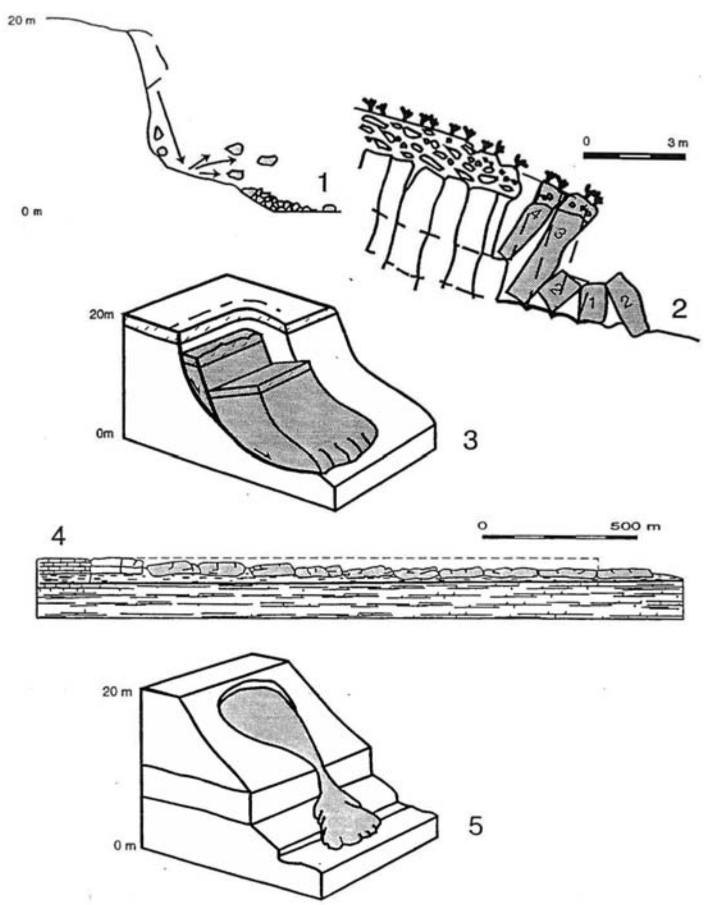

Figure 1. Mode of movement: 1) fall, 2) topple, 3) slide, 4) spread and 5) flow. Broken lines indicate the original ground surface. Displaced material is shaded. Scales are arbitrary (WP/WLI, 1993a).

Fall is the detachment of soil or rock from a steep slope along a surface on which little shear displacement occurs. The material then descends by falling, bouncing or rolling. The movement, which is governed by gravity, is very rapid to extremely rapid (see Section 3.4). Falling is typically preceded by small sliding or toppling movements that separate the displaced material from the undisturbed mass.

Topple is the forward rotation out of the slope of soil or rock on an axis below the centre of gravity of the displaced material. Toppling is sometimes caused by movement of material upslope of the displaced material and sometimes by water or ice in cracks. Topples can lead to falls or slides of the displaced material. Topples range from extremely slow to extremely rapid (see Section 3.4), sometimes accelerating throughout the movement.

Slide is the downslope movement of a soil or rock mass on rupture surfaces or relatively thin zones of intense shear strain. Movement is usually progressive, that is it does not initially occur simultaneously over the entire, of what eventually will be, the rupture surface. It propagates from an area of local rupture. Often the first signs of movement are cracks in the ground surface along which the main scarp of the slide will likely form. The rupture surface, in two dimensions can be described as linear, circular or curvilinear (curved but not circular). The displaced material can slide beyond the toe of the rupture surface and cover the original ground surface. That surface then becomes a surface of separation.

Spread is the extension of a cohesive rock or soil mass combined with a general subsidence of the fractured material. The rupture surface is not a surface of intense shear. Spreads can result from liquefaction or flow (and extrusion). The fractured mass can also translate, rotate, liquefy or flow. This mode of movement is complex, but sufficiently common to warrant its own movement mode.

Flow is continuous movement in which surfaces of shear are short-lived, closely spaced and typically not preserved. The distribution of velocities in the displaced material resembles a viscous liquid. The lower boundary of the displaced material can be a surface along which appreciable differential movement has taken place or a thick zone of distributed shear. There is a range of movement from slides to flows that depends on the water conditions, mobility and evolution of the movement.

Complex, a sixth mode of movement included in Varnes (1978), was dropped from the WP/WLI classification system and, if required, is derived by combining the other five modes of movement. Complex, however, is retained as a descriptor of the style of activity (Section 3.5).

