GEOTECHNIQUE AND THE MANAGEMENT OF LANDSLIDE HAZARDS

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ABSTRACT
Quantitative assessment of landslide hazards is an important task of geotechnical engineers and engineering geologists. The relevant problem scenaria are varied and sometimes complex, but rational methodologies are rapidly developing. It is important to remember, however, that geotechnical and engineering-geological questions form the foundation of all hazard assessment work. Quantitative treatment of such questions is not well developed and much room remains for improvement. Methods for quantitative estimation of hazard probability and failure behaviour are especially needed.

RÉSUMÉ
L'évaluation quantitative des aléas dus aux glissements de terrains est une tâche importante à laquelle sont confrontés les ingénieurs géotechniciens et les géologues du génie civil. Les scénarios relatifs à ce problème sont variés et parfois complexes, mais des méthodologies rationnelles se développent rapidement. Il est important de rappeler, cependant, que les questions géotechnique et géologique restent à la base de l'évaluation des aléas. Le traitement quantitatif de telles questions n'est pas très bien développé et il reste beaucoup de points à améliorer. Il serait particulièrement utile de proposer des méthodes permettant d'évaluer quantitativement les probabilités associées à un aléa, et de comprendre le comportement lors de la rupture.

1. INTRODUCTION

The importance of landslides as a natural hazard is difficult to quantify. In eastern and central Canada they are rare, apart from the Leda Clay region of the Ottawa - St.Lawrence Lowlands and the continental slope offshore. In the North, they are limited to certain specific types associated with permafrost (McRoberts and Morgenstern, 1974). Only the western Cordilleran region and the adjacent uplifted platform has a full spectrum of natural landslide hazards, starting from river valley slope instabilities in the Cretaceous shales and glacio-lacustrine soils of the Prairies, and continuing with rock slides, rock fall and debris flows in the mountains. Nevertheless, historical damage due to landslides appears surprisingly limited even in the West of Canada. Hungr (2004) estimated that the mean annual probability of death due to landslides for a citizen of British Columbia is only in the range of 10^{-6}. Material costs of landslides in B.C., including both direct losses and the cost of prevention amount to \$7 to \$33 per capita per year and less than 0.2% of the provincial GDP, compared to as much as 5% in some South American countries.

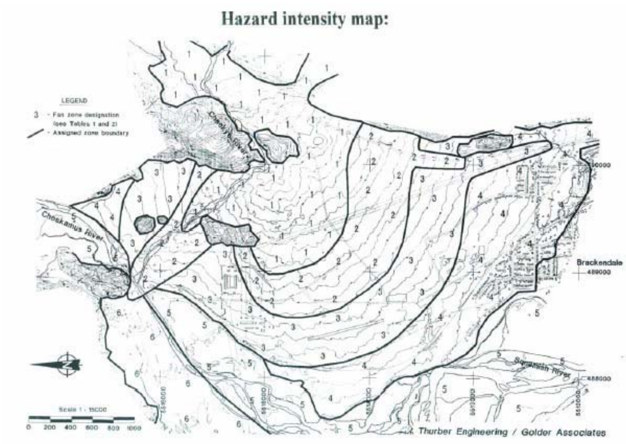
Despite these rather comfortable statistics, landslide hazards still represent a challenging problem for geotechnical engineers and geoscientists. There are several reasons. Firstly, Canada's population, as well as infrastructure are growing rapidly and future landslides may have much greater impact. Secondly, landslide damage cannot well be expressed using average numbers. For a specific family or community, a landslide accident can have devastating effects. It is for this reason of selective exposure, that landslide risks are uninsurable in North America. Thirdly, landslides have high and largely unaccountable indirect costs when they sever transportation and communication links, disrupt economic activity and damage the environment and resources (esp. forestry and fisheries). Fourth reason is that Canadian landslide expertise is frequently exported to other countries in the world, where landslide problems can be much more challenging than here. Finally, the geotechnical profession is not merely responsible for reducing damage. It must also prevent overestimation of potential hazards and risks, which can be equally costly to the society. Thus, landslide hazard assessments must be quantitative, reliable and accurate so that rational decisions can be made and both the risk costs and the costs of prevention can be minimized. The challenge of meeting these goals is discussed below.

