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

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

SITE INVESTIGATION, ANALYSIS, MONITORING AND TREATMENT

Note to Reader

This is the final publication in a series of Geological Survey of Canada Open Files that have appeared during the past several 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 peter.bobrowsky@canada.ca.

1.0 INTRODUCTION

The purpose of this contribution is to present a "what to do" and not "how to do" discussion regarding the investigation, analysis, monitoring and treatment of landslides. It presents, in general terms, what to consider when planning and carrying out site investigations, when selecting appropriate methods to analyze slopes for stability, when designing and implementing a monitoring program, and when planning and designing the treatment of an existing or potential landslide (see also Highland and Bobrowsky, 2008). The Open File reviews the fundamentals of such topics, but only provides broad details of methods and techniques, their appropriate use and limitations in summary tables with appropriate references. The methods and techniques associated with all the topics in this contribution are developing rapidly, and landslide professionals should keep themselves current through continuing professional development. It is not the intent of this chapter to reproduce the details of the methods and techniques that make up the topics of investigation, analysis, monitoring and treatment. Terminology follows Bobrowsky and Couture (2014) for all contributions in this series.

2.0 PRE-PLANNING

The following sections will more fully develop site investigation, analysis, monitoring and treatment related to landslides and potential landslides, however, some initial work is routinely required before a site investigation is launched including the subsequent tasks of analysis, monitoring and/or treatment begin.

As discussed in VanDine (2012), the initial step of the risk management process follows the recognition that a landslide has occurred, or could occur, and that human health and safety, aspects of the environment and/or financial interests have been, or could be, affected. During this step, possible landslide risk scenarios and stakeholders should be identified. (Stakeholders are persons and organizations, including government agencies that can affect, be affected by, or perceive themselves to be affected by the landslide, or by associated decisions or activities.) In addition, early in the process the scope, goals and potential methods of managing the landslide risks should be established by the landslide professional.

Elsewhere VanDine (2011) reviews the aspects that landslide professionals should minimally undertake prior to a landslide study.

In an emergency response situation, some of the prerequisites proposed by VanDine are not practical or cannot be achieved in a timely manner. In such situations, a landslide professional and their client should at least have an agreement as to the objectives and the deliverables of the landslide study.

The level of effort of a landslide study can range from overview to detailed, and should be determined, relative to the project objectives and intended use of the results, study area, complexity of the terrain, elements at risk, and available background information. Because of the unknowns involved, it is often useful to use a phased study approach trending from overview to more detailed.

The study area should be determined by the type of landslide, the geological and geotechnical complexity of the terrain involved, and the elements at risk. It should not be limited to a lot, property or political boundary, but should include other areas that could potentially affect, or be affected by, landslide. Some types of landslides can travel long distances, and therefore, where appropriate, the study area should include sources areas, travel paths and depositional areas.

3.0 SITE INVESTIGATIONS

3.1. Background

Prior to any site investigation, the landslide professional should collect, possibly with the help of stakeholders, available existing information associated with the study area. During the initial phase of work landslide risk scenarios should be identified alongside the time frame in which the work should be conducted. The landslide professional should consider the following items and their respective levels of reliability, as possible sources of existing information (cf. Jackson et al., 2012):

- large and small scale topographic and cadastral maps;
- airphotos of different years (historical to present) and scales;
- bedrock, geomorphology and surficial geology;
- terrain maps, terrain stability maps, landslide inventories, landslide hazard maps and reports;
- seismic data, where appropriate, including: seismic hazard maps and reports; ground motion data, seismic Site Class, and modal magnitude values of the design earthquake;
- water well, borehole and other subsurface drill records and hydrogeology reports;
- flood plain mapping and alluvial fan mapping;
- maps that show existing and proposed development, infrastructure such as transportation routes, utilities, surface drainage, in-ground disposal of storm water, and in-ground disposal of waste water and/or sewage;

- in areas of natural resource activity, such as forestry, mining, oil and gas, and hydro development: resource inventory maps and reports, resource development plans, watershed and terrain stability assessments, past and proposed resource road construction and other activities, and other relevant resource activity information;
- urban, planning and other anthropogenic activity reports;
- evidence and history of wildfires and other changed conditions in the area, and;
- previous geological, geotechnical and landslide reports that address the study area and, if available, neighbouring areas.

Information can be obtained from published and non-published sources through various federal and provincial agencies, local governments and other sources. For larger areas, obtaining project-specific information, in addition to existing background information may be useful. Examples include airphotos, high-resolution satellite imagery, and LiDAR (Light Detection and Ranging) images that may be used for geological and geomorphological mapping and/or topographical mapping.

Background information should be reviewed prior to undertaking subsequent phases of the site investigation, analysis, monitoring and treatment. If information is known to be available and the landslide professional did not or was not able to obtain it, this fact should be noted (Gerath et al., 2010).

3.2. Data Information Management

Organized data management – the collection, storage, analysis and presentation of data – is important in geosciences due to the extensive use of geospatial data. Landslide investigations typically necessitate data structures that are three-dimensional. Some investigation types, such as monitoring or multi-temporal inventories, also require data to be structured temporally. With the advent and development of the field of geomatics, data management has become increasingly important.

New and emerging technologies, particularly remote sensing techniques, expand opportunities to characterize landslides and increase the accuracy and precision of individual datasets (cf. Petley, 2012; van Westen et al., 2008; Delacourt et al., 2007). Consequently, data volume and computational need also increase. Data management has thus changed dramatically over recent decades, with growing emphasis on geographic information systems (GIS). This section summarizes relevant low-cost datasets available for Canada and provides guidance to ease the combination, analysis and presentation of datasets typical in landslide investigations though planning of data management.

3.2.1. Compile and collect

Various considerations are necessary during capture of data to facilitate their subsequent integration into geospatial databases. An overview of important considerations for compilation of existing datasets, and collection of new datasets is given here. Figure 1 provides access sources and general details for basic datasets, of regional or greater extent, that are useful in landslide investigations in Canada.

Several options exist for most data types; datasets that are selected for compilation and collection will be a function of budget, temporal and spatial data availability, and investigation objectives. Identification and, when necessary, compilation of previously collected datasets should be undertaken early in the investigation. Knowledge and use of these reduces time and resources needs by preventing duplication of datasets as well as by providing a basis for preliminary analysis and guidance for further data collection.

3.2.1.1. Information datasets

Topography and geology datasets are derived from pre-existing sources. For many parts of Canada they are now available in digital georeferenced forms from federal and provincial sources.

3.2.1.1.1 Topographic datasets

Pre-existing topographic datasets are produced from remotely sensed datasets and, therefore, suffer from issues inherent in the imagery from which they were derived. Government-issued topographic datasets are widely available at small scales (~1:125,000) to large scales (~1:5,000), although larger scale datasets are typically not free. All are arranged by tiles and are available for download. Provincial and territorial datasets typically have greater detail compared to regionally extensive topographic datasets.

Canadian Digital Elevation Database (CDED) DEMs are compiled from hypsographic and hydrographic elements of the NTDB (Centre for Topographic Information, 2000), which are in turn based on stereo aerial photographs. These are available as 1:50,000 and 1:250,000 NTS tiles. Contour lines are included in the NTDB, but they are often misaligned between tiles given different contour intervals or, in the case of some older map sheets, use of imperial elevation units.

Most DEMs are provided in geographic coordinate systems. They must, therefore, be converted to a metric-based projection before slope angle and hill shade tools in GIS packages can be used to produce properly scaled results.

Digital elevation models express surfaces as regularly spaced grids. Consequently, they are poor at representing abrupt topographic changes that are muted due to the averaging effect between cells. The use of a higher spatial resolution DEM, even of lower accuracy, can reduce this effect (Environment Yukon, 2012). Alternatively, the surface model can be converted to a triangular irregular network (TIN) (Peucker et al., 1978) with use of break lines.

3.2.1.2. Geologic datasets

Digital bedrock geology is available for most regions from provincial or territorial governments. Specialized reports produced by Natural Resources Canada (NRCan) and provincial ministries, as well as by some consultants, provide additional details on the geology of select areas.

Where local-scale maps exist in non-geospatial forms, they can be scanned and georeferenced for use as images. Alternatively, they can be digitized for use as vector data, which increases their utility in analysis; although labour intensive. Some Geological Survey of Canada (GSC) Open File reports provide digitized versions of past studies (e.g. Dunn and Ricketts, 1994).

3.2.2. Remote datasets

3.2.2.1. Aerial photography

Despite the advent of sub-metre-resolution optical satellite sensors during the past decade, conventional aerial photography remains the highest image resolution option and is an excellent source of historic information. The majority of aerial photographs available for Canada are from federal and provincial acquisitions. Typical scales are 1:15,000 (low altitude), 1:40,000 (moderate-altitude) and 1:60,000 (high-altitude). Aerial photograph availability is greatest for developed areas, where the earliest photography dates from the 1920s and with frequent subsequent acquisition. Surveys for most non-developed areas range in frequency from half a decade to several decades. Additionally, special surveys typically providing low-altitude flights for specific areas of interest (e.g. resource management or engineering projects) are sometimes available.

Some Canadian aerial photograph sources are transitioning to digital query and delivery. Federal aerial photographs can be acquired through the National Air Photo Library (NAPL). Provincial ministries are typically the best source for provincial aerial photographs. Acquisition of new federal or provincial aerial photography is limited.

Spatial distortions in aerial photographs are of two types: radial displacement, which increases systematically away from the nadir location, and terrain displacement, which is irregular. The distortions result in a variable scale over a single photograph that prevents its spatially accurate inclusion in a GIS. Orthophotographs, which produce orthographic view though removal of radial and terrain displacement effects, are available for many regions of Canada. They are suitable for display and analysis in a GIS, but lack stereo capability, which is of great importance for landslide investigations.

Two options exist for transfer interpretations from aerial photographs into a GIS. Interpretations made from hard-copy photographs can be subsequently digitized in a GIS, using a georectified reference based layer (e.g. orhthophotography, digital satellite image, or large-scale topographic map). Alternatively, specialized software packages now allow simultaneous soft-copy stereo-interpretation and direct digitizing of features of interest into a GIS. These require ground control points and details of the camera used.

3.2.2.2. Space-borne optical imagery

Since the 1970s a wide variety of space-borne optical imaging systems have been developed, with image resolution and temporal coverage increasing over time. The Landsat satellite series provides the longest record starting in 1972. Landsat imagery is useful for moderate-resolution needs, particularly where multispectral processing is required. Freely available orthorectified scenes for all parts of the globe are available for download.

Higher spatial-resolution satellites typically offer only a few multispectral bands. Relative to Landsat-7, ASTER offers improved (15-m) resolution in three spectral bands. Scenes are available since 2000 for a nominal cost. The Système Pour l'Observation de la Terre (SPOT) satellite series provides moderate-resolution to high-resolution imagery from 1986 onward; panchromatic resolutions ranging from 2.5 m to 10 m and multispectral resolutions ranging from 10 m to 20 m. SPOT 4 and SPOT 5 are currently operational, SPOT 6 (launched 9 September 2012) provides 1.5 m panchromatic and 8 m multispectral imagery.

The RapidEye constellation consists of five satellites offering 5 m resolution multispectral imagery with a 24-hour revisit period, designed for rapid disaster response (RapidEye, 2012). A growing number of very high-resolution commercial satellites offer high-cost sub-metre imagery. Current systems include Ikonos, GeoEye-1, Quickbird, Worldview-1 and Worldview-2.

Prior to ordering, the level of processing and type of optical satellite data must be selected. Three levels or processing are typically available: images corrected only for geometric and radiometric distortions of the sensor; georectified images; and orthorectivited images. To reduce cost, it is possible to purchase pan-sharpened multispectral imagery, which combines the spatial resolution of a panchromatic band with multispectral data (Lillesand et al., 2008). However, doing so greatly limits multispectral processing options.

Imagery can be queried and ordered form the satellite operator’s website as well as numerous contractors’ websites. Many full scene images can also be viewed in Google Earth, allowing free and immediate interpretation of many landslide features, but without the benefits of image analysis techniques.

Most high-resolution and very high-resolution satellites can also be tasked to acquire imagery of specific areas within specific date windows, offering high flexibility in data capture.

3.2.2.3. RADAR

Orbital RADAR sensors are fundamentally different from optical sensors. They are not limited by time of day or cloud cover due to their active nature and their use of microwaves, respectively. RADAR images represent surface texture, structural features and ground moisture. Thus, RADAR is suitable for detection of recent landslides, landslide-dammed lakes, as well as geologic and hydrologic conditions that may be related to landslide occurrence.

Additional applications relevant to landslide investigation are provided by RADAR interferometry (InSAR), which determines the non-random phase difference between RADAR scenes and displays the differences as an interferogram (Massonnet and Feigl, 1998). Site-specific DEMs can be generated with repeat-pass InSAR (Massonnet and Feigl, 1998). Differential InSAR, which uses either a synthetically generated DEM or, more often, additional RADAR scenes to isolate phase differences due to ground motion (Massonnet and Feigle, 1998), is commonly used in displacement detection of slow-moving landslides.

Factors affecting RADAR imagery are especially problematic in mountainous terrain. Foreshortening causes geometric compression of data whereas layover and shadow cause complete loss of data (Lillesand et al., 2008). Severity of these factors increases with terrain steepness, requiring incidence angles to be carefully chosen. Artifacts problematic in InSAR can result from vertical atmosphere stratification in areas of high topographic variability (Hanssen, 2001). Most RADAR sensors offer a range of beam modes with a trade-off between resolution and scene footprint.

3.2.2.4. LiDAR

Data from LiDAR surveys are useful in many aspects of detailed landslide site investigations, including generation of DEMs or TINS as well as mapping of geomorphic and structural features. As data collection increases, repositories of LiDAR in Canada will expand, similar to those already available in the United States (e.g. Puget Sound LiDAR Consortium, National Oceanic and Atmospheric Administration's [NOAA] coastal LiDAR collection).

Appropriate filtering is necessary to remove non-ground laser pulse returns from 3D point clouds. The resulting bare-earth LiDAR surfaces, represented by the last laser pulse returns, are typically of greatest use in landslide investigations. However, in areas of very dense vegetation, laser pulse may not reach the ground surface, resulting in vegetation-related artifacts in the bare-earth surface (e.g. Zhang et al., 2003).