3.2 Type of Material

Table 1 recognizes rock and soil as the two basic types of material.

Rock is a natural aggregate of minerals that cannot be readily broken by hand and that will not disintegrate on a first wetting and drying cycle. For the purpose of landslide classification, rock is not subdivided, but can be classified with respect to its geological origin and lithology. With respect to landslides, an important differentiation can be made between intact rock and rock mass – rock material separated by discontinuities and affected by weathering (refer to Table 9). For more information on the engineering classification of rock, refer to the Canadian Foundation Engineering Manual (Canadian Geotechnical Society, 2006). The International Standard (ISO, 2003) suggests a standard to classify rocks by genesis, structure, grain size and mineralogy, among other criteria.

Soil is an aggregate of solid minerals and rocks that is either fragmentary or can be readily separated by agitation in water. It has either been transported or formed by the weathering of rock in place. Gases or liquids fill the pores and form part of the soil. For the purpose of landslide classification, soil is divided into debris and earth. Debris has 20% to 80% of the particles larger than 2 mm. Earth has 80% or more of the particles smaller than 2 mm. Earth is further subdivided into sand, silt and clay by grain size and plasticity.

For more information on the engineering classification of soil, refer to the Canadian Foundation Engineering Manual (Canadian Geotechnical Society, 2006). Norbury (2010) has developed flow charts based on the International Standard (ISO, 2002) for the identification and classification of soil (Figure 2). That standard divides soils into cohesive (fine) and cohesionless (coarse) soils. Fine soil is further subdivided divided into silt and clay by the qualitative observations of plasticity, dilatancy and other properties.

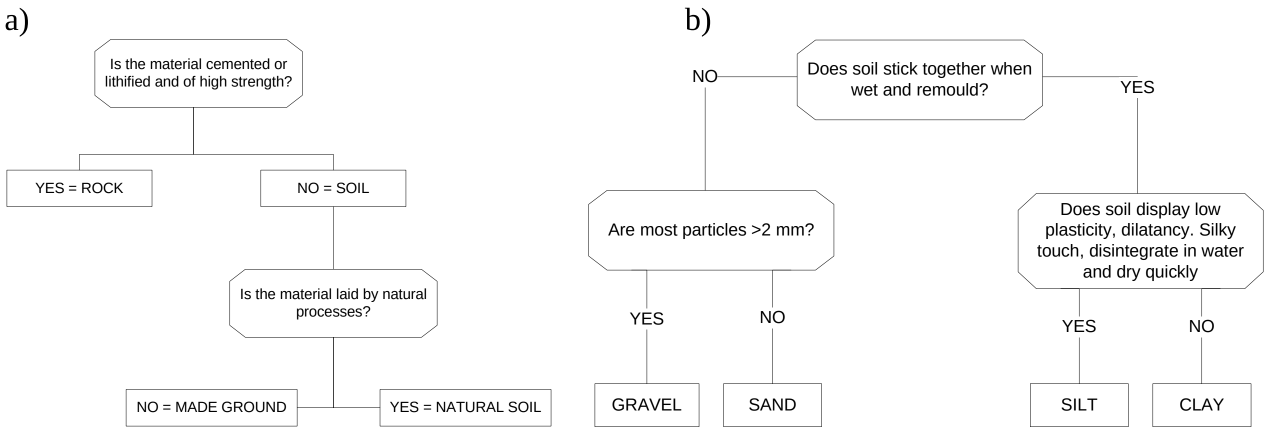

Figure 2. Flow charts for the identification and classification of soil: a) to differentiate rock from made ground from natural soil, b) to differentiate gravel, sand, silt and clay (Cruden and Couture, 2011).

3.3 Water Condition

Varnes (1978) defined four terms relating to “water content” of displaced materials in landslides: dry, moist, wet and very wet. The term “water condition”, as suggested by Hungr et al. (2001), is preferred as it also allows for the inclusion of frozen and thawed, terms that are particularly useful for the classification of landslides in permafrost terrain in northern Canada (Couture and Cruden, 2010).

The six water conditions are described in Table 2.

Table 2. Landslide water conditions.

Descriptor	Description
Dry	no moisture visible
Moist	some water but no free water; the material can behave as a plastic solid but does not flow
Wet	enough water to behave in part as a liquid, has water flowing from it, or supports significant bodies of standing water
Very wet	enough water to flow as a liquid under low gradients
Frozen	water is present as ice
Thawed	significant amounts of water in a liquid phase

Because rock or soil masses can drain quickly after movement, water conditions of displaced material can differ considerably from the water conditions of the pre-displaced material.