2. HAZARD AND RISK CHARACTERIZATION

The term *hazard* means that the possibility exists of a dangerous condition (e.g. AGS, 2000). Some publications define hazard as a probability (e.g. Varnes, 1984), but this is not logical as the established term *probability* is sufficient. A *landslide hazard* is the possibility that a landslide can impact an area. To characterize landslide hazard, it is necessary to determine the *type(s)* of landslides, *magnitudes* (usually understood as volumes of material moved), source locations, *probability of occurrence* and intensity. The important term *source*, frequently left off landslide terminology descriptions, designates the volume between the *rupture surface* (Cruden and Varnes, 1996) and the pre-slide or *original ground surface*. Its area in plan can be designated as the *source area* of the landslide.

Many landslides go through cycles of activity separated by quiet periods and the term *failure* itself requires definition. It could be defined as “the most important movement episode in the past or future history of the landslide and one that leads to complete *detachment*, i.e. the formation of a continuous rupture surface”.

In analogy to earthquakes, *landslide intensity* is a spatial function characterizing the damage potential of the landslides. Hungr (1997) suggested that it can be described using parameters such as maximum velocity, thickness of flow or deposits, potential impact forces or differential movements and strains. The probability of a certain intensity being reached at a given point in the study area is not equal to the probability of occurrence of a landslide. For example, a landslide may occur, but may not impact the point in question. Thus, intensity values must be connected with their own *encounter probabilities* (McClung, 1999), obtained as a product of the probability of landslide occurrence and the conditional *probability of impact, given occurrence*. For long-displacement landslides, such results require the prediction of *runout*, i.e. the area over-run by landslide debris downslope of the source. (The term runout is also applied to the process of covering the runout area by landslide deposits, or to the distance between the toe of the source area and the toe of the deposit.)



Hazard	Large debris flow (3-7 million m3)	Medium debris flow (1-3 million m3)	…
Average Frequency	1:3,200	1:500	…
Hazard Zone 1	V = 7 m/s * H = 5 m W = 1.0 to 1.5km	V = 4 m/s H = 4 m W = 0.7 to 1.0 km	…
Hazard Zone 2	V = 4 m/s H = 3.5 m W = 0.7-1.5 km	…	…
…	…	…	…

* V = maximum flow velocity
H = deposit depth
W = width of damage corridor

Figure1, A hazard intensity map for a volcanic debris flow fan (Cheekye Fan, B.C., Sobkowicz et al., 1995)

Ideally, a hazard assessment study will result in a detailed map of the study area, showing the predicted distribution of hazard intensity parameters (e.g. movement velocities, debris thickness, displacements, strains) together with the probabilities of encounter for a spectrum of landslide types and magnitudes (Figure 1). Such *hazard maps* can be used directly by clients to determine *hazard acceptability* according to their own standards (e.g. Cave, 1992).

The consideration of risk enters the picture once existing or future *elements at risk* (population, goods, structures, environmental values) are located in the study area. *Vulnerability* is the percentage of value potentially lost under landslide impact and is, of course dependent not only on the characteristics of the elements, but also on the hazard intensity at a given location. Thus, vulnerability is not an inherent property of a structure, but must be assessed according to location on the hazard map. The product of the *value* of an element at risk and its vulnerability is sometimes referred to as a *consequence* of the hazard. In quantitative terms, *risk* is the product of consequence and encounter probability. If the latter is an *annual probability*, the risk can be expressed as an annual *risk cost*. Each of a number of elements, subject to a range of hazard types and magnitudes produces a *specific risk* amount. Accumulation of specific risks is required to produce an estimate of the *total risk* (total risk cost) for a given study area. The accumulation process can be quite complicated, depending on the configuration of the hazard problem, as listed in the following section.

Where only material losses are concerned, *risk acceptability* can be assessed by a routine cost-benefit analysis, comparing the total annual risk cost with the annualized cost of prevention or protection. The situation is much more complicated where human lives are in danger. Human risk can be expressed in terms of probability of death of a specific individual (*PDI*, Morgan, 1992) or the probability of death of groups (*PDG*, Fell, 1994). In this author's opinion, geotechnical professionals should avoid making direct decisions concerning acceptability of human risks and should expect acceptability standards to be set by other stakeholders (Hungr, 1997, 2004). Unfortunately, few such standards exist in Canada. A somewhat informal criterion used in the subdivision approval process in B.C. states that a "probability of landslide accident" of about 1:500 is acceptable. This appears to be a derivative of an older criterion of 1:200 applied to flooding. But it is not a risk acceptability criterion in a strict sense, as the level of risk is not stated, only the probability of hazard encounter. Similar uncertainty applies to environmental risks.