3.2.2.5. Field methods

The various types of field data generated during an investigation may be integrated by manual or automated means with remotely sensed and archival geospatial data.

In the case of field traverses or geophysical surveys, GPS tracking of data collection is advisable. Data and interpretations can be coded to appropriate locations using attribute tables in a GIS, whereas photographs or other images can be hyperlinked. Data recorded by permanent or semi-permanent instrumentation can be recorded and transferred intermittently to a GIS or, if communications options are available, transferred in real time. Products of terrestrial remote sensing techniques can be merged into a GIS by converting data into an appropriate map projection.

3.2.3. Store and analyze

3.2.3.1. Geospatial databases and Geographic Information Systems

Geospatial databases are structured sets of data with referenced locations on (or near) the Earth's surface. They are optimized for organization and integration of datasets from different sources, as well as storage and structuring of datasets in a standardized way to ease sharing by users. Geographic Information Systems simply combine a geospatial database with tools to conduct analyses and produce new data and information. Consequently, GIS has become the standard tool for data management in the geosciences.

Regardless of the software package or packages used, two simple steps will avoid some problems commonly encountered with GIS. Use of the same projection for all datasets will mitigate misalignment issues. Doing so will likely require conversion or even definition of projections for some datasets. Once aligned, all datasets can easily be re-displayed within a GIS using other projections. Selection of a projection depends on spatial scale, location, and shape of the area considered. Site-scale projects commonly use the appropriate grid zone of Universal Transverse Mercator projection, whereas national-scale projects commonly use Lambert conformal conic. Projections used for regional-scale and provincial-scale projects are varied.

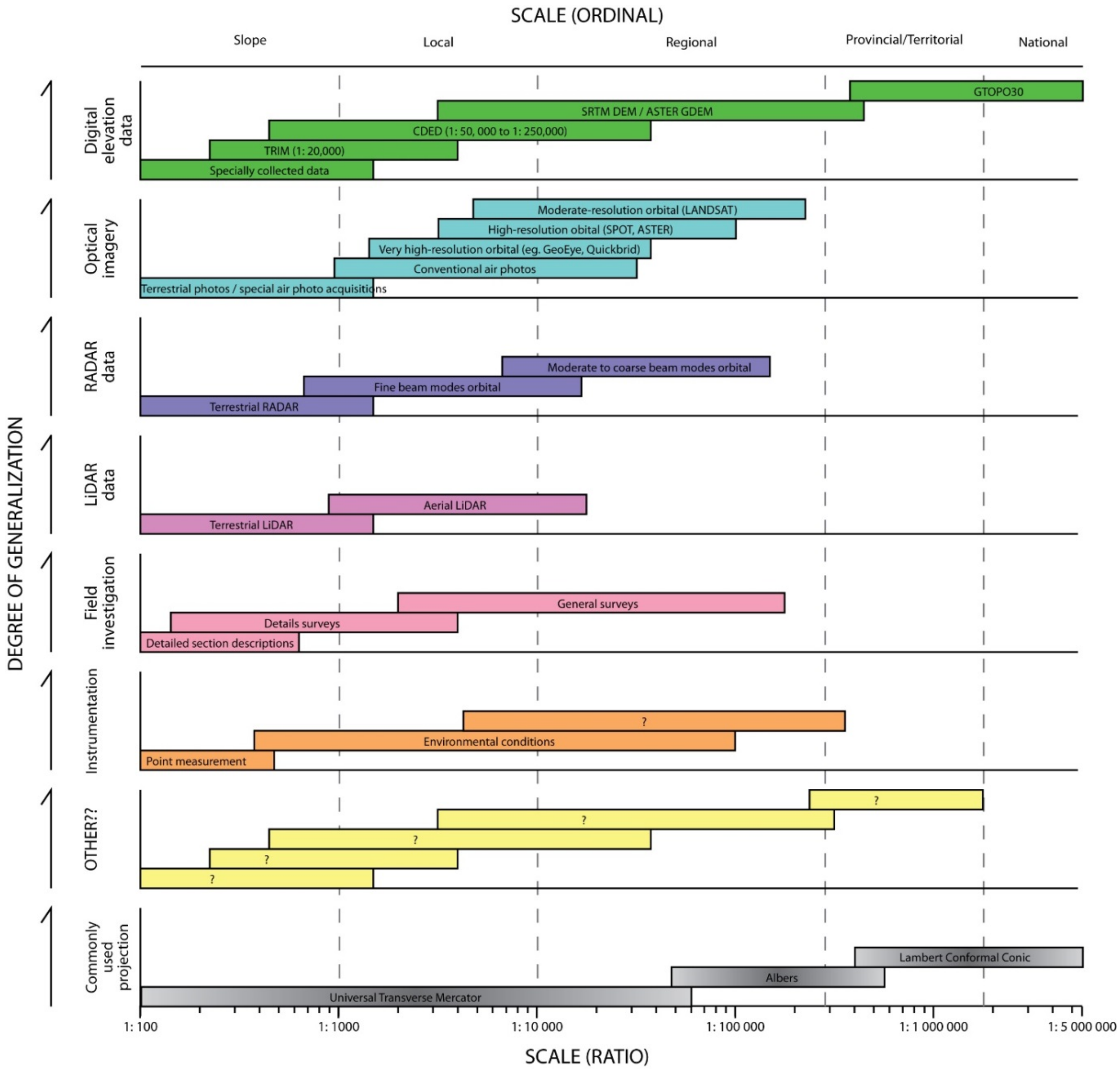

Figure 1. Geospatial datasets with respect to various scales of data available and their typical use.

3.3. Site investigation techniques

Subsurface intrusive sampling and testing techniques help geoscientists and engineers assess the nature and extent of stratigraphy and mechanical properties of the various units of soil and rock present below surface (Jackson et al., 2012; Johnson and DeGraff, 1988). These, along with surface mapping and geophysical studies, are the critical building blocks for a good geological model to be used in subsequent slope stability analyses and the design of remediation structures. Supplementary information about the sampling and testing techniques discussed here (see Table 1) can be found in most landslide investigation and engineering geology textbooks (e.g. McGuffey et al., 1996; Wyllie and Mah, 2004; Cornforth, 2005; Hunt, 2007; Gonzalez de Vallego and Ferrer, 2011). Since subsurface intrusive methods sample a small volume of soil or rock, they are often used in conjunction with surface geophysical techniques to extend their applicable range (Bichler et al., 2004).

Table 1. Example of site investigation techniques.

Method	Application
Surface	
Aerial extent of landslide	Define the spatial extents, area and volume of the landslide region
Characterize elements at risk	Identify and categorize the elements at risk and their spatial relationship with the landslide
Structural characterization	Map the structural condition of the landslide to understand the failure mechanism and movement history
Soil sampling	Identify different material present and potential for different failure mechanisms
Shear surfaces	Identify failure surfaces and movement history
Subsurface	
Borehole logging	Collect intact soil and rock samples
Borehole televiewer	Image walls of boreholes to map discontinuity orientations and conditions
Packer test	Measure water quality and hydraulic conductivity
Geophysical methods	Measure subsurface conditions, features, and material types
Trenching	Map material type, thickness and lateral extent. Retrieve samples for testing
Penetration testing	Map stratigraphy and mechanical properties of material terrestrial and submarine environments
Shear vein testing	Measure the torsional force required to shear a cylindrical volume of soil
Groundwater	
Ground water level	
Slope of ground water table	
Hydraulic gradient	
Pore pressure	
Groundwater flow	
Lab testing	
Unconfined Compressive Strength	Measure the uniaxial strength of a rock or soil material
Direct shear test	Measure the shear strength of a rock or soil material
Liquid limit	Measure the water content when the behaviour of a clayey soil changes to liquid from plastic.
Water density	

3.3.1. Sampling

3.3.1.1. Boreholes

Borehole investigations cover a wide range of different techniques to excavate a small (typically a few centimetres) diameter cylindrical hole in soil or rock masses. The specific method used depends on the expected material type, need for intact sample, depth of investigation, and topography at the site of interest. Auger drilling is a low cost, portable and rapid method for soil investigation that consists of driving a helical screw into the ground by hand or motorized equipment. BGC Engineering Inc. (2005) used a hand auger to assess the location and depth of each layer of surficial material for a landslide risk assessment along the Berkeley escarpment, Vancouver, B.C. Diamond drilling is a popular technique used to investigate soil and rock masses as is it collects continuous samples and typically has high recovery rate. A motor powers a rotating diamond tip bit which is attached to hollow drilling rods that collect undisturbed samples. Details about this and other drilling techniques and geotechnical core logging can be found in various textbooks (e.g. Wyllie and Mah, 2004; Hunt, 2007).

Downhole optical and acoustic televiewers are tools that image the wall of a borehole and allow information about discontinuity orientations to be acquired. This approach was used at Turtle Mountain, Alberta by Spratt and Lamb (2005) to obtain discontinuity orientations and image dissolution cavities. Various downhole geophysical techniques (natural gamma, magnetic susceptibility, electrical conductivity, temperature, and seismic) can be used to better define the physical properties of the various lithological units identified (for more details see Sassa, 2006 and Dunnicliffe, 1993). Borehole geophysical techniques were used by Aylsworth and Hunter (2003) in the Ottawa Valley Landslide Project to provide information about critical parameters related to regional slope stability conditions.

3.3.1.2. Trenches

Trenches are mechanical (e.g. back hoe) or manual (e.g. spade) trial excavations. They are quick and inexpensive methods to investigate surficial material allowing for the composition, thickness and lateral extent (limited, but better than for boreholes) to be described and the material to be tested and sampled. For a safe site investigation, care must be taken for proper support of the trench wall. Prior to excavation, provincial or territorial occupational health and safety (OHS) regulations and standards should be consulted and followed. Trenches have been excavated across antislope scarps at Mount Curie and Handcarp Peak Curie to investigate the stratigraphy of the sediment filling the features and infer the history of movement (Thompson et al., 1997; Hensold, 2011).

3.3.2. Testing

3.3.2.1. Penetration tests

Penetration tests measure the soil resistance to the drive of a standard size sampler or probe. The two most popular of these tests are the standard penetration test (SPT) and the cone penetrometer test (CPT). The SPT test consists of counting the number of blows per 15 cm advance of a split-spoon sampler whereas the CPT test measures the tip resistance and sleeve friction of a probe as it is pushed continuously into the ground. The penetration tests (SPT and CPT) have been used to provide information about stratigraphy and mechanical properties of the material in the subsurface at various terrestrial (e.g. Mahmoud et al., 2000) and submarine (e.g. Mosher et al., 2004) landslides in Canada. Standard procedures have been proposed for these in-situ penetration tests (e.g. ASTM, 2005; 2007; 2008a; 2011). The guideline that is followed should be specified when reporting test results.

3.3.2.2. Shear vanes

The shear vane test consists of inserting a four-bladed vane into an undisturbed clay-rich soil horizon and measuring the torsional force required to shear a cylindrical volume of soil. The maximum torsional force applied during the test can be related to the undrained shear strength of the soil. The testing procedure and correlations are presented in ASTM (2008b). Shear vane tests have been used to assess the strength of sensitive glaciomarine clays from the Ottawa-region (Crawford and Eden, 1967) and from central British Columbia (Geertsema and Torrance, 2005).

4.0 SLOPE ANALYSIS

4.1. Introduction

A slope analysis is usually carried out after a site investigation has been completed. It can be carried out either as a result of a landslide occurring, or before a potential landslide occurs. If carried out after a landslide has occurred, a slope analysis typically tries to determine the type of movement, geological conditions, geotechnical properties prior to the landslide and/or the preparatory causes and triggering factors, and/or to estimate the current stability of the slope to assist in the evaluation and design of treatment, either mitigation or remediation (see Section 6).

A slope analysis of a potential landslide is typically used to estimate how likely it is that a landslide will occur and/or where it will travel or retrogress to if it does occur; in other words, a hazard analysis. There are a number of methods to estimate the likelihood of occurrence that includes risk analysis, limit equilibrium analyses, slope displacement analysis and slope deformation analyses. Similarly there are a number of methods to estimate where a landslide will travel that include empirical analysis, analytical methods, physical models and numerical methods.

This section briefly describes a number of methods to estimate how likely it is that a landslide will occur and where it will travel or retrogress to if it does occur. The methods used depend on i) the types of movement involved or potentially involved and ii) the types of material involved.

The method of analysis and the level of effort should also be consistent with the purpose, scope and other requirements of the project and should be appropriate to size of the study area. Typically the greater the perceived hazard and risk, the greater the level of effort expended. Other factors include the relative stability; elements at risk; geological and geotechnical complexity of the terrain; availability, quality and reliability of background information and field data; and the tolerable and/or acceptable risk criteria that are available and/or are appropriate.

4.2. Methods

4.2.1. Risk Analysis

Risk analyses can be carried out for all types of landslides. In its simplest form risk (R) is the product of probability or likelihood of landslide occurrence (P) and consequence (C).

R = P x C **Equation 4-1**

In a more complex, but more realistic and practical form, risk is the product of four components as shown in Table 2.

Table 2. Four components of risk (adapted from BC MOF, 2002).

Component	Description
P(H), probability of occurrence	-probability or likelihood of a landslide occurring
P(S:H), spatial probability	-will the landslide affect a specific location?; considers where a landslide will travel or regress to
P(T:S), temporal probability	-if an element at risk is mobile, will it be at that specific location at the time of the landslide? -if an element is not mobile, it will be at that specific location at all times, therefore P(T:S) = 1
V(T:L), vulnerability	-if the element at risk is at that specific location at the time of the landslide, its vulnerability depends on the type and the character of the element; its robustness (or fragility) and its exposure to (protection from) the landslide; -if total loss of an element is assumed, V(L:T) = 1

Putting these four components together,

R = P(H) x P(S:H) x P(T:S) x V(L:T) **Equation 4-2**

If P(T:S) and V(L:T) are assumed to be 1 (refer to Table 2, above),

R = P(H) x P(S:H) **Equation 4-3**

Such assumptions must be made only after due consideration of the consequences, and when the ramifications on the specific project are considered and discussed with the stakeholders. The concept of risk analysis is developed further in Wise et al. (2004, Chapter 3), Fell et al. (2005), AGS (2007) and Porter and Morgenstern (2013).

