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Landslide risk assessment and management: an overview

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Abstract

Landslides can result in enormous casualties and huge economic losses in mountainous regions. In order to mitigate landslide hazard effectively, new methodologies are required to develop a better understanding of landslide hazard and to make rational decisions on the allocation of funds for management of landslide risk. Recent advances in risk analysis and risk assessment are beginning to provide systematic and rigorous processes to enhance slope management. In recent years, risk analysis and assessment has become an important tool in addressing uncertainty inherent in landslide hazards. This article reviews recent advances in landslide risk assessment and management, and discusses the applicability of a variety of approaches to assessing landslide risk. Firstly, a framework for landslide risk assessment and management by which landslide risk can be reduced is proposed. This is followed by a critical review of the current state of research on assessing the probability of landsliding, runout behavior, and vulnerability. Effective management strategies for reducing economic and social losses due to landslides are described. Problems in landslide risk assessment and management are also examined.

Keywords: Landslides; Probability; Runout behavior; Vulnerability; Risk

1. Introduction

Landslides, as one of the major natural hazards, account each year for enormous property damage in terms of both direct and indirect costs. Landslides, defined as the movement of a mass of rock, debris or earth down a slope (Cruden, 1991), can be triggered by a variety of external stimulus, such as intense rainfall, earthquake shaking, water level change, storm waves or rapid stream erosion that cause a rapid increase in shear stress or decrease in shear strength of slope-forming materials. In addition, as development expands into unstable hillslope areas under the pressures of increasing population and urbanization, human activities such as deforestation or excavation of slopes for road cuts and building sites, etc., have become important triggers for landslide occurrence.

Landslides have caused large numbers of casualties and huge economic losses in mountainous areas of the world. The most disastrous landslides have claimed as many as 100,000 lives (Li and Wang, 1992). In the United States, landslides cause an estimated US$1–2 billion in economic losses and

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about 25–50 deaths annually, thus exceeding the average losses due to earthquakes (Schuster and Fleming, 1986). Li and Wang (1992) conservatively estimated that in China the number of deaths caused by landslides totaled more than 5000 during the 1951–1989 period, resulting in an average of more than 125 deaths annually, and annual economic losses of about US$500 million.

Social and economic losses due to landslides can be reduced by means of effective planning and management. These approaches include: (a) restriction of development in landslide-prone areas, (b) use of excavation, grading, landscaping, and construction codes, (c) use of physical measures (drainage, slope-geometry modification, and structures) to prevent or control landslides, and (d) development of warning systems (Slosson and Krohn, 1982; Schuster and Leighton, 1988; Schuster, 1996). Schuster and Leighton (1988) estimated that these methods could reduce landslide losses in California by more than 90%. Slosson and Krohn (1982) stated that enactment of these approaches had already reduced landslide losses in the City of Los Angeles by 92–97%. However, in spite of improvements in hazard recognition, prediction, mitigation measures, and warning systems, worldwide landslide activity is increasing. This trend is expected to continue in the 21st century for the following reasons (Schuster, 1996):

- increased urbanization and development in landslide-prone areas;
- continued deforestation of landslide-prone areas; and
- increased regional precipitation caused by changing climatic patterns.

To address the landslide problem, governmental agencies need to develop a better understanding of landslide hazard and to make rational decisions on allocation of funds for management of landslide risk. However, it is widely accepted that the landslide problem is dominated by uncertainty. This uncertainty arises at all stages in the resolution of the problem, from site characterization to material property evaluation to analysis and design and consequence assessment (Morgenstern, 1997). Recent advances in risk analysis and risk assessment are beginning to provide systematic and rigorous processes to formalize slope engineering practice and enhance slope management (Fell and Hartford, 1997). In recent years, risk analysis and assessment has become an important tool in addressing uncertainty inherent in landslide hazards.

This article reviews recent advances in landslide risk assessment and management, and discusses the applicability of a variety of approaches to assessing landslide risk. Since various definitions of risk terms are available, the authors have adopted the definitions used in the IUGS Working Group on Landslides, Committee on Risk Assessment (1997).

2. Basic framework for landslide risk assessment and management

Landslide risk assessment and management comprises the estimation of the level of risk, deciding whether or not it is acceptable, and exercising appropriate control measures to reduce the risk when the risk level cannot be accepted (Ho et al., 2000). It requires the following issues to be addressed: (a) probability of landsliding, (b) runout behavior of landslide debris, (c) vulnerability of property and people to landslide, (d) landslide risk to property and people, and (e) management strategies and decision-making (Fig. 1).

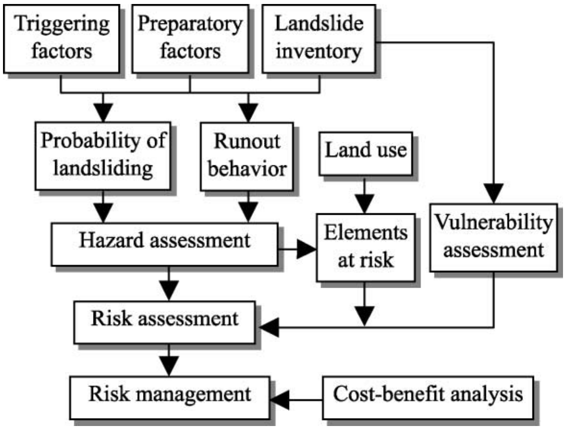

Fig. 1. A framework for landslide risk assessment and management.

In terms of conditional probability, landslide risk when defined as the annual probability of loss of life of a specific individual may be calculated as follows (Morgan et al., 1992):

$$R(\mathrm{DI}) = P(\mathrm{H}) \times P(\mathrm{S} \mid \mathrm{H}) \times P(\mathrm{T} \mid \mathrm{S}) \times V(\mathrm{L} \mid \mathrm{T}) \quad (1)$$

where R(DI) is the risk (annual probability of loss of life to an individual); P(H) is the annual probability of the landslide event; P(S|H) is the probability of spatial impact given the event; P(T|S) is the probability of temporal impact given the spatial impact; and V(L|T) is the vulnerability of the individual (probability of loss of life of the individual given impact).

For a case involving property damage the equivalent expression would be

$$R(\mathrm{PD}) = P(\mathrm{H}) \times P(\mathrm{S} \mid \mathrm{H}) \times V(\mathrm{P} \mid \mathrm{S}) \times E \quad (2)$$

where R(PD) is the risk (annual loss of property value); P(H) is the annual probability of the landslide event; P(S|H) is the probability of spatial impact (i.e. of the landslide impacting the property); V(P|S) is the vulnerability of the property (proportion of property value lost); E is the element at risk (e.g. the value of the property).

Some researchers considered the product of $P(\mathrm{S}|\mathrm{H}) \times P(\mathrm{T}|\mathrm{S}) \times V(\mathrm{L}|\mathrm{T})$ in Eq. (1) or $P(\mathrm{S}|\mathrm{H}) \times V(\mathrm{P}|\mathrm{S}) \times E$ in Eq. (2) as “consequence” (e.g. Wong et al., 1997) or the product of $P(\mathrm{H}) \times P(\mathrm{S}|\mathrm{H})$ as “hazard” (e.g. Leroueil and Locat, 1998).

Landslide risk can be assessed qualitatively or quantitatively. Whether qualitative or quantitative assessments are more suitable depends on both the desired accuracy of the outcome and the nature of the problem, and should be compatible with the quality and quantity of available data. Generally, for a large area where the quality and quantity of available data are too meager for quantitative analysis, a qualitative risk assessment may be more applicable; while for site-specific slopes that are amenable to conventional limit equilibrium analysis, a detailed quantitative risk assessment should be carried out.