3.4 Rate of Movement

Table 3 recognizes seven rates of movement (velocity) classes, from extremely rapid to extremely slow. They are based on multiples of 100, with lower and upper limits spanning ten orders of magnitude. An important boundary lies between slow and very slow movements, 1.6 m/year, below which some structures on a landslide can remain undamaged. Another important boundary lies between extremely rapid and very rapid movements, 5 m/sec, which approximates the speed that an able-bodied person can run. The term creep is considered too ambiguous and should be replaced by the appropriate modifiers, very slow or extremely slow.

Table 3. Landslide rates of movement. Velocities indicate boundaries between classes.

Class number	Descriptor	Velocity	mm/sec	
7	Extremely rapid			
	--------------------	5 m/sec	5000	5×10^{3}
6	Very rapid			
	--------------------	3 m/minute	50	5×10^{1}
5	Rapid			
	--------------------	1.8 m/hour	0.5	5×10^{-1}
4	Moderate			
	--------------------	3 m/week	5×10^{-3}	5×10^{-3}
3	Slow			
	--------------------	1.6 m/year	0.05×10^{-3}	5×10^{-5}
2	Very slow			
	--------------------	16 mm/year	0.0005×10^{-3}	5×10^{-7}
1	Extremely slow			

Estimates of rates of movement can be made by numerous means including repeated surveys of the positions of displaced objects; reconstruction of the trajectories of portions of the displaced mass; time-lapsed remote sensing; instrumentation; and eyewitness' observations.

Rate of movement, along with mass of displaced material, can be used to estimate impact forces. Rates of movement within a landslide can differ with position, with elapsed time and with the time interval over which the rate is estimated, any of which can make precise rate of movement estimates difficult.

The rate of movement descriptors can be correlated in a relative way with observed consequences as shown in Table 4. Table 5 provides some Canadian examples of rate of movement and damage.

Table 4. Typical consequences of landslides for different rates of movement.

Class number	Descriptor	Typical consequences
7	Extremely rapid	major catastrophe likely; structures can be destroyed by impact forces; escape unlikely and potential for loss of life
6	Very rapid	structures may be destroyed; some lives may be lost; rate too great to permit all persons to escape
5	Rapid	structures, possessions and equipment may be destroyed; escape is possible
4	Moderate	some temporary and insensitive structures may be temporarily maintained
3	Slow	remedial activities may be undertaken during movement; insensitive structures may be maintained with maintenance
2	Very slow	some permanent structures may be undamaged by the movement
1	Extremely slow	perceptible only with instruments; construction possible with precautions.

Table 5. Canadian examples of landslide rates of movement and damage.

Class number	Descriptor	Location	Estimated velocity	Damage/Comments	Reference
7	Extremely rapid	Frank, AB	40 m/sec	about 70 deaths; many structures destroyed	McConnell and Brock (1904)
6	Very rapid	St-Jean-Vianney, QU	30 m/min	31 deaths, some flee; 40 houses destroyed	Tavenas et al. (1971)
5	Rapid	Edmonton, AB	20 m/hr	one house destroyed; four houses uninhabitable	Soe Moe et al. (2006)
4	Moderate	Taylor, BC	0.3 m/hr	abutment movement destroyed bridge	Hardy (1963)
3	Slow	Drynoch, BC	3 m/yr	CPR, Trans-Canada Highway displaced	VanDine (1980)
2	Very slow	Little Smoky River, AB	0.25 m/yr	road bridge protected by slip joint.	Thomson and Hayley (1975)
1	Extremely slow	Checkerboard Ck, BC	13 mm/yr	monitoring required	Watson et al. (2006)

3.5 Style of Activity

The manner in which different movements of the displaced mass contribute to a landslide is referred to as the style of activity. There are five descriptors as described in Table 6.

Table 6. Landslide style of activity descriptors.

Descriptor	Description	Comments
Single	only one mode of movement	often as an unbroken mass of displaced material
Successive	two sequential identical modes of movement that do not share displaced material or a rupture surface	
Multiple	repeated movements of the same type that share displaced material or a larger rupture surface	an occurrence that typically follows the enlargement of the rupture surface, for example, a retrogressive multiple slide can have two or more slide blocks that have moved on a curvilinear rupture surface tangential to a common, typically deeper, rupture surface
Composite	different modes of movements in different areas of the displaced material, sometimes simultaneously, sometimes sequentially	the movement that occurs at a higher elevation is considered the first movement (WP/WLI, 1993 b)
Complex	sequential different modes of movement	for example, rock topples in which some of the displaced material subsequently slides can be classified as a complex rock topple-slide

3.6 Distribution of Activity

The distribution of activity broadly describes where and how a landslide is moving. In Table 7 the descriptors are explained in terms of change in the extent of the rupture surface with time, and change in volume of the displaced material with time.