Common methods of estimating probability (and risk) include, risk matrices (risk bins), event tree decomposition, and quantitative risk analysis (QRA). Each method has its advantages and disadvantages. These, along with references to some examples, are presented in Table 3.

Table 3. Some Methods of Risk Analysis, advantages and disadvantages and examples with references.

Method	Advantages/Disadvantages	Example
Risk Matrices (Risk Bins)	-relatively simple method of combining two components of risk; typically associated with qualitative risk analysis	Wise et al. (2004, Chapter 3)
Event Tree	-relatively simple and thorough method of decomposing the risk components; typically associated with quantitative risk analysis, but can provide a helpful framework for qualitative risk analysis, particularly for more complex projects	Wise et al. (2004, Chapter 3)
Quantitative Risk Analysis (QRA)	-relatively complex method that can be used to incorporate just some or all of the components of risk; as the name implies, this is always associated with quantitative risk analysis; can be used to develop F-M (frequency-magnitude) or F-N (frequency-number of fatality plots)	Friele and Clague, 2005; BGC Engineering Inc (2006)

From the beginning, the appropriate method of risk analysis must be selected and used. The method should be appropriate to the:

- situation and purpose of the analysis
- level of risk and the elements at risk or potentially at risk
- availability, quality and reliability of data, and
- form of the acceptable or tolerable threshold of risk.

Quantitative methods of risk analysis use numerical values, or ranges of numerical values, to express the various components of risk. Qualitative methods use terms, such as *very high*, *high*, *moderate*, *low* and *very low*, to express relative values or ranges of values. There are no standard definitions for terms that express qualitative relative values and to avoid ambiguity the terms should be defined. Some examples of qualitative terms are provided in Table 4. Other examples are presented in Appendix 10 of BC MOF (2002), Tables 2 to 7 of Chapter 3 and Appendix 5 of Wise et al. (2004) and Appendix B of AGS (2007).

Table 4. Examples of qualitative terms and quantitative values.

Example	Qualitative Term	Quantitative Value
Annual probability of a landslide occurring	Low	1:500 to 1:2500 (0.002 to 0.0004)
Probability of a landslide occurring along a forest road	Moderate	18% to 64% over the design life of the road (0.18 to 0.64)
Probability of a landslide reaching a specific location	High	75% (0.75)

With regard to accuracy, quantitative estimations may be no more accurate than qualitative estimations. The accuracy does not depend on the use of numbers, but rather it depends on whether all the components of the analysis have been appropriately considered and the availability, quality and reliability of the required data. The term semi-quantitative is sometimes used to describe a combination of quantitative and qualitative analysis methods. This term is inappropriate for use in risk studies, and when quantitative and qualitative estimations are combined, the results are more appropriately referred to as qualitative.

For natural processes that occur frequently in the same location, such as floods, snow avalanches, and some debris flows, probabilities of occurrence can be estimated by rigorous statistical analysis. For example, after measuring the annual flood stage on a river for many years, the flood stage of the 200-year flood on that river can be estimated objectively. Objective probability can also be used to estimate spatial and temporal probabilities, and vulnerability. Objective probability estimates assume that past events, and their pre-cursor conditions, are reasonable predictors of future conditions. This in itself is a subjective assumption, and therefore, no estimate is entirely objective.

Most landslides, however, rarely occur frequently at the same location and therefore it is difficult to objectively estimate probability of occurrence. Probabilities of occurrence of landslides are often estimated subjectively. Subjective probability is a measure of one's belief that a landslide will occur. It is based on empirical evidence combined with professional judgment. Subjective probability estimates are no less valid than objective probability estimates, provided the scientific basis for the former are well explained. Subjective probability can also be used to estimate spatial and temporal probabilities, and vulnerability.

Generally, the more knowledgeable and experienced the landslide professional, the more reliable are their subjective professional judgments. With respect to the probability of occurrence, for example, knowledge and experience include:

- landslide-specific surface and subsurface observations, field and laboratory testing results and instrumentation/monitoring results
- reliability and applicability of landslide models
- results of any other methods of slope analysis (e.g. factor of safety, slope deformation, modelling),
- published case histories, and
- general and local personal experience.

Objective probabilities are usually expressed quantitatively. Subjective probabilities can be expressed either quantitatively or qualitatively. As with objective probability, subjective probability should consider a specified time period, for example, a year or the design life of the element at risk, and the likely site and weather conditions over that period. Because no landslide professional has complete knowledge or perfect judgment, all subjective probabilities contain some uncertainty, and typically lie between 1 and 0.

Vick (2002) is a good reference on the topic of subjective probability and engineering judgment, and includes some techniques of estimating subjective probabilities and some tips for assigning both quantitative and qualitative subjective probabilities for landslide risk analyses. These are also summarized in Wise et al. (2004; Chapter 3).

4.2.2. Limit Equilibrium Analysis

Limit equilibrium analysis involves estimating a factor of safety (FS) for a specific rupture surface. A FS is the ratio of forces on a slope that resist movement (resisting forces) to those that promote downslope movement (driving forces). Examples of resisting forces include friction and cohesion. Examples of driving forces include static forces, for example gravity, and dynamic forces, for example earthquake loading.

FS = resisting forces/driving forces **Equation 4-4**

Limit equilibrium methods tend to be most suited to slide modes of movement that typically occur on planar or curvilinear rupture surfaces or on relatively thin zones of intense shear strain. When circular slope movements are involved, the potentially unstable mass can be analysed by dividing it into slices with an assumed linear base. The forces and moments acting on each slice can be calculated and summed to calculate the factor of safety for the entire rupture surface.

The stability of a slope depends on the specific rupture surface that has the lowest FS, known as the critical rupture surface. When the FS > 1, the slope is considered stable; when FS is < 1, the slope is considered unstable; when the FS = 1 the slope is considered to be in equilibrium. Although seeming relatively simple, limit equilibrium analyses require considerable experience and judgment to select representative and appropriate sub-type of movement (planar, circular rotational, and non-circular rotational), geological conditions (stratigraphy, structural discontinuities and groundwater conditions) and geotechnical properties (strength parameters of the rock or soil and their variability over the slope). Discussions on the applications, limitations and assumptions of numerous limit equilibrium methods are found in a number of publications such as Fredlund and Krahn (1977), Duncan (1996), Hungr (1997), and Krahn (2003).

Although limit equilibrium methods are typically used for circular sliding types of movements, in some instances, they can also be applied to the stability of soil and rock masses controlled by one or several discontinuities, for example joints, faults, and clay seams. In the simplest case, the limit equilibrium analysis of planar sliding consists of calculating the shear strength along one sliding surface incorporating the influence of pore water pressure and tension cracks, as appropriate (Wyllie and Mah, 2004). The general analytical solution for the stability of a wedge formed by the intersection of two discontinuities, a tension crack and sloping surfaces is summarised in Wyllie and Mah (2004). Similar methods have also been proposed for toppling (cf. Goodman and Bray, 1976) and for more complex types of movement such as bi-planar, ploughing, and buckling (Cavers, 1981; Hawley et al., 1986; Alejano et al., 2011).

Some of the common, simpler limit equilibrium methods, that satisfy force or moment equilibrium, include Bishop (1955) and Janbu (1973) whereas more rigorous methods, that satisfy both force and moment equilibrium, include Morgenstern and Price (1965), Spencer (1967) and Sarma (1973). Several methods extend the analysis from two-dimensional to three-dimensional, for example Baligh and Azzouz (1975), Chen and Chameau (1982), Hungr (1987, 1994), Hungr et al. (1989), and Hungr and Amann (2011). Recent efforts have been made to integrate limit equilibrium methods into Geographic Information System (GIS) environments, for example Reid and Brien (2006) and Grenon and Hadjigeorgiou (2010).

4.2.3. Numerical Modelling of Landslides

The application of numerical models to landslide investigations has increased considerably in the last 10 years (Stead et al., 2006; Stead and Coggan, 2012). It is important that such numerical models consider:

- boundary conditions of the slope to be simulated (2-D or 3-D)
- influence of structural geology on failure mechanism
- material property and groundwater assumptions
- *in-situ* stresses and landform evolution, and
- parameter and model uncertainty.

4.2.3.1 Continuum Methods

The two principal methods of numerical modelling are the Finite Element Method (FEM) and the Finite Difference Method (FDM). These methods are described by Jing and Hudson (2002) and Itasca (2011). Both methods are well suited for landslide investigations in both soil and rock. Numerous continuum codes can be used for slope stability analysis in soils with a wide range of available constitutive models. The application of continuum codes to rock slopes, however, requires the derivation of equivalent rock mass properties that reflect the combined intact and discontinuity properties of the slope. Recent developments in continuum numerical codes provide the engineer with the ability to:

- determine the factor of safety using the shear strength reduction technique, SSR (Dawson et al., 1999; Griffiths and Lane, 1999; Diederichs et al., 2007)
- consider the influence of continuous, non-persistent and discrete fracture networks (Hammah et al., 2009a; Sainsbury et al., 2008)
- undertake probabilistic finite element analysis using the point-estimate method (Hammah et al., 2009b)
- investigate creep mechanisms in landslides (Grøneng et al., 2010; Discenza et al., 2011)
- undertake non-coupled or coupled groundwater-mechanical analysis of landslides (Guglielmi et al., 2008; Cappa et al., 2004)
- determine the importance of spatial property variation within a slope (Griffiths and Marquez, 2007; Jefferies et al., 2008)
- investigate the importance of landform evolution on landslides (Leith, 2012)
- examine the influence of earthquake loading (described in Section 4.2.4)

Three-dimensional continuum codes are increasingly being applied to landslide studies. Refer to Ambrosi and Crosta (2011), Chemenda et al. (2009) and Groneng et al. (2010) for relevant applications and case studies. Sophisticated 3-D continuum codes exist with the facility for coupled mechanical-groundwater and dynamic analyses. Three-dimensional models require significantly more data and assumptions with important implications for model and parameter uncertainty.

4.3.2.2 Discontinuum Methods

The two most common discontinuum numerical methods used in landslide simulations are the Distinct Element Method (DEM) and the Discontinuous Deformation Analysis (DDA). These methods are described by Jing and Stephansson (2007), Itasca (2011) and Khan (2010).

The DEM method differs from continuum methods in that it allows large scale displacements on multiple discontinuity orientations, in addition to deformation of joint bounded blocks. Input data required include the elastic properties (shear and bulk modulus) and strength properties (cohesion, friction angle, tensile strength and dilation) for the rock comprising the blocks. Elastic, elasto-plastic constitutive criteria are usually used for the joint-bounded blocks, however, options exists to consider directional weakness through a ubiquitous elasto-plastic model, strain softening and creep models. The constitutive criterion for the discontinuity surfaces includes Coulomb slip, continuous yielding and an optional Barton-Bandis criterion. Input properties controlling joint failure and joint displacement are the joint cohesion, friction angle and tensile strength, and the joint normal and shear stiffness. Further details on the available constitutive intact and joint constitutive criteria are presented by Itasca (2011). DEM models of slopes include non-coupled or coupled mechanical – groundwater, mechanical thermal and dynamic models. Rock slope monitoring using thermocouple and subsurface displacement instrumentation, in addition to mechanical-thermal coupled DEM models, indicates that thermally induced displacements can play a role in progressive rock slope failure (Watson et al., 2004; Gischig, 2011).

DEM models have been successfully used to simulate numerous major landslides including Randa, Switzerland (Willenberg, 2004; Gischig, 2011), Aknes, Norway, (Kveldsvik, 2008), Mt Eiger, Switzerland (Jaboyedoff et al., 2012) and Turtle Mountain, Canada (Froese et al., 2012). Shear strength reduction, SSR, methods have also been integrated within DEM methods (Diederichs et al., 2007).

Three dimensional DEM models are increasingly being used in landslide investigations, for example the Downie Slide, Canada and the Beauregard instability, Italy (Kalenchuk, 2010). This work is particularly noteworthy because the 3-D DEM models incorporate geostatistical treatment of site investigation data and model constraint through long term slope monitoring. Three-dimensional DEM models have also been used to investigate the influence of geometry and geological structure on the kinematics of landslides, with reference to conceptual studies, potential instability at Turtle Mountain, Alberta, and rock slides at Chehalis, and McCauley Creek, BC (Brideau, 2010).

DDA methods although infrequently used in landslide analysis have been applied to simulations of the 1963 Vaiont landslide, Italy (Sitar and MacLauglin, 1997) and the Aknes rock slope, Norway (Kveldsvik, 2008).

4.2.3.3 Brittle Fracture Modelling and Landslides

Brittle fracture during rock slope failures has been recognized as an important factor in landslides involving step-path failure surfaces and the failure of intact rock bridges. Methods for modelling brittle fracture include the following.

Hybrid Finite-Discrete Element Method, FDEM: This method has found increasing application in landslide analysis over the last decade (Eberhardt et al., 2004; Stead et al., 2006). These codes allow the advantages of both continuum and discontinuum codes to be maximized along with intact rock fracture. They incorporate fracture mechanics principles and allow a transition from an intact rock/rock mass to landslide debris. A major advance in FDEM models has been the incorporation of Discrete Fracture Networks using codes such as Fracman (Golder Associates, 2012) within the FDEM models.

DEM Voronoi or "damage" models (Alzo'ubi, 2009): In this method the jointed slope rock mass in a DEM model is discretized into polygons whose sides are given intact rock properties. If the shear or tensile stresses in the rock slope exceed the strength properties of the polygonal block boundaries then fractures form and propagate through the polygonal mesh potentially resulting in slope failure.

RFPA method (Tang and Hudson, 2010): This is a modification of the FEM that has been used to investigate fracturing during rock slope failure.