3. Assessment of probability of landsliding

When assessing the probability of landsliding within a specified period of time and within a given area, recognition of the conditions that caused the slope to become unstable and the processes that triggered the movement is of primary importance. The factors which determine the probability of landsliding for a particular slope or an area may be grouped into two categories: (1) the preparatory variables which make the slope susceptible to failure without actually initiating it and thereby tending to place the slope in a marginally stable state, such as geology, slope gradient and aspect, elevation, soil geotechnical properties, vegetation cover and long-term drainage patterns and weathering; and (2) the triggering variables which shift the slope from a marginally stable to an unstable state and thereby initiating failure in an area of given susceptibility, such as heavy rainfall and earthquakes (Wu and Sidle, 1995). Obviously, the probability of landsliding depends on both the preparatory and triggering variables. However, the triggering variables may change over a very short time span, and are thus very difficult to estimate. If triggering variables are not taken into account, the term “susceptibility” may be employed to define the likelihood of occurrence of a landslide event. At present, when assessing the probability of landsliding on regional scales, it might be feasible to consider landslide susceptibility as the probability of landsliding based on the assumption that long-term historic landslide records tend to smooth-out the spatio-temporal effect of triggering factors on landslide occurrence. For large-scale hazard assessments, in which work is carried out in relatively small areas or specific slopes, data collection at this scale should relate to the quantitative parameters needed for slope stability modeling.

Numerous methods have been developed to assess the probability of landsliding. Soeters and van Westen (1996) and van Westen et al. (1997) divided these methods into inventory, heuristic, statistical, and deterministic approaches.

The most straightforward initial approach to any study of landslide hazard is the compilation of a landslide inventory, and such inventories are the basis of most susceptibility mapping techniques. On detailed landslide inventory maps, the basic information for evaluating and reducing landslide hazards or risk on a regional or community level should be provided, including the state of activity, certainty of identification, dominant type of slope movement, primary direction of movement, estimated thickness of material involved in landsliding, and date(s) of known activity for each landslide (Wieczorek, 1984). They can be prepared by collecting historic information on landslide events or from aerial photograph interpretation coupled with field checking. The presentation of landslides on inventory maps varies from detailed features of the landslides to points representing locations of the landslides, depending on both the nature of problem and the size of failures. Inventory maps can be used as an elementary form of hazard map because they show the locations of recorded landslides. Based on the landslide inventory map, landslide density or landslide isopleth can be generated by counting circles (Wright et al., 1974). The historic frequency of landslides in an area can be determined to provide realistic estimates of landslide probability throughout a region where landslides have caused a significant amount of damage. The trigger/landsliding and frequency–magnitude relations that help understand landslide probabilities may be derived from landslide inventories. However, landslide inventory and isopleth maps do not identify areas that may be susceptible to landsliding unless landslides have already occurred.

With the heuristic approaches, expert opinions are used to estimate landslide potential from data on preparatory variables. They are based on the assumption that the relationships between landslide susceptibility and the preparatory variables are known and are specified in the models. A set of variables is then entered into the model to estimate landslide susceptibility (e.g. Gupta and Joshi, 1989). One problem with the heuristic models is that they need long-term information on the landslides and their causal factors for the same site or for sites with similar geo-environmental conditions. However, the information is, in most cases, not available. Other limitations of this method are the reproducibility of the results and the subjectivity of weightings and ratings of the variables.

Deterministic approaches are based on slope stability analyses, and are only applicable when the ground conditions are fairly uniform across the study area and the landslide types are known and relatively easy to analyze. They have been widely used to assess landslide probability in small areas (Terlien et al., 1995; Wu and Sidle, 1995). For rainfall-induced failures, these models couple shallow subsurface flow (i.e. the pore pressure spatial distribution) caused by rainfalls of various return periods, predicted soil thickness, and landsliding of the soil mantle. For earthquake-induced failures, a conventional seismic hazard analysis is used to determine the peak ground accelerations (PGA) for different return periods and the stability of slopes when subjected to an earthquake with various return periods is examined using a pseudo-static analysis. Stability conditions are generally evaluated by means of an infinite slope stability model, where local equilibrium along a potential slip surface is considered. The advantage of the deterministic models is that they permit quantitative factors of safety to be calculated with due consideration for the variability of soil properties if necessary, while the main problem is the high degree of simplification that is usually necessary for the use of such models. Another problem that limits the applicability of the deterministic models is that data requirements for deterministic models can be prohibitive, and frequently it is impossible to acquire the input data necessary to use the models effectively.

Statistical models involve the statistical determination of the combinations of variables that have led to landslide occurrence in the past. Statistical estimates are made for areas currently free of landslides, but where similar conditions exist. Conventional multivariate statistical methods, such as multiple regression analysis and discriminant analysis, have been used to assess landslide susceptibility (e.g. Yin and Yan, 1988; Carrara et al., 1991). However, the use of multivariate statistical models has always been hindered by the need for continuous data. Categorical data, such as geology, can be used but it commonly involves the use of dummy variables to indicate the presence or absence of a variable. This can result in an enormous increase in the number of variables, with the increase being directly related to the number of categories in each explanatory variable. Moreover, both techniques showed limited value when the dependent variables takes only two values, that is, whether landsliding occurs or not. Under these circumstances, the assumption needed to test the hypothesis in regression analysis are violated. In such cases, another multivariate technique, that of logistic regression that is used for estimating the probability of an event occurring, is applied (e.g. Carrara et al., 1991; Chung and Fabbri, 1999). The advantage of logistic regression modeling over other multivariate statistical techniques including multiple regression analysis and discriminant analysis is that the dependent variable can have only two values — an event occurring or not occurring, and that predicted values can be interpreted as probability since they are constrained to fall in the interval between 0 and 1. Statistical techniques are generally considered the most appropriate approach for landslide susceptibility mapping at medium scales of 1:10,000–1:50,000, because on this scale it is possible to map out in detail the occurrence of past landslides, and to collect sufficient information on the variables that are considered to be relevant to the occurrence of landslides. However, one problem with the use of multivariate statistical approaches in establishing correlations between independent variables and landslide susceptibility is that there is a potential danger that such statistical methods, when used in a black-box manner with inadequate consideration of the mechanics of the physical processes involved, are liable to result in very coarse and even misleading regression correlations (Ho et al., 2000). This means that they must be applied in a suitable mechanistic framework.

For site-specific slopes, the probability of failure is usually considered as simply the probability that the factor of safety is less than unity. The performance function of slopes, denoted by $G(X)$ where X is the collection of random input parameters, is a function which defines the failure or safety state of a slope. The function is defined in such a way that failure is implied when $G(X)<0$ and safety by $G(X)>0$. The boundary defined by $G(X)=0$ separating the safety and failure domains is called the limit state boundary.

The performance function for a slope is usually taken as one of the following formats

$$G(X) = R(X) - S(X) \tag{3}$$

or

$$G(X) = F(X) - 1 \tag{4}$$

where $R(X)$ is the resistance and $S(X)$ is the action, and $F(X)$ is the factor of safety. The format of Eq. (4) is more common because the safety of slopes is traditionally characterized by the factor of safety. The format of Eq. (3), however, is preferable because it has a lower degree of non-linearity (Mostyn and Fell, 1997). The performance function of a slope is usually formulated using the simplified limit equilibrium method, such as the ordinary method of slices, simplified Bishop's method, and simplified Janbu's method.

Once the performance function is defined, the probability of failure of a slope can be estimated by the following methods:

(1) The first-order-second-moment (FOSM) method. This method characterizes the frequency distribution of the factor of safety F in terms of its mean value μ_F and standard deviation σ_F. The reliability index β is may be computed from $\beta=(\mu_F-1.0)/\sigma_F$. β may be regarded as an index of the degree of uncertainty and it can be related to the probability of failure if the frequency distribution is known.