Table 7. Landslide distribution of activity associated with the rupture surface and displaced material.

Descriptor	Change in extent of rupture surface with time	Change in volume of displacing material with time
Moving	none	none
Advancing	extends in the direction of movement of displaced mass	increases
Retrogressing	extends in the direction opposite to the movement of the displacing mass	increases
Widening	extends at one or both lateral margins	increases
Enlarging	extends in two or more directions	increases
Confined	rupture surface is evident at the scarp but not at the foot	change pending
Diminishing	none	lessens

The descriptors progressing or progressive have been dropped because those terms have other meanings associated with landslides and because they can be described by the other descriptors in Table 7.

3.7 State of Activity

State of activity describes the status of landslide movement. Table 8 summarizes the possible states of activity of a landslide or, where a landslide has not yet occurred, the condition of a slope prior to movement. It also references the example numbers given in Figure 2

Table 8. Landslide states of activity (or slope condition).

Descriptor	Landslide State of Activity or Slope Condition	Example in Figure 2
Preparatory	stability of the slope is decreasing	
Marginal	triggering cause can initiate a landslide; rupture surface may be forming	
Active	moving	1
Suspended	moved within the last cycle of seasons, but not currently moving	2
Reactivated	moving again after being inactive; typically because of similar causes and on a pre-existing rupture surface	3
Inactive	last moved more than one cycle of seasons ago	
Dormant	causes of movement remain	5
Abandoned	causes of movement changed naturally; for example, an eroding river has shifted its channel away from the toe of the landslide; typically long term	6
Repaired	recently stabilized	7
Stabilized	causes of movement removed naturally (for example, natural armouring or buttressing) or by human endeavors; typically long term	7
Relict	slope developed under different geomorphological or climatic conditions	8

A number of these states of activity are illustrated, using an idealized toppling movement as an example, in Figure 3.

4. SIZE, INTENSITY AND TRAVEL ANGLES

Other parameters that are used, and have been suggested, to describe a landslide include size, intensity and travel angle. These terms are briefly discussed in the following sections.

4.1 Size

Unlike earthquake magnitude, which is related to the energy released by a seismic event, there is no agreed upon definition of landslide magnitude, and use of the term is discouraged. Alternatively, the size of a landslide can be expressed in terms of: 1) volume of displaced material, 2) areas affected (non-overlapping area of depletion and area of accumulation), or 3) peak discharge where a confined flow is involved. Each approach has its advantages, disadvantages, specific applications and limitations. WP/WLI (1993a, 1993b, 1994) suggested that the volume of displaced material could be estimated by comparing a regular geometric figure to the irregular displaced mass. For example, a half-ellipsoid might be fitted to a rotational slide. For such estimates; the maximum length of the displaced material and the maximum width and depth measurements (see Couture, 2011) need to be estimated. Jakob (2005) suggested ten size classes for debris flows based on the volume of displaced material, typically increasing in orders of magnitude of metres cubed.