Particle Flow Codes, PFC2D/3D (Wang et al., 2003; Poisel and Preh, 2008a). In this method the jointed rock slope mass is formed by particles (2-D) or spheres (3-D) that are bonded together at their contacts. Joints can be included with the particle flow code model allowing both sliding/separation on planes of weakness or intact rock fracture when induced stresses exceed bond strength. PFC methods have been used to model both landslide triggering and flow.

Lattice–Spring Methods (Cundall and Damjanac, 2009): In this method, the slope rock mass is represented by nodes and springs; the nodes replacing the particles in a PFC model and the springs representing the bonds between particles. Intact rock facture in a jointed rock slope is represented by breakage of the springs. With this method, the capability for both 2-D and 3-D brittle fracture modelling exists.

4.2.4. Seismic Slope Analysis

Seismic slope stability analysis can be divided into pseudostatic limit equilibrium methods, permanent-displacement methods and stress-deformation numerical modelling (Jibson, 2012). The decision as to the appropriate method of analysis must consider whether the slope hazard is due to liquefaction, strain softening or other failure mechanisms. A staged approach can be used to determine an initial pseudostatic limit equilibrium factor of safety with a defined seismic coefficient, k. Based on the results of this analysis, methods that consider slope displacement along the slip surface, or pseudostatic limit equilibrium with slope displacement based seismic coefficients, can be used. For critical high risk slopes or landslides where considerable data have been collected, more complex analyses involving numerical stress-strain methods can be utilized. A useful flowchart for seismic slope analysis is presented in APEGBC (2010, Figure 4.1).

4.2.4.1 Pseudostatic Limit Equilibrium

Pseudostatic limit equilibrium method of analysis is the simplest and most commonly available. Earthquake loading is typically represented as a constant horizontal force, kW, acting through the centre of gravity of the potential slope failure. The term W is the weight of the soil/rock mass above the potential slip surface and k is the seismic coefficient, equal to a fraction of the Peak Ground Acceleration (PGA).

Jibson (2012) discusses the limitations of this method including the assumption of a constant one direction earthquake force, which can be both highly conservative and physically incorrect because the peak acceleration acts for only short periods and acts both upslope and downslope. The selection of the appropriate seismic coefficient, k, is also a perceived limitation; many assume a value of k = 0.15, but it should be emphasised that most published values of k are based on calibrations from very different slope environments to the landslide being considered. Refer to Jibson (2012) for further details.

Jibson (2012) also notes that in some cases, pseudostatic analysis can be non-conservative, for example where earthquakes induce high pore water pressures or materials experience a significant reduction in peak shear strength during shaking. He states that although pseudostatic limit equilibrium analysis is widely used it is being gradually replaced by permanent displacement and numerical modelling methods.

Wyllie and Mah (2004) describe the applications of pseudostatic limit equilibrium methods to seismic slope stability analysis of rock slope stability. Existing commercial codes for analyzing planar, wedge, circular and non-circular failure in slopes routinely include pseudostatic analysis (Rocscience, 2011). In addition to considering horizontal earthquake loading, facility exists to include vertical and inclined seismic loads using appropriate seismic coefficients. Jibson (2012) notes that it is usually acceptable to consider only a horizontal seismic coefficient.

4.2.3.2 Permanent Displacement Analysis

The most common slope displacement method is the Newmark rigid block analysis proposed by Newmark (1965). Recognizing that a yield acceleration exists, at which a rigid block above a potential failure surface has a factor of safety less than one and moves, allows a more realistic analysis than the pseudostatic limit equilibrium analysis. Those portions of the earthquake strong motion record where the yield acceleration is exceeded are integrated twice to determine the velocity of the rigid block and the cumulative Newmark displacement. Although individual peaks in the acceleration result in a temporary factor of safety less than one, it does not necessarily mean that global failure of the slope will occur.

Three principal types of Newmark analyses are used: the rigid block Newmark analysis; decoupled analysis and coupled analysis.

Rigid block analysis: This is the most commonly used analysis, although it suffers from the limitation that it assumes that the landslide does not deform internally.

Decoupled analysis: This analysis extends the rigid block analysis to consider internal deformation. The decoupled analysis involves a two-stage process. The first stage involves a dynamic response analysis of the slope with no assumed failure surface. An average acceleration–time history for the slope mass above the potential failure surface is developed through estimation of the acceleration–time histories at multiple points in the slope. The average acceleration has been referred to variously as *k* or HEA, the horizontal equivalent acceleration with peak values termed *k* max or MHEA, the maximum horizontal equivalent acceleration, Jibson (2012). The second stage involves inputting the derived acceleration time history into the rigid block analysis as before to find the permanent displacement. The site response analysis may be undertaken using public domain codes such as SHAKE (Schnabel et al., 1972).

A public domain Java code (Slope performance during an earthquake; http://earthquake.usgs.gov/research/software/slope_perf.php) exists for undertaking both Newmark rigid block and decoupled permanent displacement analysis (Jibson and Jibson, 2003).

Coupled analysis: In this analysis, the dynamic response and the permanent displacement analyses are fully coupled so the influence of the sliding on the ground motions is allowed.

Both decoupled and coupled analyses require determination of the shear wave velocity of the soil, the thickness of the potential landslide and the damping ratio. Jibson (2012) states that the Newmark rigid block analysis is suitable for fairly shallow earthquake landslides (which form 85% of earthquake-triggered landslides) but recommends coupled analysis for larger, deeper landslides. Further details on Newmark analyses and its variants are provided by Jibson (2012).

4.3.4.3 Stress-Strain Numerical Analysis

Continuum and discontinuum numerical stress–strain methods can be used to investigate the influence of earthquakes on slope stability and landslide failure mechanisms. Such analyses provide an improved understanding of the internal processes operative within a slope during seismicity but demand increased data quantity and quality in addition to the development of sophisticated constitutive models.

Soil Slopes: Seismic slope stability analyses of soil slopes are traditionally undertaken with equivalent linear seismic methods which are used to model wave transmission in layered media and dynamic soil-structure interaction. FDM models are increasingly used in the dynamic analysis of soils and soil slopes and are fully nonlinear methods. A comparison of the two methods is presented in Itasca (2011) and Naesgaard (2011). Important considerations in dynamic modelling of soil slopes using FDM models are the dynamic input (either acceleration, velocity, stress or force histories), boundary conditions (free field, viscous), mechanical damping and choice of constitutive model. A detailed discussion of the theory and procedure of dynamic FDM analysis is provided in Itasca (2011)

A considerable amount of experience has been gained in the use of the finite difference codes in seismic slope stability analysis. Naesgaard (2011) provides a useful summary of seismic slope stability analysis and available constitutive criteria. When considering seismic analysis of soil slopes that may be subject to liquefaction or flow, the use of a specialized constitutive criterion is required. The FDM code, FLAC (Itasca 2011) can use numerous constitutive models to consider total stresses (UBCTOT), a hysteretic model for non-liquefiable clays/silt soils (UBCHYST), and coupled effective stress analysis in sands (UBCSAND). Refer to Itasca (2011) and Naesgaard (2011) for further details of constitutive models used in dynamic modelling of soil slopes.

Rock Slopes: Both continuum and discontinuum numerical methods can be used to undertake seismic slope stability of rock slopes although it is not common due to the required input data and complexity of the rock mass structure. Dynamic analysis can be undertaken using both 2-D and 3-D continuum and discontinuum models, however 3-D dynamic analyses are typically limited to critical rock slopes with significant data, such as dam abutment slopes.

Bourdeau et al (2004) provide a typical example of the use of 2-D FDM modelling in the investigation of the factors influencing seismic amplification, an important factor in landslide triggering during earthquakes. In dynamic analyses, an input source is applied at the base of the FDM model which can be a synthetic acceleration waveform or an earthquake record. An example of the application of two-dimensional continuum seismic slope stability analysis is provided by Bozzano et al. (2011). Examples of the application of two-dimensional discontinuum seismic slope stability analysis of landslides/rock slopes have been published by Eberhardt and Stead (1998), Kveldsvik (2008), Bhasin and Kaynia (2004), Havenith et al. (2002) and Moore et al. (2011; 2012).

Important considerations in simulating the effect of earthquakes include the choice of boundary conditions (free field, viscous), damping parameters and the characteristics of the source waveform relative to the mesh size. Guidelines are presented in Itasca (2011). Moore et al. (2012) present a recent study using a DEM code to study the influence of compliant sub-vertical fractures (opened due to gravitational displacements) on spectral amplification. Their analyses focus on the Randa rock slide and the Rawilhorn rock avalanche, both in Switzerland, and show the effects of topographic amplification and a hitherto largely neglected amplification due to pre-existing damage from previous instability and seismically-induced damage.

4.2.5. Landslide Runout Analysis

When a potential landslide source has been identified, a runout analysis may be required to estimate hazard or risk downslope; to estimate input parameters, such as velocity and flow depth, for treatment; or to estimate possible secondary effects, such as landslide-generated waves or flooding caused by landslide dams.

The simplest form of runout analysis involves qualitative assessment of topography, based on experience and judgment, to estimate the potential travel direction, distance and velocity. Quantitative methods of analysis range from simple empirical-statistical relationships to complex three-dimensional numerical modelling. The method used depends largely on the type of landslide in question and the purpose and scope of the study. For overview or preliminary assessments, empirical methods are often adequate; for detailed risk assessment or treatment design, it is common to supplement empirical estimates with numerical modelling. Some of the available methods, with references to more detailed sources of information, are described below.

4.2.5.1. Empirical Methods

Topographical Analysis: The potential travel direction of a landslide can often be estimated using topographic maps. If digital topographic data are available, GIS mapping software can be useful, for example to identify topographic fall lines. Potential velocities and runout distances are more difficult to estimate qualitatively, but can be constrained by records of similar landslides in the area using professional experience and judgment.

i) Volume-fahrböschung Relationships: There is typically an inverse relationship between landslide volume and 'fahrböschung', the angle of the line connecting the crest of the landslide with the toe of the deposit, measured along the approximate centre-line of motion. Fahrböschung is also known as the angle of reach. Regression equations have been proposed by several workers (Scheidegger, 1973; Li, 1983; Nicoletti and Sorriso-Valvo, 1991; Corominas, 1996; Legros, 2002; Hunter and Fell, 2003) and typically take the following form:

$$\log_{10}\left(\frac{H}{L}\right) = -a\log_{10}V + b$$ **Equation 4-5**

where H is the elevation difference between the crest of the source and the toe of the deposit, L is the horizontal distance between the crest and toe along the centre-line of movement, V is the landslide volume, and a and b are coefficients. If such relationships exist, or can be established for a specific region or landslide type, they can be used to estimate the travel distance.

ii) Energy Grade Lines Relationships: These relationships are similar to volume-fahrböschung relationships, but are based on a line drawn between the centres of mass of the source and the deposit. The inclination of this line, also known as the travel angle, represents the average bulk basal friction angle of the landslide (Hungr, 1981). Using energy grade line principles established in hydraulic engineering (for example Roberson and Crowe, 1993), flow velocities at any point along the path can be estimated based on the elevation difference between the energy grade line and the flow path. The challenge with this approach is that it is difficult to accurately estimate the position of the centre of mass in the source and deposit zones. As a result, unlike volume-fahrböschung relationships, statistical correlations between landslide volume and travel angle are uncommon. The assumption of a constant bulk basal friction angle also tends to overestimate flow velocities.

iii) Volume-area Relationships: These relationships involve statistical correlations between landslide volume and depositional area. Such relationships have been proposed by Li (1983), Hungr (1990), Iverson et al. (1998), and Legros (2002). The regression equations typically take the following form:

$$A = cV^{\frac{2}{3}}$$ **Equation 4-6**

where *A* is the planimetric depositional area, and *V* is the landslide volume. Values of the coefficient *c* can range from approximately 10 for rock avalanches to 200 for lahars (Hungr, 1990; Griswold, 2004). Volume-area relationships are the basis for the US Geological Survey's GIS-based mapping program LAHARZ (Iverson et al., 1998; Griswold, 2004). Note that volume-area relationships only provide estimates of the depositional area and must be used in combination with other methods to estimate where the deposit may be located along the path. LAHARZ requires the starting point of deposition to be specified by the user.

iv) Volume Balance: Models based on the volume balance of material entrained and deposited along the debris flow travel path can be used to estimate runout distances, distribution of erosion, and deposit depths (Cannon, 1993; Fannin and Wise, 2001). Such models require the input of detailed path morphology and must be locally calibrated. Volume balance is the basis for the web-based model UBCDFLOW (Fannin and Wise, 2001).

v) Rock Fall Shadow Angle: For rock falls, Evans and Hungr (1993) proposed a runout mapping method based on the concept of shadow angle, defined as the angle between the apex of the talus slope and the distal margin of rock fall beyond the toe of the talus slope. They examined 16 talus slopes in southwestern British Columbia, which yielded a minimum rock fall shadow angle of 27.5°. Local calibration of the method is required.

vi) Other Empirical Methods: Other methods have been proposed to estimate landslide runout distances and velocities. Hsu (1975) proposed a correlation between landslide volume and excess travel distance, which is the distance beyond what would be predicted using a 'normal' average bulk basal friction angle of 32°. Rickenmann (1999) presented statistical correlations to estimate debris flow peak velocity and discharge.

4.2.5.2. Analytical Methods

i) Forced Vortex Equation: This equation for superelevation was originally formulated for open channel water flow and was adopted for snow avalanches (Mears, 1981) and debris flows (Hungr et al., 1984). It is most commonly used to back-calculate debris flow velocities based on post-event observations of trimlines in channel bends, but it can also be applied to deflection berm design (Hungr et al., 1984). The following equation is based on a lateral momentum balance at the point of maximum superelevation:

$$\Delta H = B\frac{v^2}{Rg}$$ **Equation 4-7**

where ΔH is the elevation difference between trimlines on the inside and outside of the channel or gully bend, B is the surface width of the flow, v is the mean flow velocity, R is the mean radius of curvature in the bend and g is the acceleration due to gravity.