(2) Monte Carlo simulation. This method involves a computerized sampling procedure used to approximate the probability distribution of the factor of safety by repeating the analysis many times, especially the target reliability to be evaluated is small. A set of random numbers is generated for the random variables according to the chosen frequency distributions of the input parameters.

For some landslides where piezometric levels are recorded over some period and rainfall data are available, the relationship between piezometric levels and rainfall can be modeled using physical or statistical models (e.g. Fell et al., 1991). The probability of piezometric level required for landsliding or reactivation of a slide is then assessed by analyzing rainfall for a given period. This method is ideal in principle for site-specific, relatively deep-seated landslides. However, in reality it is difficult to achieve any accuracy in the modeling because of the complex infiltration processes involved, heterogeneity of the soil and rockmass in the slope, and groundwater seeping into the slide from below and upslope area and that seeping outward. It is also apparent that a lengthy period of calibration is likely required, to experience a range of rainfall and piezometric conditions.

4. Runout behavior of landslide debris

Delimiting the extent of endangered areas is fundamental to landslide risk assessment. These require accurate prediction of the runout behavior of a landslide, such as how far and how fast a landslide travels once mobilized. Generally, runout behavior is a set of quantitative or qualitative spatially distributed parameters that define the destructive potential of a landslide. These parameters for the purpose of landslide risk assessment mainly include (Wong et al., 1997; Hungr et al., 1999):

- Runout distance—the distance from the landslide source area to the distal toe of the deposition area;
- Damage corridor width—the width of the area subjected to landslide damage in the distal part of the landslide path where impact on buildings and other facilities occurs;
- Velocity—the velocity of travel within the damage corridor which determines the potential damage to facilities and the design parameters of any required protective measures;
- Depth of the moving mass—which influences the impact force of the landslide within the damage corridor; and
- Depth of deposits—landslide deposits may build up to a sufficient depth behind a structure to cause its collapse.

4.1. Factors contributing to runout behavior of landslide debris

A realistic estimate of runout behavior of a landslide depends on an adequate understanding of the generic factors that control travel. Relevant parameters to consider include slope characteristics, mechanisms of failure and modes of debris movement, downhill path, and residual strength behavior of sheared zones.

4.1.1. Slope characteristics

The important slope characteristics include slope geometry, the nature of the slope-forming material, and upslope influence zone. It is not difficult to understand that slope geometry has an important impact on runout behavior of landslide debris. The motion behavior of the sliding material involves the redistribution of the potential energy available at failure into friction energy, disaggregating or remolding energy, and kinetic energy. Leroueil et al. (1996) and Leroueil and Locat (1998) examine the relationship between the nature of the slope-forming material and slope movements. The convergence of hydrologic pathways along catchment provides water for incorporation into an initial failure. If a landslide occurs during a runoff-producing storm, then overland flow down the catchment axis and throughflow emanating from the headscarp will spill into an initial failure. Deformation accompanying an initial failure may allow further incorporation of water emanating from bedrock springs and surface runoff into the failed material, thus increasing debris mobility (Montgomery et al., 1991).

4.1.2. Mechanisms of failure and modes of debris movement

Certain failure mechanisms such as collapse of loose soil leading to static liquefaction and large-scale rock fall may release mobile debris (Wong et al., 1997). Loose granular soils tend to collapse when sheared, which under undrained condition results in an increase in pore water pressure (Fleming et al., 1989). Consequently, failures in contractive soils often evolve into debris flows that may travel great distances because even minor strain may cause liquefaction. Dilatant soils, on the other hand, expand upon shearing and a continued influx of water is required to sustain their mobilization. Consequently, failures in dilatant soils tend to be relatively slow-moving slides, depending on the availability of rainfall amount and intensity and soil permeability (Fleming et al., 1989; Dai et al., 1999, 2000). Once a landslide mobilizes, the modes of debris movement, disintegration of the failure debris during motion and convergence of surface runoff obviously influence debris velocity and travel distance. The availability of water further affects whether it assumes characteristics typical of debris flows, hyperconcentrated flows, or sediment-laden floodwaters.

4.1.3. Downhill path

The characteristics of the downhill path traversed by the debris can affect the mode of debris travel. Important parameters include the gradient of the downslope path, possibility of channelization of debris, characteristics of ground surface on which the debris travels, e.g. susceptibility to depletion, response to rapid loading as a result of sudden debris impact, type of vegetation, extent of catchment which collects surface water and discharges into the downslope area, etc. The topography downslope of an initial failure affects the probability of debris mobilization. An increase in downslope gradient will favor the acceleration of an initial failure, whereas gentler slopes will tend to inhabit acceleration. The studies carried out by Nicoletti and Sorriso-Valvo (1991) indicated that the downhill morphology of the slopes and valleys where landslide debris moved exerts a great influence on the damage corridor width and runout distance of rock avalanches. The amount of water available for mixing with landslide debris and the gradient of the downslope channelway contribute to the transition of an initial landslide into a mobile debris flow. Incorporation of excessive volumes of water may dilute landslide debris and increase its mobility.

4.1.4. Residual strength behavior of sheared zones

The presence or absence of pre-existing shears and the degree of brittleness is particularly important (Hutchinson, 1995). If the material displays strain-softening behavior, kinetic energy can reach catastrophic proportions and long runout distance can occur (Leroueil et al., 1996). Brittleness on pre-existing shears is generally low or zero. Hence, reactivation of movement on such shears is usually slow. The post-failure movement of landslides is generally controlled by the residual strength behavior of sheared zones. In this regard, knowledge of the effect of rate of displacement on the residual strength is necessary when studying the kinematics of a potential sliding mass. Three types of variation of residual strength with an increasing rate of displacement have been recognized (Tika et al., 1996): (a) neutral rate effect — soils showing a constant residual strength irrespective of the rate of displacement; (b) negative rate effect — soils showing a significant drop in strength when sheared at rates higher than a critical value; and (c) positive rate effect — soils showing an increase in residual strength above the slowly drained residual value at increasing rates of displacement. This is of great significance in predicting the velocity and displacement of landslides. In a first-time landslide induced in brittle soil, the loss in strength from the peak to the residual value is likely to exceed the reduction in shear stress due to changing geometry. Whatever causing the initial failure, the landslide ceases to be in equilibrium and moves to a new gentler position. If the rate effect is positive, the strength increases with velocity and the landslide decelerates. The landslide moves slowly, with small momentum, and comes to rest when it is in equilibrium with its residual strength. If the rate effect on the residual strength is negative, the landslide accelerates and develops into a fast movement. In this case, long runout distance may occur. For a reactivated landslide, it is in limit equilibrium with the constant strength, since the slow residual strength does not change with displacement. In a soil with a positive rate effect, extra strength is available to resist movement at all displacements and displacement rates, and the landslide thus decelerates and comes to a rest. If the soil has a negative rate effect and if during instability a critical combination of displacement and velocity is also induced, the landslide accelerates to potentially catastrophic velocities, and large displacements occur. For instance, Tika and Hutchinson (1999) explained or at least partially explained why the Vaiont landslide developed into a catastrophic disaster from the negative rate effect of soil from the slip surface.

4.2. Methods for predicting runout distance of landslide debris

Current and past research into the runout behavior of a landslide can generally be grouped into three categories. The first includes empirical models aimed at providing practical tools for predicting the runout distance and distribution of landslide debris. The second category includes simplified analytical models, which describe the physical behavior of debris movement, based on lumped mass approaches in which the debris mass is assumed as a single point. The third includes numerical simulations of conservation equations of mass, momentum and energy that describe the dynamic motion of debris, and/or a rheological model to describe the material behavior of debris.