In order to avoid taking responsibility for hazard or risk acceptance, geotechnical professionals must find effective means of communicating their findings to clients and the public. In the writer's opinion, this requires that probabilities (of occurrence and encounter, as well as potential loss) must be expressed quantitatively. Qualitative statements, such as "low probability" are not sufficient, as such words may have very different meanings for different people. Qualitative hazard and risk assessments are useful only to provide relative guidance, for the purposes of prioritizing remedial effort or choosing the optimal siting of facilities. To seek absolute decisions regarding acceptability of hazard and risk, it is necessary to give quantitative estimates of probability. A quantitative statement, such as “the probability of this site being reached by a destructive debris flow surge is estimated as 1:100 per year” is clear and precise in conveying the professional’s degree of belief to the client, even if the number itself has not been quantitatively derived (e.g. Vick, 2003). Other professions use a similar approach, for example for weather forecasting. The probability estimates should be backed up by quantitative analysis wherever possible, even though in most cases they will be no more than informed guesses as discussed in Section 4.

3. TYPES OF LANDSLIDE PROBLEMS

Landslide problems occur in a variety of scenarios, each of which requires a somewhat different hazard assessment methodology:

a) Individual slope stability

This problem involves a natural or artificial slope. It is necessary to determine whether the slope will remain stable in the future, taking into account a variety of possible changed conditions including extreme weather, earthquake, land use change or construction. This is the routine “slope stability” problem covered by geotechnical texts. The answer may take the form of a safety factor, a reliability index or a deformation prediction. An estimate of the probability of occurrence of a failure must be derived from such indices and can be used to calculate risk, when supplemented with additional predictions concerning the character and dimensions of failure and runout.

b) Individual existing landslide

Where a landslide has already been initiated, predictions are needed with regard to future displacements, retrogression or enlargement of the slide area, or a change in movement rate and possible runout dynamics. The answer may take a variety of forms, such as the future changes of the Factor of Safety, predicted total or differential displacements, prediction of the movement mechanism, manner or amount of retrogression, probability of full detachment and major acceleration (failure), velocity, or runout distance. A special type of characterization is “activity mapping” (Van Westen, 1993), where areas of highly unstable terrain (*landslide terrain*) are zoned according to current state of activity, based on movement observations.

c) Landslide susceptibility zoning

In this problem, a given area is to be zoned in terms of susceptibility to produce landslides. In its most ideal form, *landslide susceptibility* can be considered as a spatially-distributed function, defined as “expected *landslide density*” measured in terms of events per year per km^2 of area for small landslides, or in m^2 of potentially unstable terrain per km^2 of area per year. Qualitative susceptibility maps (e.g. high, medium and low susceptibility) are probably more common, but are useful only for making relative choices such as route selection. The map can be used to control development of an area, i.e. to avoid building directly on top of the potentially unstable zones, or it can serve as an indicator of source instabilities that may propagate and feed hazard zones downslope (see Type e2 below). A separate susceptibility map should be prepared for each landslide type. The predicted probabilities may need to consider changes in land use, esp. clearcut logging, burning or earthquake (e.g. Rollerson and Sondheim, 1985, Rollerson et al. 1998). Such maps are most often used for shallow landslides (e.g. Evans and King, 1998), although detailed susceptibility maps have also been prepared for areas of frequent deep-seated landslides (e.g. Brabb et al., 1972). Excellent reviews of the several qualitative and quantitative methods for producing landslide susceptibility maps have been published by Van Westen (1993) and Soeters and Van Westen (1996). An example of a raster-based susceptibility map prepared using GIS for a study area in Hong Kong is shown in Figure 2.

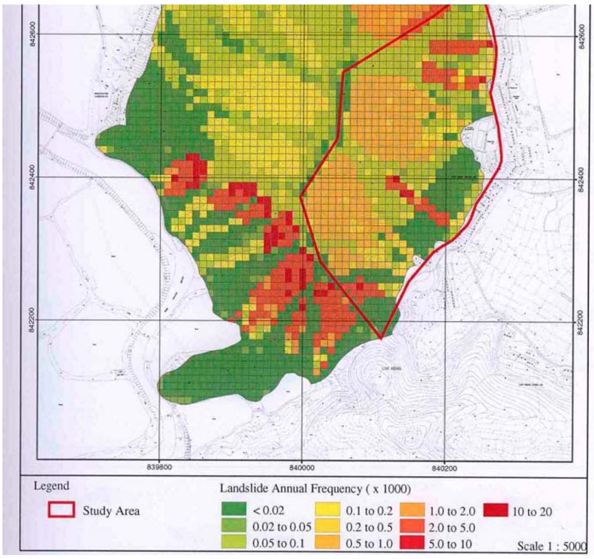


Figure 2, An example of a raster-based landslide susceptibility map of a study area in Hong Kong (courtesy Ove Arup Associates, Hong Kong)