Leading Edge Model: This model was originally developed to estimate debris flow runout (Takahashi and Yoshida, 1979). It was modified by Hungr et al. (1984) for runup against adverse slopes, such as terminal berms, and was subsequently applied to snow avalanches (Hungr and McClung, 1987; McClung and Mears, 1995). The following equations are based on a longitudinal momentum balance at the point of maximum runup:

$$H = \frac{V^2}{G}\sin|\alpha|$$ **Equation 4-8**

$$V = v_0 \cos(\alpha_0 - \alpha)\left[1 + \frac{gh_0 \cos\alpha_0}{2{v_0}^2}\right]$$ **Equation 4-9**

$$G = g(\mu\cos\alpha - \sin\alpha)$$ **Equation 4-10**

where H is the runup height, α is the adverse slope angle (negative), α_0 is the approach slope angle (positive), v_0 is the approach velocity, h_0 is the approach flow depth and μ is the basal friction coefficient.

4.2.5.3. Physical Models

The first large debris flow deflection works in British Columbia were designed with the help of 1:240 scale model tests with a bentonite slurry (Nasmith and Mercer, 1979). The requirements for dynamic similitude in physical modelling of debris flows, however, are very complex (Iverson, 1997), making physical model testing relatively costly and therefore infrequently used.

4.2.5.4. Numerical Methods

Numerical models simulate landslide movement by time-step solutions of a governing set of equations of motion. Such models allow unique geometry and local material characteristics to be accounted for explicitly, and provide estimates of velocities and flow depths at different points along the path. Both discontinuum and continuum numerical models have been developed to simulate landslides in 2-D and 3-D. For both, calibration of model input parameters is required.

i) Discontinuum Models: These models treat landslides as solid bodies, or assemblages of solid bodies, with up to four different movement types: falling, bouncing, rolling and sliding.

The simplest models treat the landslide as a single body or lumped mass. Lumped mass sliding block models, which are related to the energy grade line methods mentioned above, have been applied to landslides and are routinely applied to snow avalanches (cf. Perla et al., 1980). Lumped mass bouncing ball (fall-collision-rebound) models are routinely used for rockfall simulation. Available rock fall models include RocFall (Stevens, 1998), CRSP (Pfeiffer and Higgins, 1990) and STONE (Guzzetti et al., 2002). Calibration is required to constrain the restitution and friction coefficients that are used in these types of models.

ii) Discrete/distinct element models: These models are a multi-particle extension of the lumped-mass approach described above. In such models, landslides are modelled as a collection of individual particles that interact with each other and with the ground surface by falling, bouncing, rolling, and sliding to simulate large-scale deformations. The particles can be of a variety of shapes and sizes, and a variety of inter-particle and particle-bed contact relationships can be modelled. The Particle Flow Code (PFC) model, developed by Cundall and Strack (1979), uses circular (in 2-D) or spherical (in 3-D) particles that can be bonded together or broken apart under certain conditions (Poisel and Roth, 2004). PFC has been used by several landslide professionals to simulate landslides (Calvetti et al., 2000; González et al., 2003; Pirulli et al., 2003; Poisel and Preh, 2008b).

iii) Continuum Models: These models are based on established depth-averaged (shallow flow) hydrodynamic models of landslides. In contrast to the solid body approach of discontinuum models, continuum models treat the landslide as a fluid-like material. Flow spreading in depth-averaged continuum models is governed by internal stress gradients, and basal shear stresses provide resistance to forward motion. Different rheological models (for example, frictional, Voellmy and Bingham) can be used to estimate the basal shear stress at a given time and location within the flow. A number of different continuum models are currently in development around the world (Hungr et al., 2007). Available models include DAN (Hungr, 1995), TITAN2D (Pitman et al., 2003) and FLO-2D (FLO-2D Software, 2007). Extensive calibration work has been carried out using DAN (Hungr and Evans, 1996; Ayotte and Hungr, 2000; Revellino et al., 2004; Pirulli, 2005; McKinnon, 2010) and a 3D version of the model, DAN3D, has been developed (McDougall et al., 2006).

4.2.5.4.1 Associated Techniques

i) Model Calibration: Calibration is required to constrain numerical model input parameter values. Typically, rheological parameters are constrained by systematic adjustment through trial-and-error or statistical back-analysis of full-scale prototype events. On a case-by-case basis, calibration is achieved by matching the simulated travel distance, deposit distribution, flow velocities, and travel times to those of the prototype landslide, usually through subjective visual assessment. More advanced calibration techniques have recently been proposed by Galas et al. (2007), Cepeda et al. (2010) and McKinnon (2010).

ii) Probabilistic Mapping: Runout predictions based only on a single set of input parameter values can be misleading unless they are placed in the proper context. Depending on the level of required conservatism, the results may represent a worker's 'best guess', with a subjective probability of exceedance of 50%, or they may represent a more conservative estimate, with an exceedance probability of 10% or less. Many of the methods outlined above can be applied in a probabilistic framework that addresses this issue and provides results that are suited to quantitative landslide risk assessment (McDougall, 2012).

One type of probabilistic approach is to determine the best-fit results for each individual case, as described above, and plot the results as a histogram, which can be fitted to a probability density function. The probability density function can then be used to assign exceedance probabilities to parametric model runs, or to define input value probabilities for use in Monte Carlo-style predictive runs (Dalbey et al., 2008). This approach is commonly used in rockfall mapping.

Another approach is to determine the best-fit results for each group of similar cases as a whole and then attempt to quantify the resulting variance. The results can be used to place confidence bounds on predictions (Schilling et al., 2008), which can be translated into explicit exceedance probabilities.

5.0 MONITORING

In general, known landslides that are a risk to public infrastructure, private property, and personal safety should be monitored in order to minimize the potential risk. The monitoring program, whether it is simple or complex, must be designed based on the geological, physical, and environmental conditions of both the landslide hazard and the elements at risk. As the definition of landslides includes a very broad range of natural phenomena, the range of techniques commonly used to monitor their stability is also quite broad.

There are two paramount reasons for monitoring landslides:

- To understand the dynamics of the mass movement to facilitate the assessment of the hazard;
- To assess the degree of instability through detection of changes which enable the development of accurate early warning systems and precautionary measures.

5.1. Slope Engineering

Landslides occur naturally, as a result of human construction, and in engineered slopes. The nature of the problem, however, remains consistent: unstable slopes that can negatively affect personal safety or property must be monitored to ensure minimal risk. Known landslides can be separated into two categories, those in which support methods can be implemented to reduce or eliminate the hazards, and those in which monitoring must be performed to reduce the effect of the hazard through implementation of early warning systems. In both instances monitoring is used to delineate the hazard; however, in the first case, intensive monitoring is generally reduced once the hazard has been reduced or eliminated through support/remedial measures.

Landslides occurring in natural terrain include (but are not limited to) debris flows, rock slides, rockfalls, rock avalanches, quick clay/sensitive clay failures, and traditional landslides. The occurrence of natural slope landslide can occur in any geological, geomorphological, or physical setting. This category also includes natural landslides which develop due to engineered constructions. Landslides occurring in engineered slopes can include structures such as dams, embankments, and retaining walls.

Each of the monitoring methods discussed in the following section can be successfully applied to both natural and engineered slopes.

5.2. Monitoring Methods

Monitoring methods for slope instability include a wide variety of instruments and techniques. Commonly slopes are monitored for displacement, differential movement, hydrological changes, strain, and ground temperature, whereas the physical environment is monitored for temperature and precipitation. Table 5 contains essential remote sensing based techniques for landslide monitoring; they are arranged according to the method used to collect or generate the data. Table 6 presents *in situ* monitoring techniques. A broader discussion of each major category is contained in Sections 5.2.1-5.2.4.

Table 5. Fundamental remote sensing based landslide monitoring methods.

Method	Application	Accuracy
Terrestrial		
Lidar	Full field displacement/discrete failure	mm – dm (~with distance)
Photogrammetry	Full field displacement/discrete failure	mm – dm (~with distance)
Robotic Total Station Targets	Discrete location displacement	mm – cm (~ with distance)
GB-InSAR	Full field displacement	mm
Digital Image Correlation	Full field displacement	Mm
Airborne		
Lidar	Full field displacement	cm – m (~with distance)
Multispectral Imaging	Environmental changes	cm – m
Spaceborne		
Very High Resolution Imaging	Physical and environmental changes	dm – m
InSAR	Full field displacement	mm – cm

Table 6. Fundamental *in situ* based landslide monitoring methods.

Instrument Type	Application	Accuracy/ Comments
Deformations/Displacements		
Inclinometers (Vertical & Horizontal)	Monitor horizontal or vertical offsets within ground mass	1-2 mm/30 m
ShapeAccelArray (SAA)	Monitor settlement and deflection	Sub 1 mm
Extensometers	Monitor dilation or contraction across geologic features	Sub 1 mm
Settlement Gauges	Monitor vertical settlement or uplift	1-2 mm
Tilt Sensors & Tilt Beams	Monitor tilt changes at discrete locations	0.1 mm/m
Pendulums & Plumblines	Monitor horizontal offsets from vertical	0.5 mm
Fibre optics BOTDR	Monitor 3D shear strain	0.5 mm

Differential GPS	Monitor horizontal and vertical changes to surface positions	5-10 cm vertical and horizontal
Time Domain Reflectometry	Monitor the progression shear strain perpendicular to drillhole axis	1mm/m
Groundwater/Seepage		
Piezometers	Monitor water levels and/or water pressures	0.5-1 mm
Weirs & Fumes	Monitor seepage rates and changes	0.1-1 litre/min
Temperature Probes	Monitor groundwater temperature at discreet locations	0.1 degree C
Thermister Strings	Monitor groundwater temperature at multiple locations along an axis	0.1 degree C
Water Chemistry	Monitor various chemical and physical properties of groundwater to identify changes. pH, salinity, etc.	various
Environmental/Climatic		
Air Temperature	Monitor temperature	0.1 degree C
Precipitation	Monitor amount and rate that site receives water	0.1 mm absolute
Barometric Pressure	Monitor barometric pressures at the site	0.01 KPa
Humidity	Monitor surface humidity at the site	various
Wind; Direction & Speed	Monitor wind	various
Evaporation	Monitor surface evaporation conditions	various
Sun Light Hours	Monitor hours of sunlight	0.1 hrs/day
Snow Pillows	Monitor snow accumulation and rate at which spring melt occurs	cm/day
Seismic Activity		
Strong Motion Accelerometer (SMA)	Triggered device that will record major seismic events that occur at a remote site	will only record events > M 6.0
Seismograph	Major seismic recording device. Would only be required under special circumstances	can capture very small seismic events
Upcoming Methods		
Acoustic Emission	Micro-particle ground motion	unknown
GNNS GeoCube	Monitor horizontal or vertical movement	sub 1 mm

5.2.1. Remote Terrestrial Techniques

High resolution terrestrial remote sensing techniques enable engineers to identify instabilities, detect movement, and characterize slope deformation. The most commonly employed and published technique is LiDAR – Light Detection And Ranging (colloquially referred to as laser scanning). Other well established techniques include: terrestrial digital photogrammetry, robotic total stations, and ground-based interferometric synthetic aperture radar (GB-InSAR). These techniques present interesting advantages in comparison with existing monitoring methods; their application frequently leads to a better understanding of landslide failure mechanisms, rock fall rate and spatial distribution, as well as pre-failure deformation.

The principle of each of these instruments is the ability to generate data depicting the physical location of the landslide area at a given point in time. The ability to use one of these methods for monitoring displacement within a landslide requires a temporal repetition of data collection. Different data analysis methods can then be used to quantify slope movements, based on the comparison between sequential high resolution 3D datasets. If there are significant morphological variations between successive acquisitions (e.g., rockfall), simple change detection procedures can be applied. In the case of relatively slow and homogeneous displacements with no significant morphologic changes, it is possible to characterize more completely the displacement and deformation of a moving mass. Figure 2 illustrates the scanning on an active landslide zone in British Columbia above a railway track. LiDAR-derived information is being used to assess the kinematic stability and displacements of the slope face.

Figure 2. LiDAR scanning in western British Colombia to assess kinematic stability and monitor displacements.

The use of terrestrial digital remote sensing techniques for the characterization and monitoring of landslides may lead to new perspectives in their understanding, stability assessment and mitigation. The literature in this field is significant, Table 8 includes a few key papers on the various methods.

5.2.2. Airborne Techniques

Airborne monitoring of landslides is typically conducted using LiDAR, photogrammetry, or multispectral imaging techniques. The techniques are very different in terms of capability. Airborne LiDAR Scanning (ALS) data, collected from an airplane or helicopter, is most commonly used to delineate terrain surface models and identify large unstable masses. Sequential ALS data can be used to map differential change on a slope over time which can aid in the understanding of active slope processed (Lato at el., 2014). Oblique Helicopter Photogrammetry (OHP) is a developing method of collecting photos for 3D surface data generation. Optimally, OHP data is collected at a range of 100-500 m from the rock face using high quality handheld camera equipment. The view angle of the camera with respect to the slope of interest can be adjusted in real-time by the photographer. Data collection is therefore only restricted to the flight path of the helicopter operator; as a result occluded regions can be minimized through flight planning (Lato et al., 2015).

5.2.3. Spaceborne Techniques

Current state-of-the-art in real-time monitoring of active slopes developed for early warning of landslides is very expensive. Satellite radar interferometry is used to complement real-time monitoring such as GPS, TLS, *in-situ* field measurements, and others. Interferometric Synthetic Aperture Radar (InSAR) techniques are being used to measure millimetre displacement on slow-moving landslides. Key references are included in Table 8.

An interferometric phase image (interferogram) represents the phase differences between the backscatter signals in two or more SAR images obtained from similar positions in space. In case of spaceborne SAR, the images are acquired from repeat pass orbits. Once the topographic phase is removed, the phase differences between two repeat-pass images are the result of changes in topography, changes in the line-of-sight distance (range) to the radar due to displacement of the surface and change in the atmospheric conditions between scenes. For non-moving targets, the phase differences can be converted into a digital elevation model. InSAR techniques are being used to monitor gradual landslide motion under specific conditions, provided coherence is maintained over the respective orbit cycle. Landslide movements are measured in millimetres to centimetres per orbit cycle of the radar satellite. This orbit cycle can range from 44 days for ALOS, 24 days for RADARSAT 2, 11 days for TerraSAR X, and 2.5 days for Cosmo-SkyMed.