4.2.1. Empirical models

The widely used empirical methods mainly include mass-change method and the angle of reach. The mass-change method is based on the phenomenon that as the landslide debris moves downslope, the initial volume/mass of the landslide is being modified through loss or deposition of materials, and that the landslide debris halts when the volume of the actively moving debris becomes negligible (Cannon and Savage, 1988). The average mass/volume-change rate of landslide debris was established by dividing the volume of mobilized material from the landslide by the length of the debris trail. The influence of slope gradient, vegetation types, and the channel morphology on the average volume-loss rate was established by stepwise multivariate regression analysis. This method does not explicitly account for the mechanics of the movement process. Another empirical approach is the angle of reach, defined as the angle of the line connecting the crest of the landslide source to the distal margin of the displaced mass. Scheidegger (1973) noted that the angle of reach apparently decreases with increasing magnitude of rock avalanches. This trend was first documented for rock avalanches exceeding 0.1 to 1 million m^3. Corominas (1996) conducted a detailed study on the influence of various factors that affect the angle of reach using landslide records, and showed a linear correlation between volume and angle of reach for all types of failures. He found that all kinds of mass movement show a continuous decrease in angle of reach with increasing volume starting from magnitudes as small as 10 m^3. He then categorized the landslide records according to their failure mechanisms into rockfalls, translational slides, debris flows, and earth flows. Regression equations for calculating the angle of reach of each landslide type were developed, and it is clearly indicated that the angle of reach decreases with an increase in debris volume. Earth flows have the highest mobility, and rockfalls have the lowest mobility. However, a common problem with the angle of reach method is that the scatter of the data is too large to permit reliable use for any but the most preliminary predictions of the travel distance. Therefore, this method should be applied with some judgment. For instance, if the material of a slope is known to be dense and dilatant, larger angle of reach will be applicable, than if the material is loose and contractant.

Empirical methods are generally simple and relatively easy to use, the information required by these methods is usually general and readily available. When a local historic landslide database is available, the empirical relationships can be readily developed. However, empirical methods can only provide a preliminary estimate of the profile of the travel path.

4.2.2. Analytical methods

The analytical methods include different formulations based on lumped mass approaches in which the debris mass is assumed as a single point. The simplest type of analytical methods is the sled model (Sassa, 1988), which assumes that all energy loss during debris movement is due to friction and describes the landslide as a dimensionless body moving down the profile of the path. Therefore, the movement of a landslide is controlled by a single force resultant, representing the gravity driving force as well as all movement resistance. The ratio of the vertical to horizontal displacement of the center of gravity of the block equals the friction coefficient used in the analysis. This method can provide an effective means for the calculation of runout distance, velocity and acceleration of debris movement. However, this method is applicable only for small-scale rockslides of limited displacements, which do not disintegrate during motion. Sassa (1988) improved the sled model by considering the effect of pore fluid pressures at the sliding plane. He considered the frictional resistance along the sliding plane to be a function of the intrinsic internal friction angle and the pore pressure coefficient, B. The B value can be determined by either laboratory methods as suggested by Sassa (1988) or back calculation from the landslide cases. Thus, the apparent friction angle in the improved sled model can be expressed as the combined effects of the intrinsic internal friction angle of debris material, and the motion-induced pore pressure.

Hutchinson (1986) developed a model for the prediction of runout distances of flowslides in loose, cohesionless materials by assuming that the shape of a debris flow is a uniformly spread out sheet. In the model, the basal resistance of the debris mass is assumed to be purely frictional, and the excessive fluid pressure in the debris mass is assumed to be dissipating according to the one-dimensional consolidation theory. As debris moves downslope, the shear resistance on the sliding plane increases due to a dissipation of excessive pore pressure. The debris mass halts when the resultant force along the sliding plane becomes zero. Based on these assumptions, the transient downslope movement of debris masses can be calculated.

For large, deep-seated slow-moving landslides, shear rate-dependent reduction/increase of residual strength may be an important consideration. The present knowledge of the effect of shear rate on residual strength allows the formulation of a soil model linking the strength on a pre-existing shear zone with displacement and rate of displacement. This model can be used in the study of stability and the prediction of instability of slopes containing shear zones near or at residual strength under static (i.e. alteration of loading of the sliding mass and fluctuation of the groundwater table) (e.g. Skempton et al., 1989; Bracegirdle et al., 1991), and dynamic (i.e. earthquakes) loading conditions (e.g. Lemos and Coelho, 1991).

The lumped mass cannot account for lateral confinement and spreading of the flow and the resulting changes in flow depth, and should therefore be suitable only for comparing paths which are very similar in terms of geometry and material properties. To apply these methods, some specific parameters are required, such as pore pressure parameters and debris thickness, relation of residual strength with shear rate. An assumption on the initial pore pressure distribution is needed for the sliding-consolidation method, while the apparent friction angle of the debris along the sliding plane is needed for the sled model.

4.2.3. Numerical methods

Numerical methods for modeling runout behavior of landslide debris mainly include fluid mechanics models and distinct element method. Continuum fluid mechanics models utilize the conservation equations of mass, momentum and energy that describe the dynamic motion of debris, and a rheological model to describe the material behavior of debris. The Bingham rheological model is regarded as one of the most well developed rheological models for describing the flow properties of earth materials (Sousa and Voight, 1991; Chen and Lee, 2000). By solving a set of governing equations with a selected rheological model describing the flow properties of the debris, the velocity, acceleration and runout distance of debris can be predicted. Typical examples of those applications of continuum models were given by Sousa and Voight (1991), and Chen and Lee (2000). Generally, the continuum fluid mechanics models are very sophisticated and the rheological properties required are difficult to determine. Hungr (1995) developed a modified continuum model. The method is different from the classical continuum fluid mechanics modeling methods discussed above. In his model, debris mass is discreted into column elements, and the rheological properties of debris at the sliding plane are accounted for. The longitudinal rigidity of the flowing mass is considered in conjunction with the lateral earth pressure coefficient. The friction resistance is assumed to act only at the base of the sliding plane. Pore pressure effects are incorporated with the pore pressure coefficient — the ratio of pore pressure to the total normal stress at the base of the column element. The friction angle can be assumed to be a function of displacement to simulate shear strength decays from peak to residual. The pore pressure coefficient can be expressed as a function of location or elapsed time to simulate drainage and consolidation effects. This method is easy to use, and the debris movements at different time intervals can be simulated.

Continuum fluid mechanics models are very sophisticated. Rheological models have to be selected, and the required rheological parameters have to be determined by either laboratory methods or by back-analysis from the landslide cases with similar geological conditions. However, they are able to provide all the information required for landslide risk assessment.

Another method commonly used for simulating runout distance and velocity is the distinct element method, which can be effectively used to model large strain particle movement. This method is very sophisticated and the analysis is very time-consuming. However, it is an invaluable tool in understanding the failure mechanics of landslides through back analysis.

After determining the probability of landsliding and the areal extent that would be potentially affected by the landslide, landslide hazard can be delimited, and elements at risk, which mean the population, buildings, economic activities, public services utilities and infrastructure in the area potentially affected by landslides, can be readily defined.

5. Assessment of vulnerability

Vulnerability is a fundamental component in the evaluation of landslide risk (Leone et al., 1996). Vulnerability, in the present context, may be defined as the level of potential damage, or degree of loss, of a given element (expressed on a scale of 0 to 1) subjected to a landslide of a given intensity (Fell, 1994; Leone et al., 1996; Wong et al., 1997). Vulnerability assessment involves the understanding of the interaction between a given landslide and the affected elements. Generally, the vulnerability to landsliding may depend on (a) runout distance; (b) the volume and velocity of sliding; (c) the elements at risk (buildings and other structures), their nature and their proximity to the slide; and (d) the elements at risk (persons), their proximity to the slide, the nature of the building/road that they are in, and where they are in the building, on the road, etc. (Finlay, 1996). The vulnerability of lives and property to landsliding may be different. For instance, a house may have similar and high vulnerability to a slow-moving and a rapid landslide, but persons living in the property may have a low vulnerability to the slow-moving landslide but a higher vulnerability to the rapid landslide (Fell, 1994; Fell and Hartford, 1997).