An important aspect of quantitative landslide susceptibility mapping is validation. Chung and Fabbri (2003) proposed a convenient way to validate maps against landslide inventories. To do this, the susceptibility map contoured with respect to susceptibility for landsliding (or predicted slide density) is overlaid with an inventory map, showing actual landslides that occurred over a given period. The cumulative area within

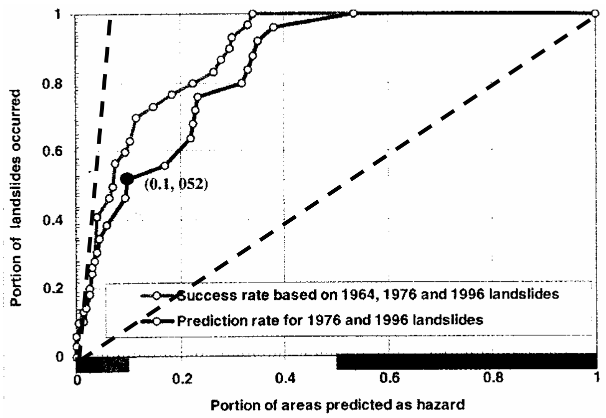


Figure 3, Example validation curves from a study area near La Baie, Quebec (Chung and Fabbri, 2003). The two inventory maps used in the validation procedure result from different time intervals. The two diagonal lines represent an "ideal" map and a "random" map.

each of a number of susceptibility classes is measured, normalized by the total area of the map and plotted on the abscissa of a diagram (Figure 3). Then, the cumulative area (or number, as in Fig. 3) of all landslides contained within the area of the given category is normalized by the total area (number) of all the landslides and plotted as ordinate. An "ideal" map, that predicts the occurrence of landslides precisely, would produce a diagram shown by the steep line in Figure 3, which connects the origin with a point situated at an x-distance representing the ratio between the area of all landslides and the area of the map. The flatter diagonal line, on the other hand, represents a "random" map with zero predictive capability. The position of the actual validation curve between the two limits represents the quality of the map.

Chung and Fabbri (2003) point out that, when the inventory map used in the above procedure is the same map that was used to calibrate the susceptibility model, the curve is merely the measure of "success rate". In other words, it measures how well has the model been fitted to the given data. The true prediction rate is validated only if the inventory map used is different from the calibration map, originating from a different part of the study area or a different period in time. The disadvantage of such a procedure is a reduction in the size of the database available for calibration.
The validation concept can be used to systematically choose the best susceptibility algorithm. Combinations of different predictors can be used to produce "draft" susceptibility maps as represented by Figure 2. Each map is validated against an inventory and that combination producing the best "fit" is accepted. Some promising developments in this area involve the application of neural network analysis (e.g. Mihai, 2003).

d) Set-back lines.

A special case of landslide susceptibility zoning is applied to the required set-back distance for construction above the crests of a potentially unstable slope (e.g. Cruden et al., 1989). The distance can be defined deterministically, with an appropriate Factor of Safety, or probabilistically (retrogression distance versus probability of occurrence within the lifetime of the structure). The latter can be used to derive risk, although the author does not know an example.

e1) Hazard maps in the runout area, based on the analysis of deposits.

Rapid landslides such as debris flows, debris avalanches or rock falls threaten areas that are far removed from the landslide source. Ideally, the distribution of landslide intensity and encounter probability should be mapped in the runout zones, in order to guide development decisions and provide parameters for the design of protective measures (Sobkowicz et al., 1995)

In this case, the history of the runout area itself provides data on landslides that periodically reach it. Thus, for example, a database of debris flows depositing on a given deposition fan can be established from historical records or from an analysis of the fan stratigraphy (Hungr and Rawlings, 1995). Synthetic debris flow hydrographs at the fan apex will then serve as initial conditions for runout analyses, with no need to study the landslide sources in the watershed above (e.g. O'Brien et al., 1993).

A special case of this type of analysis is the mapping of rock fall "shadow" areas below source cliffs (Evans and Hungr, 1993), or the estimation of risks on a transportation route bordered by cliffs, based on statistical analyses of previous events. (Bunce et al., 1997, Hungr et al., 1998b).

e2) Hazard maps in the runout area, based on the analysis of sources.