Reliable measurements of surface displacement can be achieved under specific conditions. These include using radar image pairs or numerous scenes (more than 25), with similar viewing geometries, short perpendicular baselines (less than 100 m), short time intervals between acquisitions, and correcting for the effect of topography and atmospheric conditions. The InSAR deformation maps or profiles provide linear motion along the line-of-sight. However, under some geotechnical assumptions assessments can be refined to vertical and horizontal components. In the early stages of the research, 3D-motion using ascending and descending orbits and additional viewing geometries is produced.

InSAR processing techniques include differential InSAR, PSInSARTM /CTM TM, and more recently Squeeze SAR TM. The differential InSAR uses only two or three scenes or orbit cycles and provides a more general and simplified snapshot of the deformation activity of the landslide. It is a powerful tool to measure displacements because it offers a synoptic view of the landslide. The more detailed point targets or corner reflector data using PSInSARTM/ CTM TM or Squeeze SAR TM processing techniques are more complex. The InSAR deformation profiles for both point and distributed targets show the spatial and temporal heterogeneities of terrain movements and assist in defining the parameters controlling the dynamics of low-velocity landslides. This simple guideline on InSAR monitoring of Canadian landslides should be revised as more case studies are documented. The uses of InSAR monitoring are rapidly increasing with the availability of more frequent satellite revisits from our future RADARSAT Constellation Mission (RCM), combined with improved InSAR processing techniques taking advantage of several viewing geometries, distributed targets and smaller corner reflectors.

5.2.4. In Situ Techniques

In situ monitoring techniques are generally employed as part of the surface and sub-surface investigations that take place on a landside site. Despite the quality and quantity of the detailed information that can be collected and analysed by remote sensing methods, at some point, decisions have to be made regarding whether the investigations need to shift toward intrusive *in situ* monitoring techniques. Remote sensing information, coupled with surface investigations and geological mapping, will enhance the understanding of the physical characteristics and the genesis of the landslide mass to a certain point. This work will always result in many questions regarding the geometry and mechanism of the slope failure and the rate of the actual ongoing ground movements.

Drilling investigations and excavations are the usual intrusive methods that are employed to recover detailed information regarding the slope geometry, the failure mechanism of the slope and the current rate of movement. It is noted that these intrusive methods can be very costly and therefore require compelling justification for the expenditures. Usual justifications are for either commercial reasons or in the interest of public safety. Around the world today, most major intrusive investigations and *in situ* monitoring programs that are carried out on landslides are for the protection of commercial interests and to mitigate the related financial liabilities.

Drilling and excavations (either surface or underground) provide many opportunities for the inclusion of *in situ* monitoring methods, which will provide key information on the behaviour and physical nature of the landslide mass. These *in situ* monitoring methods are summarized in Table 6.

The *in situ* monitoring instrument types which are most commonly used and provide the key information for landslide monitoring are Inclinometers and Extensometers (under Deformation / Displacement Instruments) and Piezometers and Weirs and Flumes (under Groundwater / Seepage Instruments). The roles of these key *in situ* monitoring instruments are summarized below.

- Deformation/Displacement:
    - Inclinometers: The installation of inclinometer casings in near vertical drillholes are used to accurately measure the magnitude and time progression of deformation zones that are occurring near perpendicular to the drillhole alignment. This monitoring technique can also be carried out in near horizontal drillholes. Inclinometers represent a very precise monitoring technique which is used extensively in landslide masses to determine movement directions, magnitude of movements and movement rates.
    - Extensometers: There are many variations of extensometer type instruments, which are intended to measure convergence or divergence on an approximate

straight line between two end points. Extensometers are designed for many applications on surface or within drillholes. Readings can usually be done by a manual method, but are easily adapted for automated electronic readings. Extensometer instruments can be designed to provide extremely precise data. They are intended to measure extension or contraction movements, which are occurring between the end points either within or on a landslide mass.

- Groundwater/Seepage:
  - Piezometers: There are many variations of piezometer type instruments. These instruments are intended to measure water levels within a slope or a landslide mass, which is equated to the water pressure acting on the slide mass slip plane. This piezometric information is critical to understanding the mechanism for a slope failure and for determination of the current stability of a slide mass. Standpipe piezometers are the simplest and most common water level measuring instrument, but there are many different variations which provide extremely accurate water pressure data.
  - Weirs and Flumes: There are many different variations on weirs and flumes which are used to monitor seepage flow rates either entering or exiting a slide mass. Naturally occurring seepage or seepage from excavations or drillholes are usually routed to a collection point where measurement can be carried out accurately in a weir or flume. Data are also required on the water input into the slope due to precipitation (Environmental/Climatic). The accurate measurement of seepage input and output flows is commonly used as input data for flow modelling of a landslide slope mass. This modelling may indicate critical periods within the annual cycle when slope stability is reduced and movement may be renewed.

5.3. Landslide Warning Systems

Landslide warning systems often serve as an interim risk management measure in absence of, or to complement, engineered structures. Warning systems are particularly helpful in situations where significant landslide risks have been identified either regionally or site-specifically, and funds are currently not available to address all sites that exceed a limit of tolerable risk. In those cases, landslide warning may allow residents or workers to evacuate at a critical time when a landslide is likely to occur.

Landslide warning can be based on deformation measurements and warning levels may be defined when such deformations reach specified thresholds. Alternatively, because most landslides are associated with some hydroclimatic factors, a combination of such factors could be linked to specified warning levels. Figure 3 displays a landslide monitoring station equipped with an extensometer, gravity-referenced inclinometer, and temperature sensor. The system is powered by a rechargeable battery via a solar panel, and data recorded by the system as well as the health of the system are checked via cellular connection.

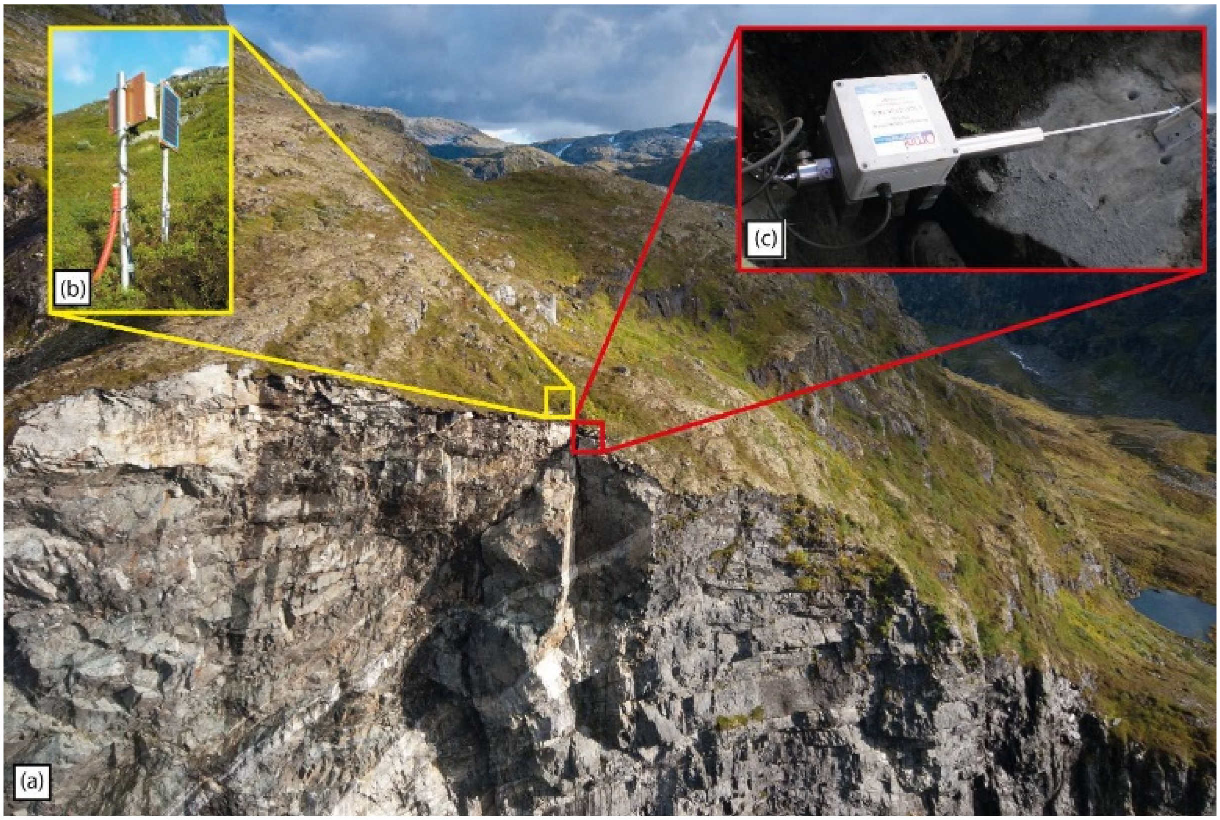

Figure 3. *In situ* measurement system located in the tension crack of an unstable rockmass 800 meters above a small community. As shown in inset figures (b) and (c) the monitoring unit is connected to a solar panel and control system to report measurements via cellular uplink. The measurements taken (c) are extension and inclination across the crack, as well as air temperature.

5.3.1. Early warning systems

Reliable prediction of landslide occurrence based on climatic thresholds has been accomplished in numerous countries and has been described in many publications, some of which are included in Table 7. A large number of researchers have used rainfall intensity-duration curves and plotted rainfall data from landslide-producing and non-producing storms. Envelopes or separating lines were drawn to extract the intensity-duration data that allow classification of a storm to be either debris-flow producing or not.

An Example: The District of North Vancouver in collaboration with BGC Engineering developed Canada's first operating real-time debris flow warning system, which operated during the rainy seasons of 2009/2010 and 2010/2011. The system is based on discriminant function analyses of 20 hydrometric input variables consisting of prior rainfall and storm rainfall intensities for a total of 63 storms. Of these, 27 resulted in shallow landslides and subsequent debris flows, while 36 storms were sampled that did not result in debris flows. The discriminant function analysis identified as the three most significant variables the 4-week antecedent rainfall, the 2-day antecedent rainfall, and the 48-hr rainfall intensity during the storm. The resulting classification functions provide a scale representing the likelihood of debris flow initiation. Several complexities were added to render the classification functions into a usable and defensible warning system. Back-calculation of the model's 21-year record confirmed that 75% of all debris flows in the past 20 years would have occurred during warning- or severe warning levels. Antecedent rainfall is automatically calculated as a sliding time window for the 4-week and 2-day periods every hour. The predicted 48-hr storm rainfall data are provided by the Fluid Dynamics Centre at the University of British Columbia and are updated every hour as rainfall is recorded during a given storm. The warning system differentiates five different stages: No Watch, Watch Level 1 (the warning level is unlikely to be reached), Watch Level 2 (the warning level is likely to be reached), Warning and Severe Warning.

5.3.2. Technical considerations and data connectivity

In general, a typical warning system will consist of four major elements that collectively will provide a total system approach to risk management. These elements are: data recording, data transfer, data review, and warning communication. Key references to these topics are included in Table 8.

The ability to notify any change in alarm status on a warning system will be dependent on the successful implementation of these elements, all of which are susceptible to failure for various reasons. For instance, equipment failure might compromise the data collection and data transfer elements; and the lack of qualified people generally constitutes a typical source of trouble for the data review element. On the other hand, the warning communication element can be severely affected if an emergency response protocol that clearly defines roles and responsibilities in the event of an incident is not available.

Therefore, for any warning system, it is important to take the necessary steps to guarantee that the system will function as designed on a near-continuous basis. Thus, the overall approach that must be taken when designing and operating an early warning system is to create a series of tasks that will ensure adequate functioning of each of the warning system elements (Table 7).

5.4. Summary and Limitations

The science of landslide monitoring is diverse and complicated. The numbers of options are immense. Each technique is accompanied by a long list of limitations, sources of errors, and a subject matter expert who can demonstrate its successful implementation on various projects. When designing a monitoring program and deciding which technique(s) to use, it is critical to first establish what parameters are essential to monitor and what resolution and accuracy are required. These decisions are generally determined through analysis of existing knowledge of the landslide with respect to its size, failure mode, activity level, and elements at risk.

The primary internal limitation of any monitoring systems is that it can only produce data in the manner and/or spatial region which it is programmed to collect. Because the determination of stability (or hazard level) can only be accessed through analysis of these data, it is critical that the monitoring system be specifically designed for each potential mode of instability. As well, each instrument or technique will have associated sources of error and inaccuracies; this is the responsibility of the engineer/geoscientist to understand when designing a monitoring system.

The cost of equipment, installation, and data analysis is often the largest external limitation of any monitoring program. This, however, must be dealt with on a case by case basis, and engineering judgement and expert opinion can help in determining the best approach for the most successful results.

Table 7. Suggested tasks required to provide an effective warning system.

Element	Task
Data recording	Design a sensor network that provides complementary types of instruments with varying sensitivities to movement and climatic influences Perform regular system health checks Develop well-defined plan for maintenance and repair to reduce potential downtime for the system
Data transfer	Provide a main communication link that gives access to data and at least one secondary (back up) link
Data review	Develop a protocol to ensure data are reviewed on a specified frequency and in a repeatable manner (weekly review for early detection of increasing acceleration; yearly review for long-term trend analysis) Develop kinematic model for unstable mass and update as monitoring data become available Establish thresholds for alarm triggers (absolute and velocity-based)
Warning communication	Develop set of rules for notification of increased alert level (Emergency Response Protocol-ERP) Run orientation sessions (training) and drills (testing) for the ERP Have debriefing session after any alert incident

In addition, it should be noted that by initiating a monitoring program, there may be an implied responsibility for the long-term continuation of the monitoring program in the eyes of the public or involved government agencies. Therefore, caution is recommended to any party intent on starting an instrumentation and monitoring program at a landslide site. When establishing a monitoring program, the “owner” should consider two things. Firstly, determine and establish up front, with all external parties, the circumstances and conditions by which the monitoring program will be shut down or discontinued. And secondly, the party must be careful to never commit to a monitoring program which cannot be sustained for the long term. Complex monitoring programs carry major responsibilities, which are both expensive and require a highly trained and dedicated professional workforce. Table 8 identifies important publications that explain various remote sensing techniques and their application for mapping terrain and monitoring slope activity.