The assessment of vulnerability is somewhat subjective and largely based on historic records. For example, the vulnerability of a house immediately at the base of a steep slope down which a debris flow may occur is clearly higher than for a house at the limits of deposition area (because the velocity of flow is much less) (Fell, 1994; Fell and Hartford, 1997). Given a particular facility type and the probable depth of debris at the facility location, the appropriate vulnerability factor may be assessed systematically by expert judgement. Another method for assessing the vulnerability of person and/or property to landsliding is based on the statistics of detailed historic records. For instance, Hong Kong is virtually unique in the world in terms of the detailed records kept on landslides and their consequences. Finlay (1996) presented an example where vulnerability is assigned

Table 1
Summary of Hong Kong vulnerability ranges and recommended values for death from landside debris in similar situations (from Finlay, 1996)

Case	Vulnerability of person		Comments
	Range in data	Recommended value	
Person in open space			
1. If struck by a rockfall	0.1–0.7	0.5[a]	May be injured but unlikely to cause death
2. If buried by debris	0.8–1.0	1.0	Death by asphyxia
3. If not buried	0.1–0.5	0.1	High chance of survival
Person in a vehicle			
1. If the vehicle is buried/crushed	0.9–1.0	1.0	Death is almost certain
2. If the vehicle is damaged only	0–0.3	0.3	Death is highly likely
Person in a building			
1. If the building collapses	0.9–1.0	1.0	Death is almost certain
2. If the building is inundated with debris and the person buried	0.8–1.0	1.0	Death is highly likely
3. If the building is inundated with debris and the person not buried	0–0.5	0.2	High chance of survival
4. If the debris strikes the building only	0–0.1	0.05	Virtually no danger[a]

[a] Better considered in more detail, i.e. the proximity of person to the part of the building affected by sliding.

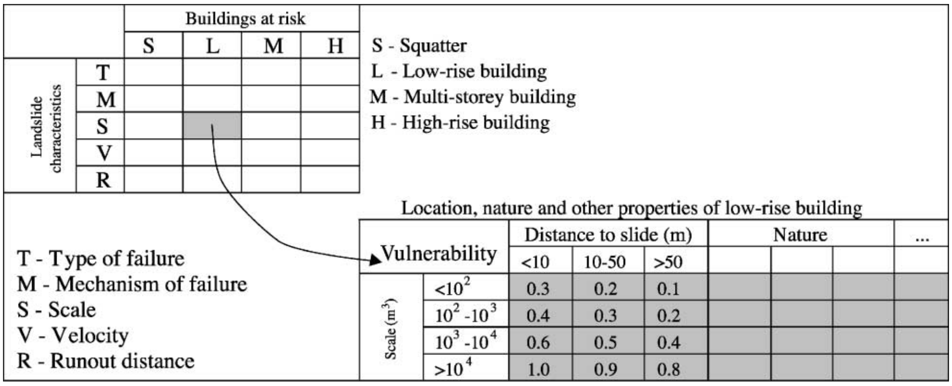

Fig. 2. An example of structural vulnerability matrix.

by reference to historic data (Table 1). An alternative option based on the statistics of historic records is the vulnerability matrix method proposed by Leone et al. (1996). This method is flexible and can cater for a wide range of situations and can, to a certain degree, reduce subjectivity, compared with the methods mentioned above. With this method, the vulnerability of elements at risk depends on the characteristics of the landslide and the technical resistance of the building, such as the type, nature, age, etc. For instance, Fig. 2 gives a correlation, in terms of vulnerability, between exposed elements and the characteristics of landslides. The applicability of this method, like other methods, also requires statistical analysis of detailed records on landslides and their consequences. When assessing landslide risk, we must account for the indirect cost, such as interruptions in economic activity, if we are to calculate the risk in all of its aspects in real terms, in addition to the direct damage caused by landsliding.

6. Landslide risk assessment

There are a variety of risks to be addressed in landslide risk assessment, generally comprising distributed landslide risk, site-specific landslide risk, and global landslide risk.

6.1. Distributed landslide risk assessment

Distributed landslide risk assessment is aimed at providing a risk map that depicts the level of risk in terms of fatality or economic loss at different locations of a given region quantitatively or qualitatively. The spatial distribution of landslide risk may be obtained by spatial subdivision of the area under study and multiplication of spatial landslide probability, affected zones, land-use or spatial distribution of population or property, and vulnerability. This type of calculation can easily be calculated within the GIS (Leone et al., 1996).

A priority ranking system for selection of slopes for detailed investigation and necessary upgrading, which can systematically ranks old slopes in an order of priority based on their probability of failure and the consequence of failure, is a commonly used empirical approach for risk assessment, based on an inventory database of all potentially unstable slopes in an area. For instance, the Geotechnical Engineering Office (GEO) of the Hong Kong Government established New Priority Classification Systems (NPCSs) for slopes and retaining walls developed as part of the GEO Slope Information System (SIS), under which a total score can be calculated for soil cut slopes, rock cut slopes, fill slopes and retaining slopes, reflecting the relative risk of landslide involving the feature. The total score is obtained from the multiplication of an instability score and a consequence score. The instability score is based on an assessment of a number of key parameters that affect the likelihood of failure. The consequence score reflects the likely consequence of failure. The higher the total score, the higher the priority for follow-up action on the feature generally (Wong, 1998).

6.2. Site-specific landslide risk assessment

Site-specific risk assessment serves to provide a systematic assessment of the hazards and level of risk in terms of fatality (or economic loss, as appropriate) at a given site, or a potential landslide. This facilitates the consideration of whether the risk levels are acceptable and the evaluation of different risk mitigation measures, usually on the basis of cost–benefit analyses. In general, the event tree technique is well suited to a site-specific quantitative risk assessment given its greater degree of refinement. Once the probability of landsliding, runout behavior of landslide debris or elements at risk, and vulnerability terms have been derived, risk values may be simply obtained by Eqs. (1) or (2). Event-tree analysis can be used to quantify the risk from the potential failure. The procedure consists of the following steps (Wu et al., 1996):

- Examine possible triggering factors, such as earthquakes or/and rainstorms;
- Identify possible failure modes;
- Estimate probability of failure for each failure mode;
- Evaluate runout behavior of landslide debris for each failure mode;
- Assess the risk for each failure mode; and
- Sum the risk for all possible failure modes.

6.3. Global landslide risk assessment

A global risk assessment, on the other hand, is aimed at defining the relative contribution to the total risk (e.g. number of fatalities per year), which can provide a reference for landslide risk management and consideration of resources allocation and policy-making. It can be calculated by summing site-specific risk of all slopes in the region under study.

7. Landslide risk management

Once the risk from a landslide or areas susceptible to or affected by landsliding are identified, measures may be taken to mitigate landslide risk to the community if necessary. The community faced with a landslide has a variety of strategies to deal with it, and these strategies may be grouped into planning control, engineering solution, acceptance, and monitoring and warning systems. Planning control may be seen as reducing expected elements at risk; the engineering solution strategy as reducing either the probability of landsliding or the probability of spatial impact of a landslide; the acceptance strategy as acceptable or unavoidable; and the monitoring and warning system strategy as reducing expected elements at risk by evacuation in advance of failure. The risks assessed as mentioned above can then be compared with the acceptance criteria to decide upon the landslide mitigation measures required.