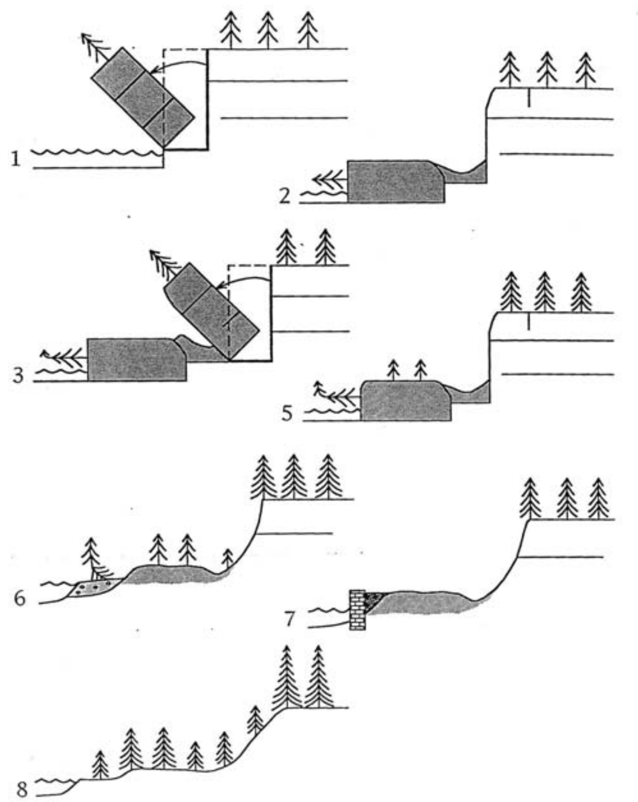

Figure 3. Topples in different states of activity: 1) active, 2) suspended, 3) reactivated, 5) inactive/dormant, 6) inactive/abandoned, 7) inactive/repaired (short term) or inactive/stabilized (long term), 8) inactive/relict. (States 5 to 8 are subsets of inactive)

4.2 Intensity

Hungr (1997, page 217) suggested the term landslide intensity, analogous to the well-known term, earthquake intensity, and suggested a definition, *a set of spatially distributed parameters describing the destructiveness of the landslide*. Maximum rate of movement (see Section 3.4) is considered the most important parameter. Other parameters include total displacement, differential displacement (relative to the points adjacent to the point under consideration), depth of moving mass, depth of deposits after the landslide stops and depth of erosion. Hungr (1997) also suggests other derivative parameters such as peak discharge per unit width (unit discharge), kinetic energy per unit area, maximum thrust or impact pressure and maximum normal or shear strain at or below the ground surface. Currently there are no standards for estimating or recording landslide intensity or the associated parameters, other that maximum rate of movement.

4.3 Travel Angle

For predictive purposes, a first-order estimate of the extent of a landslide's surface of separation is its travel angle (Cruden and Varnes, 1996), considered synonymous by some to the angle of reach, or fahrböschung (Hungr et al., 2005). It is the slope of a line connecting the highest point on the main scarp of the landslide to the distal end of the displaced material. Travel angles are smaller when landslides travel freely along topographically unconstrained paths. By comparison to similar measurements of past landslides, a rudimentary travel angle estimate can be made based on the type material and the mode of movement.

Geertsema and Cruden (2008) studied travel angles of 62 large landslides in both rock and soil in the Canadian Cordillera. The 26 landslides solely in rock had travel angles between approximately 9.5º and 26º. Many began as rock falls. The lowest travel angles were associated with movements over glaciers. A subset of ten rock slides that transformed into soil slides or debris flows had travel angles between approximately 10º and 12º. The lowest recorded travel angle involving rock occurred on a tributary of Muskwa River in northern BC, where in 1979 a rock slide triggered an earth flow with the resulting travel angle of 3.5º.

Geertsema and Cruden's (2008) landslides in soil from northern BC included some in glaciolacustrine and some in diamicton, the latter interpreted to be tills derived from clay shale. Travels angles ranged between 6.2º to 14º. Tills in most other parts of the Canadian Cordillera were found to have steeper travel angles. The lowest recorded travel angle belonged to the 1962 Lakelse Lake landslide within sensitive glaciomarine sediments that had a travel angle of 1.4º. This compares with a larger sample size in similar material in eastern Canada where five retrogressive flows had an average travel angle of 1.7º, and four spreads had an average travel angle of 3.2º (Quinn et al., 2011).

Corominas (1996) and Hungr et al. (2005) have found that the larger the landslide volume, the smaller the travel angle. In a plot of landslide volume against the tangent of the travel angle, Geertsema and Cruden (2008) found this correlation to be less clear in the Canadian Cordillera (Figure 4), however they found a good correlation between travel angle and material type, with marine soils having the lowest travel angles and rock avalanches (typically rock fall-debris flows) having the largest travel angles.

5. CAUSES

The change of a slope from a stable to an active state passes through two intermediate states: a preparatory state in which preparatory causes make the slope less stable without initiating movement and a marginal state in which triggering causes can initiate movement (see Section 3.7).

There are forces acting on every slope: those that tend to promote downslope movement (driving forces) and those that oppose downslope movement (resisting forces). For a particular rupture surface, the ratio of the resisting forces to the driving forces can be estimated and expressed as the factor of safety (FS). A FS > 1 indicates that the resisting forces along the rupture surface are greater than the driving forces; a FS < 1 indicates that the resisting forces are less than the driving forces; a FS = 1 indicates equilibrium between the resisting and driving forces.