Table 8. Key references and case studies for landslide monitoring.

Key reference	Topic
Remote Sensing	
Pedrazzini et al., 2011	Integration of terrestrial remote sensing-based discontinuity characterization and slope monitoring into the hazard assessment analysis and warning system implemented within the risk management procedure for a quarry
Abellan et al., 2014	Review of the applications of terrestrial LiDAR for slope stability assessment and monitoring
Eberhardt et al., 2008	Demonstration of the capability of monitoring active landslides with robotic total stations
Lato et al., 2011	Review and recommendations concerning the integration of LiDAR-based measurements into rockfall hazard management systems
Lato et al., 2014	Review of airborne LiDAR, terrestrial LiDAR, and terrestrial Photogrammetry for mapping change in active environments.
Bateson et al., 2015	Application of the ISBAS algorithm for monitoring slope deformation
Singhroy, 2008	Satellite remote sensing applications for landslide detection and monitoring
Kromer et al. 2015	Mapping millimetre-scale ground deformation along transportation corridors using terrestrial LiDAR for precursor failure movements
In Situ Monitoring	
ICOLD, 1989	International perspective on the state of the art regarding the *in situ* monitoring and data acquisition for major structures. Provided information is directly applicable to landslide and slope stability problems.
Baker, 1991	Details of the investigations and *in situ* instrumentation installations carried out for the geotechnical monitoring of a major slope instability.
Moore et al., 1991	Details of how *in situ* instrumentation and near real-time monitoring can be used to reduce risks due to potential slope failures.
Early warning Systems and Data Connectivity	
Wieczorek and Glade, 2005	Climatic factors influencing triggering of debris flows
Guzzetti et al., 2005	Evaluation of Flood and Landslide Risk to the Population of Italy
Baum and Godt, 2010	Early warning of rainfall-induced shallow landslides and debris flows in the USA
Jakob et al., 2011	Regional real-time debris-flow warning system for the District of North Vancouver, Canada
Froese and Moreno, 2014	Structure and components for the emergency response and warning system on Turtle Mountain

6.0 SLOPE TREATMENT

6.1. Introduction

Slope treatment is required in areas where a risk evaluation has determined that it is unacceptable to leave a slope in its current condition. Treatments can be applied to both pre-existing landslides and to the prevention of future landslides. Mitigation involves treatment to reduce the seriousness or impact of the landslide, while remediation involves treatment to reverse the damage caused by the landslide. This section will provide various options available for slope treatment under different geological and environmental conditions.

6.2 Treatment Considerations

Any treatment program will have to be consistent with the objectives of the study. The study area will have to be defined and the appropriate level of effort applied to the treatment program will depend on the consequences of failure. Linear projects such as transportation routes will typically involve a larger study area and will have different treatment options than a localized structure.

Many factors must be considered in determining appropriate treatment options for unstable slopes. The variability of soil conditions, environmental factors and economic constraints results in a unique approach for almost every landslide. The best possible data gathering and sound engineering judgement must be used to arrive at a safe and economical solution to the problem.

Table 9 provides a summary of the more common treatment methods for unstable slopes. The methods are divided into active and passive classifications. As shown in the table, there are numerous options available and often a combination of options is selected for specific site conditions. Treatment options will be affected by the local geology, the scale of the problem, the consequences of failure, the economic situation and the resources available.

6.2. Passive Methods

Passive methods are methods that do not involve physical stabilization of the slide mass but rather attempt to avoid the problem. This is often a good approach during planning stages of a project. Once design and development has begun, relocation or alteration of the design can become costly and less desirable for the project stakeholders. The unstable areas must be identified during the investigation to allow avoidance options to be determined.

Some regulatory agencies have developed guidelines or standards for dealing with landslide prone areas. These documents typically prescribe methods of analysis and the levels of deformation that are deemed acceptable for certain types of developments (typically residential areas). For example, in British Columbia, the Guidelines for Legislated Landslide Assessments for Proposed Residential Developments produced by the Association of Professional Engineers and Geoscientists of B.C (Gerath et al., 2010)

Passive methods are also used where ongoing movements are small and the trigger mechanism is understood. In this case the acceptance of the risk and the implementation of monitoring can be used. For example, at the Gardiner Dam in Saskatchewan filling of the reservoirs activates small movements annually (Rahman and Kilgour, 2000). These movements are small, understood and monitored. The following sections summarize various alternative passive methods to slope treatment.

6.2.1. Risk Assessment

6.2.1.1. Accepting the Risk

Risk based principles can be used to conduct probabilistic assessments of slope reliability.

Based on the results of such studies, it may be possible to accept the risk of landslide occurrence and therefore leave things as they are. In some cases, small movements may be ongoing, however, if they are understood, it may be possible to accept the movement. In some locations, risk tolerance may be defined by local regulators. However, in other areas risk acceptance levels may not be possible to define.

Table 9. Summary of treatment methods for unstable slopes.

CLASS	PROCEDURE	METHOD	DETAILS
Passive methods	Risk assessment	nothing required	risk is acceptable
		regulatory methods	covenants, restrictions
		non-regulatory methods	land swaps, education
	Avoidance	avoid unstable ground	relocate structure, bridge over
	Monitoring and warning	instrumentation	survey hubs, GPS, LiDAR inclinometers, extensometers
Active methods	Reduce driving forces	unload crest	excavation, replacement with lightweight fill
		re-grade slope	create a new stable slope
		surface drainage	trench drains, interceptors, fill cracks
		subsurface drainage	horizontal drains, drilled wells, tunnels, adits
	Increase resisting forces	construct toe berm/ shear key	fill placement as buttress; increase shear resistance below shear plane
		surface treatment	rock fill blanket
		install anchors	drill and grout steel bars
		install piles	drilled or driven piles
		retaining structure	MSE walls, gravity walls, pile walls, tieback walls
		deep soil mixing	slurry mixtures
	Increase internal strength	drain subsurface	lower water table with drains; vacuum dewatering, siphoning
		in-situ reinforcement	installation of soils nails or micropiles
		reinforced backfill	geosynthetic reinforced soil
		bioengineering	root support and drainage
		chemical stabilization	mix soils with additives
		electro-osmosis	increase strength of clays
		thermal treatment	artificially dry or freeze soil
	Protection measures	slide deflection	deflect slide material around, above or below structure
		catchment basin	catchment basin or series of basins to collect debris, reduce volume of slide.

6.2.1.2. Regulatory Methods

Regulatory methods may be used in local areas or regional districts that have developed guidelines or rules for landslide risk assessment and stability analyses. For example, in British Columbia, APEGBC has published a document entitled Guidelines for Legislated Landslide Assessments for Proposed Residential Development in British Columbia. These guidelines provide guidance for professionals carrying out stability analyses for proposed residential developments and indicate how to relate the results of these analyses to a level of landslide safety for residential development when required by provincial legislation.

In 2005, the Québec government produced a guideline on the interpretation and use of existing landslide maps in the Saguenay- Lac-Saint-Jean area (Québec, 2005). The intent of this guideline is to help local and regional authorities interpret and use the hazard maps produced by the government in order to improve safety and control land-use. The guidelines discussed risk management tools and cover common causes and triggers for the most common types of landslides in the region. The guidelines also provide the minimum requirements that will necessitate a geotechnical report when further investigation is required.

Jurisdictions can control *land-use* in landslide prone terrain. This can be accomplished by refusing to allow development in areas of landslide susceptibility or by imposing covenants or restrictions on the types of developments that are allowed. Mitigative measures may also be required to allow the proposed development to proceed.

For example, the New Zealand Geological and Nuclear Sciences (GNS) published a document entitled Guidelines for assessing planning policy and consent requirements for landslide prone land (Saunders and Glassey, 2007). This document is primarily aimed at educating land-use planners with the concepts and relevant issues to be considered when incorporating landslide hazard information and assessment in the planning process. The guidelines outline the criteria used to assess landslide hazards, provide examples of issues, objectives, policies, rules, and assessment criteria. The guidelines discuss landslide concepts to assist planners in understanding landslide processes in addition to proposing a risk-based approach to land-use planning and approval.

Another example is the Land management handbook produced by the British Columbia Ministry of Forests (Chatwin et al., 1994). The document is targeted to field personnel primarily in the forestry industry who are operating in areas with existing or potential slope stability problems. The handbook covers landslide processes and characteristics, techniques for recognizing landslide-prone terrain, mitigation measures to manage unstable terrain, and road deactivation and re-vegetation of unstable terrain.

A more general treatise on landslide studies for a North American audience primarily targeting the non-specialist (home owners, developers, planners and others) that addresses all landslide aspects from identification to monitoring and mitigation is the joint Geological Survey of Canada and US Geological Survey treatise freely available online in several languages (Highland and Bobrowsky, 2008; http://pubs.usgs.gov/circ/1325/).

6.2.1.3. Non-Regulatory Methods

Non-regulatory methods are used to encourage avoidance of the potential landslide risk. Local jurisdictions can prevent or reduce potential development on landslide susceptible terrain by purchasing the unstable terrain for parkland, swapping the land for an area of more suitable terrain, or allowing increased density on safer portions of the land while imposing covenants and/or restrictions on the more vulnerable areas. Governments can also provide financial incentives to encourage developers to locate structures in safer areas or for environmental protection of landslide prone terrain. Education and public awareness can also provide incentive for developers to reduce the potential risk as it may be difficult to sell developments in know hazardous areas.

6.2.2. Avoidance

In some cases, the risk of landslide occurrence is high and avoidance of development is the best approach. Avoidance may involve relocation of the route or structure if the project is still in the planning stages. In the cases where there are few location constraints to the project or as noted above, if the project is still in the planning stages, avoidance may be highly cost effective as the location with little or no risk can be selected. Alternatively, where development has begun or constraints are in place on the resultant structure, avoidance may not be feasible. It can also involve construction of a facility such as bridge or tunnel to avoid the affected area. Avoidance may also involve the removal of unstable ground.

Avoiding unstable ground can be used effectively when geological reconnaissance or investigation has delineated a landslide area. The earlier the landslide is identified, the easier and less costly it will be to avoid. Avoidance can involve relocating a linear route or a specific structure away from the affected area or it can involve bridging over the unstable zone.

6.2.3. Monitoring and Warning

Managing the risk through the use of slope monitoring or early warning systems is commonly used on projects where there is some knowledge of the slope instability and it is not cost effective to relocate the structure or linear feature. There are many techniques that can be used for slope movement monitoring including conventional survey hubs, differential global positioning systems (dGPS), LiDAR (land based and aerial), slope inclinometers, tiltmeters, piezometers, extensometers, strain meters, acoustic instruments and vibration meters. All of these systems can be used independently, or often in tandem, to monitor movements of an existing or potential slide.

Warning systems can be set up to warn of impending failures. Real time systems that monitor rainfall have been implemented in several jurisdictions (for example, Hong Kong and San Francisco). Procedures are typically based on empirical and theoretical relations between rainfall intensity and landslide activity. Such systems can trigger sirens, flashing lights or radio and television broadcasts to warn local residents or operators of transportation systems.

The Alberta Geological Survey (AGS) has undertaken a long-term monitoring strategy of the South Peak on Turtle Mountain that includes an early warning to residences of a possible catastrophic rock avalanches. AGS has installed a variety of sensors including, crackmeters, tiltmeters, extensometers, reflective prisms and dGPS receivers. The sensors are monitored in real time and a warning management system automatically notifies officials of any change in the mountain that warrants further investigation by experts.

6.3. Active Methods

Active methods typically involve some form of construction to stabilize or reduce the potential for a slope failure to occur. Methods of stabilization are typically divided into reducing the driving forces, increasing the resisting forces or increasing the internal strength of the slide mass.

6.3.1. Reduce the Driving Forces

Driving forces are those which tend to cause movement or drive the slope to failure. These include the weight of the soil in the upper portion, the weight of surface water and vegetation on the upper slope and porewater pressure acting on tension cracks. It can also include flattening the slope and/or decreasing its height.

6.3.1.1. Unload Crest

The most common method of reducing the driving forces is to unload the slope by removing material from the crest area. This also flattens the overall slope angle and typically increases the slope stability. Slope stability sensitivity analyses can help determine the amount of material that needs to be removed to achieve a desired factor of safety. If this material can be placed at the base of the slope as a toe berm, this will increase the effectiveness of the excavation. If the removed material has some potential use, it will increase the economic viability of this option. In some cases, it may be required to replace the excavated material with a lighter material, such as pumice stone, foamed concrete or Styrofoam (extruded polystyrene). In 1997 in Summerland, BC unloading is the crest occurred at the North Beach Rock Slide on Highway 97 near where about 50,000 cubic metres of rock was removed from the crest of a large planar rock slide to reduce the movement to very small values.

6.3.1.2. Re-grade Slope

Slope re-grading usually consists of selective removal and filling of portions of the slope to create a more stable configuration. Re-grading can result in a reduction of driving forces. Early in the design phase, it may also be possible to raise the grade of the structure or linear feature to improve overall slope stability. This method is particularly effective in deep-seated landslides. This can also be used to remove material that contributes to slope instability, such as colluvium and landslide debris.

6.3.1.3. Surface Drainage

Drainage of the upper slope using trench drains (French Drains) is a very cost effective way to reduce the driving forces. Trench drains are typically installed by excavating trenches from 1 to 5 m deep at regular spacing either parallel or perpendicular to the movement direction. The trenches are excavated and backfilled with free draining gravel or drainage pipes that allow surface water to be transported away from the slope. Other surface drainage improvements can be achieved by re-grading of small gullies and directing surface water away from the area of instability. Water may be carried in trenches or in surface conduits such as half pipes or closed pipes.

The sealing of existing cracks and fissures with low permeability material is also an important part of improving surface drainage. Drainage blankets consist of free draining granular material can also be used to shed water off the slope. Surface drainage treatment can be particularly effective when combined with a subsurface drainage technique.