7.1. Planning control

Planning control is one of the effective and economical ways to reduce landslide losses. It can be accomplished by (a) removing or converting existing development, and/or (b) discouraging or regulating new development in unstable areas (Kockelman, 1986). The latter option is the most economical and effective means for local governments if feasible.

New developments can be prohibited, restricted or regulated in landslide-prone areas. Landslide-prone areas can be used as open space, parks, woodland and recreation, or specific land-uses or operations that might cause mass movement or that might be vulnerable to failure, such as irrigation, construction of roads and buildings, can be prohibited. In the US, excavation, grading, and construction regulations have been developed to ensure that construction in landslide prone area is planned and constructed in a manner that will not impair the stability of hillside slopes (Schuster and Fleming, 1986; Schuster, 1996). These commonly include regulating, minimizing, and prohibiting excavation and fill activities in landslide-prone areas, requiring a permit prior to scraping, excavating, filling or cutting any lands, and requiring proper engineering design, construction, inspection, and maintenance of cuts, fills, and drainage systems. Landslide hazard maps at various scales are highly valuable tools in assessing the landslide potential for a proposed subdivision or parcel. They can also be used as a basis for site-specific regulation, including prohibition of development on active landslides, requirement for detailed geotechnical analysis and mitigation, and specific grading regulations.

Recurrent damage from landslides can be avoided by evacuating areas that continue to have slope failures. This may be an effective management strategy for reducing landslide risk for large-sized recurrent renewed landslides. For large-scale potential landslides, if there are obvious indications of instability, evacuations must be considered.

7.2. Engineering solution

Engineering solution is the most direct and costly strategy for reducing landslide risk. Two general approaches are available for mitigating landslide risk. One is correction of the underlying unstable slope to control initiation of landslides, and the other is controlling of the landslide movement.

7.2.1. Correction of the underlying unstable slope

The most commonly used remedial measures for correction of the underlying unstable slope are modification of the slope geometry by excavation or toe fill, drainage of surface and ground water, use of retaining structures, and internal slope reinforcement. These remedial measures are excellent site-specific management tools for landslides if correctly designed and constructed. The major negative aspect in their use is their high cost. For this reason, they are often used where landslide costs are very high because of high population densities and property values.

Slope geometry modification by removal of all or part of the earth driving the landslide is the most efficient way of increasing the factor of safety of a slope, especially in deep-seated slides (Bromhead, 1997). The slope gradient can be flattened by removing unstable material from the crest of the slope or/and adding material to the toe to enhance the stability of a slope. However, such an approach may not be easy to adopt for long translational slides where there is no obvious toe or crest, where the unstable area is so complex that a change in topography to improve the stability of one area may adversely affect the stability of another.

Drainage is the most widely used method for slope stabilization. Underground drainage systems and pumping wells remove ground water and decrease pore water pressure, thus increasing the shear strength of soil. Surface water is drained from the unstable areas by surface ditches so as to reduce surface water infiltration into the potential slide mass. In the design of underground drainage systems to stabilize slopes, the capacity of each drain or outlet pipe should be accounted for. The underground drainage system should have the capacity to decrease pore water pressure at the failure surface in order to stabilize the landslide as much as possible.

Slope stability can also be increased by placing retaining structures to increase the resistance to movement. These include gravity retaining walls, crib-block walls, gabion walls, passive piles, piers and caissons, cast-in situ reinforced concrete walls, reinforced earth-retaining structures with strip/sheet-polymer/metallic reinforcement elements, etc. Generally, the following minimum information is required to determine the type and size of a restraining structure: (a) the boundaries and depth of the unstable area, its moisture content and its relative stability; (b) the type of landslide that is likely to develop or has occurred; and (c) the foundation conditions, since restraining structures require a satisfactory anchorage. In addition, the site conditions for construction may also affect the choice of retaining structures. Internal slope reinforcement is aimed at modifying the fundamental properties of in-situ slope soils to improve the internal resistance against sliding by block bolts, micropiles, soil nailing, anchor, grouting with cement or chemicals, stone or lime/cement columns.

7.2.2. Controlling of the landslide movement

An alternative landslide risk-mitigating strategy of engineering solutions is to control the movement of landslide debris so as to reduce the spatial impact of landslides on downslope property. Traditional mitigation measures address landslide hazards through the installation of mechanical barriers where necessary to protect structures. The most frequently used designs include diversionary structures or levees to direct landslide debris into predetermined depositional areas, debris defenses intended to absorb kinetic energy, and retaining walls designed to withstand and/or deflect impacts (Montgomery et al., 1991). However, the volume of a potential landslide likely to impact a specific site should be estimated qualitatively or quantitatively. Knowledge of material properties of landslide debris and topography below the landslide site could be used to estimate the mass and velocity of landslide debris likely to impact a site as an input to the predictive models of runout distance outlined previously. Debris defenses on hillslopes below the landslide sources typically consist of a series of post set in concrete and connected by either wooden cross members or a chain-link fence. Such structures might decelerate small failures, but they are relatively ineffective on very steep slopes or for containing large failures, and thus should not be employed to protect structures (Montgomery et al., 1991). Retaining walls can be installed downslope of landslides to stop moving landslide debris. However, care should be taken to consider their effectiveness and economics because they are vulnerable to overtopping by either high velocity landslide debris or accumulated deposits from repeated events. As well, they are relatively expensive to build, requiring specific design considerations for both the volume and velocity of landslide events.

7.3. Acceptance

A community may need to accept the risk from a given landslide under the condition that the risks are perfectly understood. The selection of this option is based on considerations that the risks from landslides are offset against the benefits which the community obtains in the particular locations, or that risks from landslides are tolerable (Bromhead, 1997).

Before the acceptance strategy is adopted, acceptable risk criteria should be established. Fell (1994) and Fell and Hartford (1997) provide a summary of the issues that affect establishing levels of tolerable risk. IUGS Working Group on Landslides, Committee on Risk Assessment (1997) defines the tolerable risk as a risk that society is willing to live with so as to secure certain benefits in the confidence that it is being properly controlled, kept under review and further reduced as and when possible, and provides the following general principles that can be applied when considering tolerable risk criteria:

- The incremental risk from a hazard to an individual should not be significant compared to other risks to which a person is exposed in everyday life;
- The incremental risk from a hazard should, wherever reasonably practicable, be reduced, i.e. the As Low As Reasonably Practicable (ALARP) principle should apply;
- If the possible loss of life from a landslide incident is high, the risk that the incident might actually occur should be low. This accounts for the particular intolerance of a society to incidents that cause many simultaneous casualties, and is embodied in societal tolerance risk criteria;
- Persons in the society will tolerate higher risks than they regard as acceptable, when they are unable to control or reduce the risk because of financial or other limitations;
- Higher risks are likely to be tolerated for existing slopes than for planned projects, and for workers in industries with hazardous slopes, e.g. mines, than for society as a whole;
- Tolerable risks are higher for naturally occurring landslides than those from engineered slopes;
- Once a natural slope has been placed under monitoring, or risk mitigation measures have been executed, the tolerable risks approach those of engineered slopes;
- Tolerable risks may vary from country to country, and within countries, depending on historic exposure to landslide hazard, and the system of ownership and control of slopes and natural landslide hazards.

In theory it is desirable to establish such criteria and develop the F–N curve for landslide hazard. The F–N curve is a plot showing the number of fatalities (N) plotted against the cumulative frequency (F) of N or more fatalities on a log–log scale (Wong et al., 1997; Ho et al., 2000). Tolerable risk criteria also usually require that maximum involuntary risk of death to a single individual in a specified location should not exceed a specified threshold (Morgenstern, 1997). Establishing such criteria for landslide hazards should make use of existing data to construct F–N curves. The concept in each case would be to gather data on the frequency of landsliding causing fatalities or juries, and analyzing this for the population of slope features, and the reaction of the public to the fatalities or juries, and the measures taken by the owners of the slopes, or government authorities, to mitigate the risk. However, Morgenstern (1997) stated that few organizations have a rich enough database to progress very far in this direction, with an exception of Hong Kong. Under this condition, two approaches may possibly be used. First, event tree models of landslide failure and consequence based on conditional probabilities can be constructed and used to determine theoretical F–N relations (e.g. Wong et al., 1997). However, careful calibration wherever possible is essential if this approach is to lead to credible results. Secondly, social and political judgements can be used on a case-by-case basis to help determine acceptable risk (e.g. Bunce et al., 1995).