This method uses analyses of the complete paths: from landslide source areas on the slope to the deposition area below (e.g. Hungr, 2002). The first step in doing this involves the preparation of a landslide susceptibility map on the slope, similar to that shown in Figure 2. The runout of each potential landslide originating there is then extended into the deposition zone. Figure 4 shows potential debris avalanche/debris flow delivery lines (downslope trajectories) generated by GIS for the same Hong Kong study area as shown in Figure 2. Each delivery line connects a pixel on the susceptibility map with points located in the runout zone. The distance along each delivery line reached by landslides originating in various pixels is determined using a set algorithm (see below). This may be a complicated process in quantitative terms, as the source probability of various landslides at the source must be multiplied by the conditional probability of runout reaching a certain point in the hazard zone. Both probabilities are strongly dependent on the type and magnitude of each landslide. Thus, a separate hazard map should be produced for different landslide classes. A combined hazard map can also be produced by overlaying the individual maps. The result is again a distribution of intensity and probability of encounter in hazard polygons, which can be used to estimate total risk (e.g Hungr et al., 1998a).

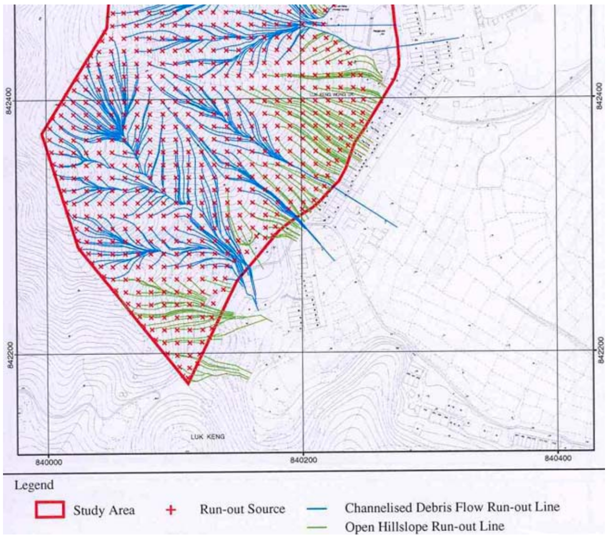


Figure 4. GIS - produced “delivery lines” connesting the landslide susceptibility pixels of Figure 2 with the debris flow (blue)/ debris avalanche (green) areas downstream. (courtesy Ove Arup Associates, Hong Kong)

4. GEOTECHNICAL ISSUES

The general methodology for hazard and risk assessment has received much attention recently in the literature and is reasonably well understood (e.g. Fell and Hartford, 1997). The chain of events leading to landslide damage takes the form of a simple event tree with a single branch: instability of a source volume, failure, acceleration and runout, impact of a given intensity and consequences. The difficult aspects lie in the geotechnical predictions required to build quantitative understanding of the hazard processes. Particularly important are estimates of the probability of occurrence of slope failure and conditional probabilities connecting each step along the event tree. The accuracy of a quantitative hazard or risk assessment depends entirely on these geotechnical components.

4.1 “A Priori” Probability Estimates.

Slope stability, the first question in a hazard assessment, is traditionally answered with the use of a Factor of Safety. Through experience, certain established values of the factor have been established, connected with specific classes of problems and regional contexts. Use of such values can be thought of as a proxy for a probabilistic assessment, using the following rationale: if many similar slopes designed with the same minimum Factor of Safety performed satisfactorily in the past over typical design periods of time, then the probability of failure of a new slope designed the same way is also likely to be acceptable.

More recent analytical techniques calculate “probability of failure” or “reliability” derived from the variance of strength parameters and other input variables. The results of a probabilistic slope stability analysis cannot at present provide an absolute estimate of the probability of failure, especially not in a temporal framework (e.g. Morgenstern, 1995). The reason is that these methods account only for natural variation of certain input parameters and sometimes for some measure of model uncertainty. Important uncertainties connected with the interpretation of the failure mechanism, geological complexities, sampling or testing errors and temporal variation of parameters and conditions cannot be covered. A true probabilistic design method would require calibration through comparisons of analyses with observations of the performance of real slopes (El-Ramly et al., 2002). Before such a body of experience is built up, probabilistic methods of slope stability analysis will remain less useful for estimation of absolute failure probability than the Safety Factor approach, which does possess a degree of calibration. This is not to discount the usefulness of such methods in providing insight into the role of certain types of uncertainty. However, we must admit that we are presently unable to calculate *a priori* quantitative estimates of failure probability.

The second question in hazard analysis is the determination of the character of failure. There are many cases, where eventual instability can be taken for granted. What remains uncertain, however, is how the failure will develop. Will it involve high velocities and large displacements? There are no established analytical techniques to answer this question and the available approach is almost entirely empirical, as described in the following paragraphs.