6.3.1.4. Subsurface Drainage

Subsurface drainage to reduce driving forces can consist of drilled vertical wells or sub-horizontal drains. Vertical wells can be very effective when horizontal layers of impermeable material (such as bentonite seams) do not allow water to percolate down to the groundwater table. Perched water on these impermeable layers can significantly reduce slope stability. At the north portal of the Edmonton SLRT (spell out) Project, large diameter drilled vertical drains were effective in reducing perched water levels above bentonite seams within the slope.

Sub-horizontal drains drilled on the slope can also be effective to lower the groundwater table or drain water from a sub-horizontal permeable layer that overlies an aquitard. These drains are typically drilled at a 2 to 5 degree angle above horizontal and are fitted with slotted PVC pipe. The pipes can discharge freely or be connected to a larger diameter collector pipe.

A success story for the use of subsurface drainage is the Downie Slide, located upstream of the Revelstoke Dam in southwestern British Columbia (Imrie et al., 1992). The risk of failure on the Revelstoke Dam was a concern based on the Vaiont Slide failure that occurred in Italy in 1963 which destroyed the town of Longarone in the valley below the Vaiont Dam and caused some 2000 casualties. To improve the stability of the slide, a series of drainage adits and drain holes were constructed within the slide. Since installation, the groundwater levels in the slope have been reduced to less than pre-reservoir levels. In addition, a significant reduction in the rate of down-slope movement has occurred within the past 25 years of monitoring.

6.3.2. Increase the Resisting Forces

Increasing the resisting forces improves the stability of the slope. These techniques involve applying a resisting force near the toe of the slide, constructing some form of retaining structure or installing reinforcing elements such as anchors or piles through the slide mass.

6.3.2.1. Construct Toe Berm/Shear Key

The most common and typically the most economic external force method is to construct a toe berm at the base of the slope. Toe berms are typically constructed of soil available locally and may contain drainage layers and/or geotextile separation. If the material can be excavated from the crest of the slope this will double the effectiveness as it will both reduce the driving force and increase the resisting force. The toe berm or buttress must be designed to be stable against sliding along its base and against bearing failure of the additional weight. The buttress must also be checked for failure within in its own mass. The size of the toe berm required is estimated from the results of stability analyses. If there is inadequate room or soil support for a toe berm, structural systems such as anchors, piles or retaining walls may be required. A general guideline is that the width of the buttress typically ranges from about one third to almost the full height of the slope being buttressed.

In addition, a shear key can be used to increase the shear resistance of the slope. In this case, a ‘key’ is excavated in to competent material below the failure surface. This key is then backfilled with compacted fill, slurry, or concrete.

6.3.2.2. Surface Treatment

Surface treatments can be effective for small shallow type failures in soils that are susceptible to erosion such as silts and fine sands. Such treatments usually involve placement of a blanket of blasted rock fill or coarse granular fill on the surface of the sliding mass. This blanket improves drainage, reduces the potential for surface erosion and increases the overall friction angle along the potential failure plane. Where working room is limited, sometimes a layer of the existing slope material is removed to make room for the surface blanket of more competent material.

6.3.2.3. Install Anchors

Anchors are commonly used to stabilize slopes by applying resisting forces to a potentially moving slide mass. They are usually installed by drilling and grouting steel bars into the slope. Anchors are probably more common on steeper slopes composed of more competent soils where there is a limited right of way. The soil must have adequate strength to develop the pullout capacity of the anchors. Stability analysis or deformation analysis is required to design the length, size and spacing of the anchor elements. Anchors are commonly used for stabilizing steep slopes along transportation corridors in steep mountainous terrain. They can also be used in conjunction with shotcrete or high strength steel mesh facing to create structural support.

6.3.2.4. Install Piles

Piles are becoming a more common means of stabilizing a slide mass. They are typically drilled caissons filled with concrete and reinforcing steel, however, they can also consist of driven piles. The piles extend across the potential sliding plane and increase the shear resistance. The embedment depth is based on slope stability analysis. Piles can also be used to construct a retaining structure at the toe of the slope. Pile walls can be cantilever structures or tied back with anchors. Various specialized techniques have recently been developed for analysing pile stabilized landslides. Alberta transportation has successfully used pile walls to remediate and stabilize landslides affecting Alberta highways (Abdelaziz et al., 2011).

6.3.2.5. Retaining Structures

Where there is insufficient space to allow construction of a toe berm, it is often necessary to design some form of structural retention system to improve stability. Rigid walls are not able to tolerate large deformations and therefore tend to attract large forces. Walls that are more flexible are usually preferred. Some of the more common types of walls that are used include mechanically stabilized earth (MSE) walls, masonry block gravity walls, concrete gravity or cantilever walls, gabion gravity walls, sheet pile walls, pile walls (cantilever or tie back), slurry walls, shotcrete and anchor walls and soil nailed walls. Each of these wall systems have distinct advantages and disadvantages depending on the slope geometry, soil and groundwater conditions, environmental factor, space availability and economic constraints. A detailed review of each option is beyond the scope of this document.

Recently, the use of MSE retaining walls has become more common due to their flexibility and reasonable cost. The backfill behind the facing elements is reinforced with steel trips or layers of geosynthetics. The reinforcement develops stress from the soil either by friction along the surface or passive resistance on elements with width normal to the movement direction. Such walls are particularly favourable in seismically active areas because of their flexibility and ability to distribute loads. Facing materials vary from wrapped geosynthetics to concrete masonry blocks to precast concrete panels. A trend of allowing the face to be vegetated for a greener look is also becoming popular.

6.3.2.6. Deep Soil Mixing

Deep soil mixing is a relatively new technique that has been used to stabilize unstable soils. The technique involves the installation of a series of soil cement mixed barrettes in the failed slope area. Replacement of the weaker soil with soil cement elements increases the shearing resistance across the potential failure plane.

6.3.3. Increase Internal Strength

Increasing the internal strength involves improving the overall strength of the slide mass. This can be accomplished in many different ways such as installing bulk reinforcement into the slide mass or by treating the soil mass in some way. Some of the more common methods for improving the internal strength of the slide mass are discussed below.

6.3.3.1. Drain Subsurface

Subsurface drainage can be used to improve overall internal strength of a slide mass. This usually involves lowering the water table with some form of deep wells or sub-horizontal drains. The drains can be fitted with vacuum devices to increase effectiveness. Siphoning techniques can also be used.

6.3.3.2. In-situ Reinforcement

Installation of *in-situ* reinforcement such as soil nails or micropiles is an effective way to stabilize some soil masses. Soil nailing involves the installation of closely spaced steel bars, cables or tubes that forms a coherent reinforced soil mass. Soil nailing differs from anchor tiebacks in that the nails are not tensioned and act as passive dowels.

Reticulated root piles can also be used to provide slope stabilization. Root piles are typically small diameter micropiles or pin piles that are installed with a single steel rod. The piles are installed at various angles to create a monolithic block of reinforced soil that supports the sliding mass. The “root like” soil reinforced zone obtains its strength form the three dimensional geometry of the micropiles.

6.3.3.3. Reinforced Backfill

It is possible to create steep slopes using reinforced backfill. Reinforcement types are typically divided into extensible (geosynthetics) and non-extensible (steel). Extensible reinforcement consisting of various types of geosynthetics (HDPE – High Density Polyethylene, PET – polyethylene terephthalate synthetics and others) allows more deflections and is commonly used for retaining walls and steeps slopes less than about 8 to 10 metres high. Non-extensible reinforcement consisting of steel strips or steel rods is typically used for higher walls or slopes where less deflection can be tolerated such as at bridge abutments.

Reinforced slopes using layers of geosynthetics to increase stability are becoming more common. Such slopes often have a facing consisting of wrapped geosynthetic or some form of welded wire mesh basket. The trend of obtaining a green facing by allowing vegetation to be grown on the slope or on benches between facing elements is becoming very popular.

6.3.3.4. Bioengineering

Slope stabilization using bioengineering has been in use for some time. Vegetation planted on a slope can increase the stability through root support reinforcement, by reducing the amount of water on the slope (evapotranspiration) and by allowing more effective drainage of the slope. Grasses and woody plants are most commonly used for slope bioengineering. The use of vegetation for stabilization is best suited on slopes that have shallow failure mechanisms or erosion related concerns and is strongly affected by the climate and soil conditions of the local area. Vetiver grass, for example, is one of the most common species used in tropical regions around the world. It is best to consult local experts if bioengineering is being considered for a slope stabilization project.

In recent times, the combination of vegetation and structural elements has gained popularity. The vegetation can provide support to the near surface soils and the structural elements such as live cribwalls, soft gabions or vegetated concrete blocks provide the structural support.

6.3.3.5. Chemical Stabilization

Chemical treatment of soils has been used to stabilize failed soil embankments. The concepts are similar to those used to treat poor quality subgrades for highways and airport construction. Typically, a lime slurry or grout is injected into the soil under pressure using some form of perforated nozzles. The slurry mix can either naturally penetrate fissures or cracks in the ground or be mixed into the soil using a higher pressure nozzle (jet grouting). Such techniques are more applicable in flatter terrain where access is relatively easy. These techniques have been used in the southeastern United States and in the UK.

6.3.3.6. Electro-osmosis

Electro-osmosis has been used to increase the *in-situ* shear strength of silts and clays. Typically used to stabilize embankment foundations, electro-osmosis has also been used to stabilize slopes although it is not common due to operational costs and uncertainties about its effectiveness. In field tests on soft Leda Clay in eastern Canada, the undrained shear strength was increased by about 50% using electro-osmosis.

6.3.3.7. Thermal Treatment

It is possible to increase soil strength using high temperatures that will remove moisture from the soil and potentially fuse fine grained particles together. This technique has not been used much due to the high cost of thermal treatment.

Ground freezing has been used more, particularly for the collection of samples and for tunneling. However, freezing is typically used for temporary conditions because it is very costly to keep the ground frozen for any length of time. Temporary freezing does not usually provide a permanent strength increase of the soil. However, freezing has been successful for longer term applications with the use of thermo-syphons. Some examples include: The hospital and visitors centre in Inuvik, Northwest Territories (Holubec, 2008).

6.3.4. Protection Measures

Where it is not possible to avoid unstable ground it may be feasible to construct protection structures. Such structures may consist of dikes, berms or walls that deflect slide material away from vulnerable structures or catchment basins that halt or slow down slide debris. These methods are discussed below.

6.3.4.1. Slide Deflection

Slide deflection berms have been used on numerous projects to deflect debris flows, landslides and snow avalanches around small developments, bridge structures and other sensitive structures. This typically involves construction of a lengthy berm made from native materials along one side of the channel or construction of a new channel. Deflection dikes can be effective near the apex of alluvial fans to deflect debris in a controlled manner along one side or both sides of the fan. An example of such a deflection dike is located at Port Alice, BC on Vancouver Island.

Another example of a slide deflection berm is the Mt. Stephen deflection dike located in the Rocky Mountains near Field, BC. A large rock fill berm channelizes avalanches and debris flows over a concrete cut and cover tunnel constructed by CP Rail in the 1980s. The structures have been effective at reducing the impact on the railway. However, periodic maintenance is required.

6.3.4.2. Catchment Basins

Where avoidance or deflection is not practical, it may be possible to slow down or catch debris flows or landslides using catchment basins, energy dissipaters and/or check dams. These structures usually involve excavation of large basins used to reduce the speed of slides. Check dams and energy dissipaters consisting of concrete structures, mounds, walls, piles or concrete fins are also used to impede slide progress. Many examples of large concrete check dams and catchment basins are located on the Sea to Sky Highway 99 between Vancouver and Squamish, BC. These structures require regular maintenance to clean out trapped debris.

6.4. Emergency Management

Emergency management of recent or on-going landslides will depend on the consequences of failure and the risk to persons and infrastructure. Once a landslide is identified, a preliminary risk evaluation must be conducted to determine a reasonable course of action. This risk evaluation will look at:

- likelihood of a failure or re-occurrence of an event,
- the consequence of failure in terms of injury or death to persons and economic loss,
- the need to undertake immediate landslide monitoring and/or investigation and analysis,
- the need to notify all potential stakeholders,
- the need to warn or evacuate people and/or to shut down or close infrastructure,
- potential methods of stabilization or slope treatment.

The perception of the potential loss can also play an important role in the evaluation of a landslide. Communication to all stakeholders (persons of interest) is critical in managing an emergency.

Risk scenarios must also be evaluated. A landslide may trigger another event which could lead to a catastrophic loss or damage to property. For example, a landslide could enter a large body of water generating waves that could damage properties and structures a considerable distance from the initial event. Risks must be examined in terms of costs and benefits to determine if they are acceptable or if remedial action is needed. Once the risk has been evaluated, it must be controlled to reduce the frequency and severity. Monitoring and warning systems are often deployed as an interim measure until the risk evaluation and risk control measures can be determined and implemented.

The final phase involves implementation of the risk control or action plan measures. This can involve any of the treatment options or combination of options discussed in this contribution. The components involved in slope stability emergency management are quite extensive and not discussed in detail here. For a better review of this aspect of landslide study refer to several contributions in Bobrowsky (2013).

A recent example of emergency management involved the development of a large rock slide on Highway 97 in south-central British Columbia in 2008. The potential slide forced the closure of the highway for 17 days while detailed monitoring and investigation programs were carried out. There was potential for the slide to affect some houses below and for the slide to enter a large lake causing wave damage. A detailed communication plan was developed through the local media and nearby residents to ensure that all stakeholders were informed of the process and timing for the action plan. The slide area was unloaded to reduce the probability of catastrophic occurrence and to allow the highway to re-open.

6.5. Limitations or Treatment Methods

All of the treatment options discussed in this section have limitations. Some of the more important limitations are as follows:

- knowing the size, extent and depth of the potential failure,
- having adequate space to implement a specific remedial option,
- having adequate resources to implement a specific remedial option,

- choosing a method that adequately addresses the stability concerns,
- choosing a method that keeps deformations to acceptable levels,
- requiring significant monitoring or inspection,
- having too high a cost to permit stabilization.

For most landslides, it is unlikely that all of the desired information will be available to allow assessment and develop the best treatment option(s). Local experience is a key factor in estimating some geological and environmental aspects of the slide conditions. Engineering judgement is always required in landslide assessment, risk evaluation and treatment application.

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