Defining tolerable risk is a complex problem that varies for individuals and societies. Using an agreed figure for acceptable risk as a guide, risk contour map can be produced and planning-decisions based on them. In Hong Kong, an interim risk guideline (Geotechnical Engineering Office, 1998) was issued for landslides and boulder falls from natural terrain. The maximum allowable individual risk was set at 10^{-5} for new developments, and 10^{-4} for existing developments. For societal risk, the preferred criteria have no acceptable line on the F–N curve, and the principle of ALARP should be applied to all risks below the unacceptable line. A region of intense scrutiny is set between 1000 and 5000 fatalities. The recommendation is used as a guideline and not meant to be mandatory. An alternate option, by adding a broadly acceptable limit of 10^{-5} for a fatality and 10^{-8} for 1000 fatalities, was proposed (Fig. 3). It may be rational to accept the risk if the calculated risk from a specified potential landslide is below the acceptable risk. For societal risk, it is important to recognize that there is a degree of uncertainty in the analysis of risk, and that the individual and societal risk criteria are only a mathematical expression of the tolerance of society to risk. They are not precise, and should be used only as a general guide.

7.4. Monitoring and warning systems

Potentially unstable slopes can be monitored so that the potentially affected residents can be warned and, if necessary, evacuated. For specific landslides or potential slopes of such a large magnitude that stabilization works or engineering solutions were not only impracticable but would also not be cost-effective in relation to the property in risk, monitoring and landslide warning would be an alternative option to reduce landslide risk. The response of a particular slope when subjected to an earthquake is generally examined using the critical acceleration under which the slope would be brought to a state of limit equilibrium according to a pseudo-static analysis. When the acceleration imposed on the slope exceeds its critical acceleration, displacement or failure will result. A warning can be issued if an earthquake that can produce peak ground acceleration exceeding its critical acceleration can be predicted in advance. If a

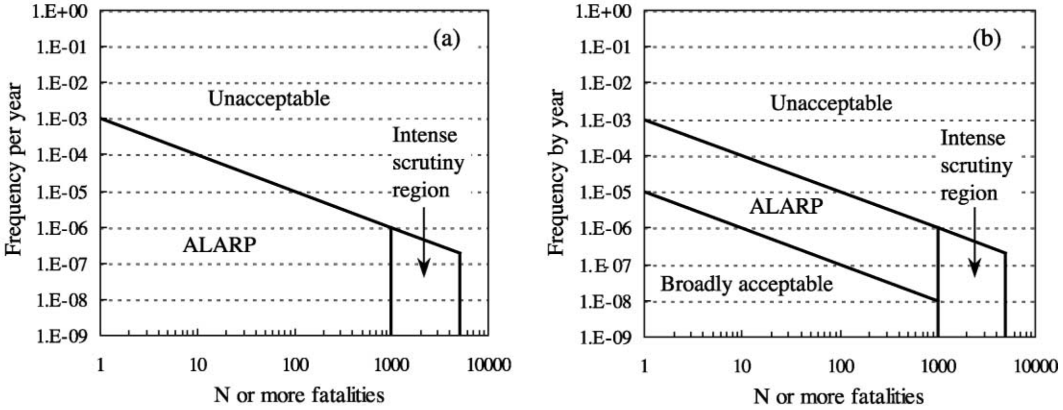

Fig. 3. Interim societal risk in Hong Kong: (a) preferred option; (b) alternate option.

slope is most possibly to be brought to failure by rainfall, a monitoring system can be installed, and landslide warning based on real-time monitoring data may be issued.

The primary objective of a monitoring program for a particular slope or landslide is to assess the existing conditions, in particular to determine whether or not the landslide is active, and if it is, where it is moving and the rate at which it is moving, so as to warn of impending emergencies. The monitoring instruments should be located and installed with reference to the geological conditions such that the overall picture of slope movement can be defined. Monitoring typically covers: (a) magnitude, rate, location and direction of deformations, including surface deformations by using crack gauges/surface extensometers, GPS or multipoint liquid level gauges, and subsurface deformations by using inclinometers, borehole/slope extensometers, or multiple deflectometers; (b) pore pressures and piezometric levels by using piezometers and tensiometers, hydro-meteorological parameters by using rain gauges; and (c) seismic accelerations if necessary. In addition, the general fact that slope movements in rock and soil masses are accompanied by the generation of acoustic emission or noise makes it possible to detect acoustic emission as an indication of landslide real-timing warning (Kousteni et al., 1999). In selecting the method of monitoring and the type of instrumentation, the required accuracy and durability in relation to the available time and the expected rate of deformation have to be considered. For instance, a borehole inclinometer will precisely detect minor deformations but its lifetime will be very limited when it traverses an active failure surface. Alternatively a downhole slope extensometer will not give quite the same information and not with the same sensitivity and accuracy but it may endure large displacements. Recently, satellite-borne synthetic aperture radar (SAR) interferometry (InSAR) has been a powerful tool for detecting and monitoring mass movements of unstable slopes (e.g. Rott et al., 1999; Kimura and Yamaguchi, 2000). The main contribution of InSAR to slope monitoring is that InSAR produces three-dimensional maps of the earth's surface, based on the evaluation of phase difference of two SAR images (interferogram) of the same area using a couple of satellites on different, albeit similar, orbits. A necessary condition for generating an interferogram is that the electromagnetic characteristics of the scene must stay constant between the two acquisitions. Differential SAR interferometry enables researchers to evaluate any variations over time of the altimetric profile of the area under observation and then to monitor slow movements with typical displacements on the order of centimeters (Rott et al., 1999). However, for slowly sliding surfaces interferograms over long time spans are needed to obtain detectable phase shifts. This prevents the application over densely vegetated surfaces due to decorrelation of the SAR images. Other constraints are imposed by the SAR illumination geometry and the availability of repeat pass interferometric data. The ability of InSAR to provide continuous maps of surface deformation is a considerable advantage over conventional techniques. Other advantages are the global access, the synoptic observation of large areas, and the regular repeat coverage.

Based on the monitoring data, the performance of a slope can be assessed. If the assessment indicates that the landslide is active, or potentially unstable, three strategies as mentioned above are applicable. The first one is to do nothing and accept the consequences of failure. Secondly, the slope can be stabilized and a monitoring program installed can be used to verify the effectiveness of stabilization works. Thirdly, a monitoring program can be used to warn of instability so that evacuation can be carried out prior to failure occurring.

Another important area of landslide research involves the development of real-time warning systems for issuing landslide warnings in large areas during major storms. Such a system is generally based on (a) empirical and theoretical relations between rainfall characteristics and landslide initiation; (b) geological determination of areas prone to landslides; (c) real-time monitoring of a regional network of telemetering rain gauges; and (d) precipitation forecasts made by the weather service authorities (Keefer et al., 1987). The U.S. Geological Survey in cooperation with the U.S. National Weather Service developed a real-time landslide warning system for the San Francisco Bay Region, California, and this system was used to issue the first regional public warnings over public radio and television stations during the storms of 12–21 February 1986, which produced 800 mm of rainfall in the San Francisco Bay Region. According to eyewitness accounts of landslide occurrence, the warnings accurately predicted the times of major landslide events (Keefer et al., 1987). In Hong Kong, the Geotechnical Engineering Office (GEO) also relies on a rainfall-monitoring system and an empirical rainfall/landslide relation for issuing regional landslide warnings to the public (Brand et al., 1984).