Many rock slopes in mountainous regions exhibit large-scale deformations. The important question to be answered is whether slow deformations will continue indefinitely, or progress into an episode of fairly large deformations with limited speeds, or accelerate suddenly and catastrophically and create a long-runout rock avalanche. Some understanding of the failure process can be gained from parametric studies. For example, Nichol and Hungr (2002) showed that large-scale toppling of a mountain slope tends to be slow and self-stabilizing in weak rock and in the absence of major down-slope dipping discontinuities, but can be catastrophic in stronger rock when the latter are present. More often, however, analytical predictions can only be used to supplement field observations as a component of the observational method. They cannot derive probability estimates directly.

A promising approach towards prediction of failure behaviour for natural slopes uses failure typology. Hungr and Evans (2004), for example, observed that rotational slides in weak rocks tend to be relatively slow and ductile, while structurally-controlled translational slides in the same rock can be catastrophic.

Similar typological approach can be used for other landslides. Flow slides that involve significant strength loss through soil structure collapse or liquefaction, such as quick clay slides or flow slides in loose saturated sand, nearly always involve rapid failure. The concept of undrained "Brittleness Index", proposed by Bishop (1973) is a useful measure of the propensity of a soil to lose strength, although it is difficult to determine in situations other than controlled laboratory tests. Susceptibility to earthquake liquefaction of loose saturated granular soils can be estimated in probabilistic terms (e,g, Liao et al., 1988). The probability of a slope failure involving static liquefaction, on the other hand, cannot be determined by analysis.

Shallow debris slides on steep slopes, involving colluvial veneers, residual or volcanic soils, are also generally extremely rapid, as a result of sudden cohesion loss (Hungr, 2003). The resulting debris avalanches will travel to the foot of the slope, often enlarging along the way (Revellino et al., 2003) and may convert into debris flows, if they enter confined channels (Hungr et al., 2001).

Rotational and compound slides in overconsolidated, insensitive clays and the associated earth flows are usually slow-moving and their future behaviour can be predicted with reasonable accuracy from past experience. However, the potential for unexpected surging still requires judgmental prediction.

Some landslides exhibit anomalous failure behaviour. For example, the extremely rapid failure of the 1963 Vaiont Slide has inspired a variety of explanations. One of the most plausible invokes the brittleness of strong limestone beds subject to internal shear, due to the non-rotational shape of the rupture surface (Hutchinson, 1988).

Of special concern are landslides which display a long period of ductile deformation, followed by a sudden brittle failure. The Attachie Slide in overconsolidated clays and silts of northern British Columbia exhibited several tens of metres of gradual displacements over many decades, forming a distinct topography of scarps and benches characteristic of other slow landslides in the area. In the spring of 1975, following a period of rain, the slope failed catastrophically and produced a displacement of about 1 km over several minutes, damming the Peace River and raising a displacement wave on the opposite bank. Fletcher et al. (2002) explained this change of failure behaviour by gradual deterioration of the soil structure through a process of cracking and softening, producing a brittle mass of blocks and matrix.

Even though such considerations are absolutely crucial to the determination of the probability of occurrence of a rapid failure, none can presently be translated into a quantitative prediction. The probability of occurrence of a catastrophic slope failure can usually be quantified only on the basis of experienced judgment (Vick, 2003). Hungr (1997) suggested a scale for judgmental probability estimates, based on multiples of five (Table 1). This allows for frequency estimates that are more accurate than an order of magnitude, yet can be supported by simple observations. For example, in humid, temperate climate, landslides in the Very High category will exhibit fresh signs of disturbance. Those in the High category may be re-vegetated, but with clear impact on the forest succession. Both are also likely to be within the scope of eyewitness records. Landslides in the Low category may leave no trace on vegetation, as there is enough time to develop new forest succession.

Table 1, Suggested ranges of annual probability for subjective estimation (Hungr, 1997)

Term	*Range of Probability (1/year)*
Very High	> 1/20
High	1/100 to 1/20
Medium	1/500 to 1/100
Low	1/2500 to 1/500
Very Low	<1/2500

4.2 Frequency Analysis

Most quantitative probability estimates in geotechnics rely on frequency analysis of previous occurrences.

Some types of landslides, such as debris flows, are cyclic at a given location. This allows conventional frequency analysis to be conducted, similar to flood analyses. For example, García et al. (2003) used routine hydrologic analysis of debris flow streams in the Vargas State of northern Venezuela, to derive synthetic flood hydrographs for major, low probability storms. They then calibrated a debris flood / debris flow runout model (O'Brien et al., 1993) with data on debris flow magnitude and peak discharge from the December, 1999 disaster, to derive empirical bulking factors that change the flood hydrographs into debris flow hydrographs. The calibrated model could thus be used to derive hazard intensity maps connected with different return periods.