Figure 5 illustrates an example of change in the FS with time for a slope that has not previously experienced a landslide, and indicates some of the causal factors: weathering, rainfall, erosion and overloading.

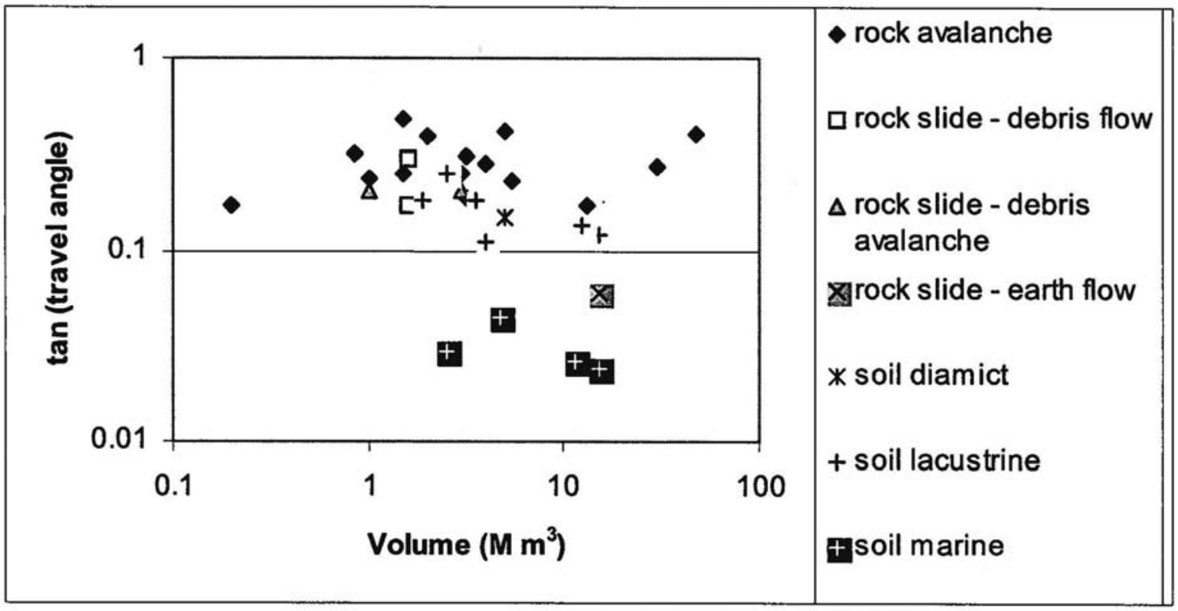

Figure 4. Volume versus tan of the travel angle for 31 Canadian Cordilleran landslides in various materials (Geertsema and Cruden, 2008).