The above approach can be used only where reliable rainfall records exist, associated with major debris flow events. Unfortunately, few locations have such data. Most often, debris flows disasters are caused by cells of concentrated rainfall or rain on snowmelt events, whose intensities are not well represented in available climatic data (Revellino et al., 2003, Church and Miles, 1984).

Cumulative Frequency-Magnitude (CFM) curves of debris flows on a deposition fan can sometimes be derived by compiling an inventory of dated events from a reconstruction of the internal stratigraphy of the fan. The Cheekye Fan near Vancouver, B.C. is an example (Figure 5, Sobkowicz et al., 1995)

Unfortunately, most landslide types are not cyclic at a given location. Meaningful frequency analyses can then only be carried out on a regional basis, producing estimates of landslide density in various size categories, per year, per unit area. For example, a review of available inventories of large rock avalanches (over 20million m^3 in volume) showed that these occur at an annual frequency of 1:500 to 1:5 000 per 10 000 km^2 of mountainous terrain (Hungr and Evans, 2004). CFM curves for large rock avalanches have been shown by Whitehouse and Griffiths (1983). Such curves provide excellent means for estimating the regionally-based probability of occurrence.

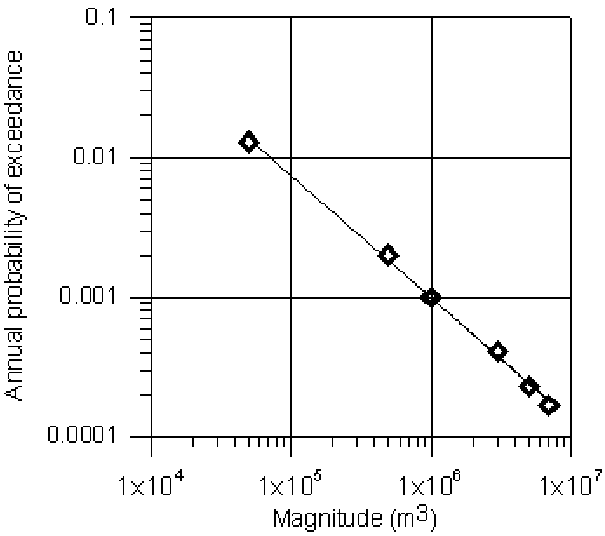


Figure 5, Cumulative frequency-magnitude curve for volcanic debris flows on the Cheekye Fan near Squamish, B.C., derived from analysisng the stratighraphy of the fan. Note: Magnitude is the volume of deposits in m^3 (after Sobkowicz et al., 1995)

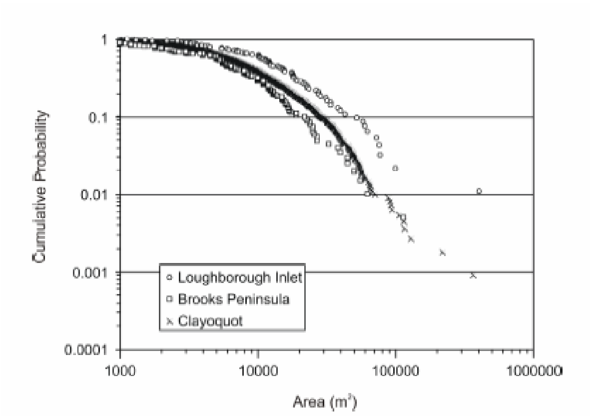


Figure 6
Areally-based cumulative frequency-magnitude curves for debris avalanches in three study areas in British Columbia (Guthrie and Evans, 2004b). Note: maginitude is expressed as plan area of the "total disturbed area", i. e. including the source, path and deposit.

Similarly, CFM curves for rock fall can be derived from eyewitness observation records, or by counting impact marks on road pavement (e.g. Bunce et al., 1997, Hungr et al., 1998b). The latter article demonstrated their use for estimating human risks caused by rock fall on a transportation route.

The concept of spatially-based cumulative frequency-magnitude curves is potentially most useful for prediction of debris avalanches. Unfortunately, collection and interpretation of CFM curves from debris slide and debris avalanche inventories is exceedingly difficult.