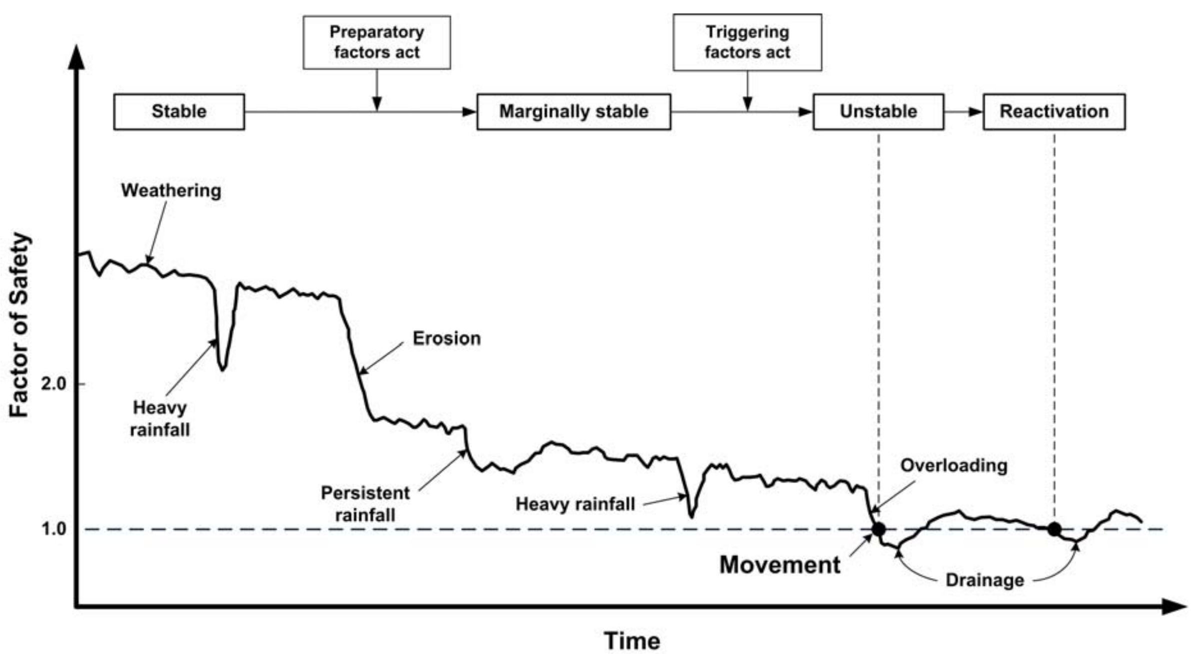

Figure 5. An example of changes in FS with time, indicating some causal factors.

A particular cause can be either preparatory or triggering, or both in sequence. It can act over a long period of time, for example, gradually eroding the toe of a slope, or over a short period of time, for example, rapid drawdown after a flood. WP/WLI (1994) included a checklist of landslide causes. This list, with modifications that focus on Canada, is presented as Table 9. The causes are divided into ground conditions, geomorphological processes, physical processes and artificial processes, as discussed elsewhere. The causes assume that a slope is pre-disposed to a landslide, typically by its gradient and/or by the existence of groundwater. Seldom can a landslide be attributed to a single cause.

Table 9. Checklist of landslide causes (modified from WP/WLI, 1994).

Ground Conditions	
Weak materials	Adversely-oriented, mass discontinuity
Sensitive materials	Adversely-oriented, structural discontinuity
Weathered materials	Contrast in permeability
Sheared materials	Contrast in stiffness
Jointed or fissured materials	
Geomorphological Processes	
Tectonic uplift	Erosion of the lateral margins
Glacial rebound	Subterranean erosion (solution, piping)
Fluvial erosion of the slope toe	Deposition loading the slope or its crest
Wave erosion of the slope toe	Vegetation removal (by forest fire, drought)
Glacial erosion of the slope toe	
Physical Processes	
Intense rainfall	Ice damming
Rapid snow melt	Thawing
Prolonged exceptional precipitation	Freeze and thaw weathering
Rapid drawdown (of floods and tides)	Shrink and swell weathering
Earthquake	
Artificial Processes	
Excavation of the slope or its toe	Mining
Loading of the slope or its crest	Artificial vibration
Drawdown (of reservoirs)	Water leakage from utilities
Deforestation	Defective surface drainage
Irrigation	Dumping of loose materials

Ground conditions are the setting on which a process (or processes) act to prepare or trigger a landslide. They include the surface and subsurface characteristics and fabric of the rock or soil, and therefore require both surface and subsurface investigations of a slope to be determined.

Geomorphological processes change the morphology of the ground and can often be documented by geological and topographic maps, airphotos and remote sensing images, repeat ground surveys or simply by observations by the local population.

Physical processes change the physical environment of slope and can be documented by site, local or regional instrumentation such as piezometers, extensometers, snow, snow-melt and rain gauges and seismographs.

Artificial processes are the human modifications that a slope undergoes and can be documented by maps, airphotos, construction and excavation records, historical photos and records. Identification of artificially-induced landslides is useful for administrative purposes and in risk analyses.

6. INDIRECT EFFECTS

The physical effects of a rapid landslide are not confined to the direct effects of the displaced material along its surface of separation. Indirect effects can extend kilometres beyond the toe of a landslide's deposits. The two most common indirect effects are landslide dams and landslide-generated waves.

6.1. Landslide Dams

Landslides dams are formed by landslides whose displaced material moves sufficiently rapidly and with sufficient volume to block watercourses. Costa and Schuster (1988, page 1055) suggested *landslide dams form most frequently where narrow, steep valleys are bordered by high, rugged mountains*. In Canada approximately 30 landslide dams have been identified in the Cordillera and Peace River Lowlands by Cruden et al. (1993), Clague and Evans (1994), Cruden et al. (1997), Lu et al. (1998), Geertsema and Clague (2006), Miller and Cruden (2008), and Kim et al. (2010). Evans and Brooks (1994) have identified several landslides dams in the St. Lawrence Lowlands in Quebec and Ontario, therefore, mountain topography is not always required. All kinematic modes of movement are represented by Canadian landslide dams.