Areally-based CFM curves for debris avalanches, compiled from airphoto studies, have been reviewed by Pelletier et al. (1997), Dai and Lee (2001), Guthrie and Evans (2004a,b) and others. Some of these show a linear "fractal" relationship on a log-log scale similar to Figure 5, with a slope approximating -1.0. Most, however, exhibit a curvature ("rollover") towards the left-hand side (Figure 6). This is at least in part caused by censoring, i.e. under-recognition of smaller events. Recently, however, some authors found that in certain locations there may be physical reasons for the curvature. If the event magnitude is expressed as the total disturbed area, as in Figure 6, then it is dependent not only on the size of the landslide source, but also on the length and steepness of the slope that accommodates the landslide path. Thus, the frequency and magnitude relationship may reflect the topographical setting of the study area. The data shown in Figure 6, originating from Vancouver Island, shows non-linearity for areas less than 10000 m^2 (corresponding to volumes of about 5000 m^3. Hong Kong data, on the other hand, is linear down to 100 m^3 (Dai and Lee, 2001). Such differences make CFM relationships difficult to export from one region to another.

For the purposes of calibrating landslide susceptibility maps, landslide inventories can be converted into maps of landslide density. This is accomplished by defining polygons of relatively uniform occurrence, or by mapping unstable areas on a grid of pixels. The difficult next step is assigning a representative time interval to the inventory, so that landslide densities can be quantified in terms of events/km^2/year, or m^2 of unstable terrain per km^2/year. The time interval may be a recognizable geological period (e.g. post-glacial period, a period of airphoto coverage or a known period of dated records. In each case, the problem of under-recognition must be dealt with. Especially, smaller landslide scars are often obliterated by weathering or vegetation, or systematically under-reported. One way to improve sampling of landslide densities is to use longer sampling intervals for larger events and shorter ones for small ones (e.g. Hungr et al., 1998b). Once the applicable landslide densities are obtained, they must be parsed into magnitude categories using a CFM curve.

A serious potential problem in deriving landslide densities is that the usual working assumption is that of constant rate of occurrence, consistent with a rather simplistic application of the Uniformitarian Principle. In fact, many landslides tend to occur in clusters, sometimes with wide spatial as well as temporal spacing. The location of a given cluster may be determined by the track of a specific storm precipitation cell, as much as by geology or other variables (e.g. Guthrie and Evans, 2004b). Yet, detailed climatic data required for resolving the influence of local rainfall is rarely available. Suitable approach towards addressing this problem of process variability has not yet been developed.

A second problem is the question of stationarity: once a dense cluster of landslides removes a large proportion of soil cover from steep slopes of an area, another cluster may not be possible for a considerable period of time. An extreme example of this is the shallow instability of steep slopes of the Campania Region of Italy, that involves a pyroclastic veneer overlying limestone. Once the veneer has slid, the affected slopes remain permanently benign, while adjacent "intact" slopes continue posing hazard (Revellino et al., 2003). A mechanically-applied frequency analysis applied to such a situation would identify the intact slopes as "safe", producing a completely erroneous result.

Research is urgently needed to provide methods dealing with these problems.

4.3. Runout Analysis

Various runout mechanisms, including sliding, flow or fall and rolling connect the source areas of rapid landslide with the hazard zones downhill. Runout analysis is an area of active research at present and practical methods are gradually being developed.

The most prevalent empirical method includes the travel angle (fahrböschung) method. The travel angle is the vertical angle between the crest of the source and the toe of deposit. It has been correlated with landslide type, volume and other parameters (e.g. Corominas, 1996). Another simple empirical approach uses the concept of geometrical similarity between deposits of landslides of a certain type, allowing correlations between inundation areas and volumes (Iverson et al., 1998). All such correlations tend to be highly scattered. Nevertheless, they have the advantage of being easily incorporated into GIS-based models and can easily be applied in a probabilistic manner.

A number of analytical models of landslide motion have also been developed recently. Landslide movement is a complex phenomenon that cannot be easily captured in a simple constitutive relationship. It appears that various rheological models need to be applied to different types of landslides. The concept of "equivalent fluid", used implicitly by many researchers over the years and formalized by Hungr (1995) and Mc Dougall and Hungr (2004) gives promise of practical usefulness. However, detailed calibration against real landslide cases is required for the full spectrum of landslide types. Dynamic runout models can be applied in a probabilistic manner, to determine risk (e.g. Tse et al., 1999).

5. CONCLUSIONS

It could be said that the statistical and methodological aspects of landslide hazard assessment are relatively simple and well-developed. Many of the underlying geotechnical aspects, on the other hand, are exceedingly challenging. What is urgently required is improved techniques of landslide frequency analysis, better and more quantitative understanding of rapid failure initiation mechanisms and better calibration of runout models. Without these elements, quantitative hazard and risk analyses will remain largely subjective.

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