Smaller dams in larger rivers are typically overtopped within a few hours or days. The downstream slope of the dam is eroded rapidly if the soil is fine-grained and loose. Catastrophic breaching of landslide dams is typically restricted to steep higher dams. Typically erosion rapidly re-establishes the former longitudinal profile of the river. Smaller rivers can require several years or even decades to erode displaced material of the damming landslide. In other cases, the dam remains permanent.

Costa and Schuster (1988) suggested a six-fold descriptive classification of landslide dams assuming that the displaced materials enter the valley floor and watercourse at right angles. Table 10 summarizes those classes and provides some Canadian examples.

There are also Canadian examples of landslides in which the displaced material entered into the valley floor in a direction sub-parallel to the flow of the watercourse, for example Gold Creek at the Frank Slide (McConnell and Brock, 1904) and John-John Creek at the Brazeau Lake Slide (Cruden, 1982). In such cases, water storage was small and rapidly circumvented the displaced material to create a new channel adjacent to the depositional edge of the landslide.

Table 10. Classification of landslide dams (adapted from Costa and Schuster, 1988) and some Canadian examples.

Class of dam	Description of Formation	Canadian Examples
partial	single lobe of displaced material does not extend to the opposite side of the valley floor	Drynoch, BC (VanDine, 1980)
complete	single lobe of displaced material spans the valley floor	Notre-Dame-de-la-Salette (Ells, 1908) ; Attachie Slide, BC (Evans et al., 1996); St-Jude, QU (Locat et al., 2012)
divergent	single lobe of displaced material fills the valley floor from side to side and diverges for considerable distances upstream and downstream	Meager Creek, BC (Guthrie et al. 2012; Frank Slide, AB (McConnell and Brock, 1904)
convergent	contemporaneous displaced material from landslides from both sides of the valley meet, or whose lateral margins are juxtaposed, on the valley floor.	Hines Creek, AB (Miller and Cruden, 2008)
multi-lobed	multiple lobes of displaced material of the same landslide extend partially or completely across the same valley floor.	Spirit River, AB (Miller and Cruden, 2008)
uplifted	formed by a landslide rupture surface that extends under the valley floor and uplifts the valley bottom.	Eureka, Montagneuse and Saddle Rivers, AB (Miller and Cruden, 2008)

6.2. Landslide-generated Waves

Landslide-generated waves can result from both subaerial and subaqueous landslides. When a landslide enters a body of water, waves radiate out from the area of the displaced material and can, not only affect dams, docks and other facilities on the body of water, but can affect road, bridges and land adjacent to the body of water. Such effects can be felt over distances many times the dimensions of the displaced material. The volume of the displaced material and its velocity on entering the body of water are the prime factors that determine the energy involved and the size and propagation of the waves that are generated. Other factors include the shape of the displaced material and its density and porosity. The displaced material is most simply modeled as a single, solid, rigid body sliding into the water at right angles to the shoreline (Panizzo et al., 2005).

Two western Canadian examples are 1) the wave that occurred at Knight Inlet, BC where approximately 500 years ago a large rock fall into the inlet generated a wave that may have engulfed up to a hundred people in the Kwalate Village site several kilometres away (Bornhold et al., 2007), and 2) the 2007 Chehalis Lake rock slide in southwestern BC that triggered a 38 m displacement wave (Brideau et al., 2012).

In eastern Canada, a landslide opposite Notre-Dame-de-la-Salette, QU, in 1908, displaced the ice cover of Lievre River. Thirty-three lives were lost from the resulting wave and many of the wooden buildings in the village were destroyed by the impact of blocks of ice carried by the displacement wave.

Subaqueous landslides can also cause waves that result in tsunamis (Clague, 2001). When rivers enter bodies of water, some of the river-transported sediment forms deltas and fans deposits, which are, because of the nature of their mode of deposition, marginally stable. Movement of such submerged, saturated sediment can be triggered by a number of causes including earthquakes (for example, the 1929 Grand Banks, NL event (Clague, 2001)), extreme tidal drawdown (for example, Kitimat, BC (Murty, 1979)) and/or by construction activities (for example Skagway, Alaska (Cornforth and Lowell, 1996)). The displaced material typically liquefies and can travel long distances as a flow, displacing the water and resulting in a tsunami.

Such waves are not hazardous in open water, however, as they approach a shoreline their amplitude increases. Wave run-up depends, among other factors, on off-shore bathymetry, orientation of the shoreline to the incident wave and shore topography. Wave run-up is typically small on steep, straight shorelines but is enhanced by shallow, broad bays and inlets (Clague, 2001).

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