The relationship between landslide occurrence and rainfall characteristics forms the basis for the development of regional real-time landslide warning systems. Many attempts have been made to establish relationships between rainfall and landslides. These relationships are generally based on the assumption that there exists a direct relationship between the occurrence of landslides and the quantity of rainfall, in terms of rainfall intensity and duration of rainstorm events, or short-term rainfall (e.g. 24-h rainfall) and antecedent rainfall. For instance, Caine (1980) collected a worldwide set of rainfall data recorded near reported sites of landslide occurrences and derived a rainfall/landslide threshold by fitting a lower bound to a log–log plot of peak intensities versus duration. Similar rainfall intensity and duration thresholds were developed, based on historical rainfall events, for the San Francisco Bay Region (Cannon and Ellen, 1985), for the highly susceptible La Honda region in the central Santa Cruz Mountains, California (Wilson and Wieczorek, 1995), and in the central mountains of Puerto Rico (Larsen and Simon, 1993), respectively. In Hong Kong, Brand et al. (1984) noted that a rainfall intensity of about 70 mm/h appeared to be the threshold value above which landslides that resulted in casualties occurred, and that landslides are unlikely for a rainfall of less than 100 mm in 24 h, but are almost certain when 175 mm is exceeded.

In establishing a rainfall/landsliding relation for a particular region, there are debates over the role of the antecedent rainfall in landslide occurrence. Previous studies in certain parts of the world (e.g. Lumb, 1975; Wieczorek, 1987; Wilson and Wieczorek, 1995) on the relationship between rainfall and landslides have concluded that both the antecedent rainfall and a critical intensity of rainfall are equally important factors in triggering landslides. The significant period of antecedent rainfall, however, may vary from hours to weeks depending on local site conditions, particularly the soil permeability of slopes and the depth of failure. In the case of highly permeable soils in most tropical areas where the failure surface of landsliding is generally shallow, the period of necessary antecedent rainfall is considered to be very short, and antecedent rainfall is therefore not an important factor (Brand et al., 1984).

Another issue is the rainfall parameter used for establishing rainfall/landsliding relations. Wieczorek (1987) examined landslides initiated in storms of different intensity and duration in a 10-km^2 area near La Honda, California, and concluded that deep slides in soils usually occurred as a result of long duration, moderate intensity storms, whereas very shallow slides of soil over bedrock occurred due to short duration, high intensity storms. A similar observation was made in Puerto Rico by Larsen and Simon (1993). This indicates that the relationship between rainfall and landslides may be failure-volume dependent. Dai and Lee (2001) studied the relationship between rainfall and the number of landslides in Hong Kong, and found that with an increase in failure volume of landslides, the most important rainfall variable may vary from rainfall of short duration (12-h rolling rainfall) to that of relatively long duration (24-h rolling rainfall).

A lengthy period of data on landslides and rainfall is necessary for establishing reliable rainfall/landslide relationships. For instance, a study carried out by Dai and Lee (2001) indicates that the period of historic data has a great influence on the analytic results, and that the rainfall/landsliding relation should be updated, as new data become available.

Regional warning systems could alert the general public to the potential landslide activity, although the amount and intensity of rainfall necessary to initiate landslides undoubtedly varies with site specific geological, hydrological, and soil or rock properties. Such systems can only provide information on when landsliding would occur, and are thus most useful if used in conjunction with regional landslide hazard mapping to both delineate potentially hazardous areas and determine the timing of landslide initiation.

7.5. Decision-making

The choice between available options is dependent on the preference of the decision-maker considering all possible outcomes of each of the options. After the probabilities and consequences have been estimated, methods of decision analysis may be used to arrive at management decisions by identifying the alternatives of actions, possible outcomes, and respective consequences or cost for each scenario. The alternative with the least expected cost is usually chosen if the expected value is the criterion for decision. Cost–benefit analysis is the most widely used method in the process of decision-making. It involves the identification and quantification of all desirable and undesirable consequences of a particular mitigation measure. When measuring the cost of risk, a monetary value is generally used. By identifying the various available options together with relevant information for assigning design parameters, the cost and benefit of each mitigation measure can be assessed.

8. Discussion

Landslide risk assessment and management has led to the development of a new paradigm which demands a pluralistic approach to risk assessment and risk management and for value-focused decision making. It embeds the use of science in risk assessment and risk management and landslide studies within a socio-political framework, and subsumes within the decision making process the nature of landslides and the nature of human activities. This is not to diminish the role of scientists and of engineers in decision-making in landslide hazard mitigation. On the contrary, the new paradigm relies crucially on a better understanding of landslide processes and on greater sophistication, transparency and rigor in the application of science, but within a collaborative and consensual decision-making framework.

However, in the present knowledge, there are few reliable techniques available for assessing landslide hazard that is defined as the probability of occurrence of a given magnitude of failure. Those available often require detailed geotechnical information on the existing conditions. Because of the high cost involved they are generally only achievable at the site investigation level in cases where high risk is anticipated. Probability of landsliding and runout behavior of landslide debris are more commonly assessed by historically based, largely stochastic analysis of precedents. The accuracy with which landslide probability can be determined thus depends largely on the length, quality and nature of the information record. Probability of occurrence can be determined either directly from landslide record or indirectly by establishing the landslide-triggering threshold of the initiating agent and analyzing agent behavior. With both approaches, the minimum information requirements are a record of events including descriptions to characterize location, date, associated triggering conditions, causes, nature and length of warning, as well as landslide magnitude characteristics such as volume, material type and nature, and extent of runout. The main drawback of the precedent approach is the uncertainty associated with applying the findings to areas beyond where the precedence was established. For this reason or because there is insufficient record of past activity, hazard assessments are sometimes based on theoretically determined causative factors rather than on precedence. The outcome of this approach is the ranking of terrain susceptibility to landsliding. The validation of landslide susceptibility mapping and its usefulness depends on the maintenance of appropriate records indicating the magnitude and frequency of on-going landslide activity and its relationship with terrain and triggering conditions.

Although it is still only possible to predict slope failure in most general terms and virtually impossible to forecast the location, magnitude and timing of specific future events, regional scale landslide risk studies could result in the identification of tracts of land with different levels of hazard and risk. Such a hazard and risk zoning provides an ideal framework for land-use planning, development control, the application of building codes/ordinances, guidelines for engineering practice. At large and site-specific scales, landslide risk studies can provide the information necessary for decision-making. The process of landslide risk assessment and management depends on the completeness and quality of basic information on historic landslide data, and other physical and social data. In developing an inventory of all landslides in the area under study, one should determine the ages of different landslide deposits, with the aim of estimating recurrence intervals and determining risk where possible, and incorporate landslide trigger data, such as rainfalls and earthquakes, to establish time-frequency probabilities for singe major storms and for high-rainfall seasons. It is very clear that limited historic data often constrains the use of vulnerability assessment and risk analysis in land-use planning.

To move toward the goal that landslide risk can be rapidly assessed and effectively managed, a comprehensive landslide information system is required. In this regard, Geographical Information Systems (GIS), linked with remote sensing technology and telecommunications/warning systems, have emerged as one of the most promising tools to support the landslide risk assessment and management process. Establishment of a landslide database is the basis for landslide risk assessment and management. The landslide records generally include geotechnical, lithological, geomorphologic information, the date and extent of failure, and consequence from individual landslide sites. Data on existing engineered slopes, which may have influence on property in the event of failure, are also required. These data include slope geometry, evidence of past instability, sign of distress, slope-forming material, age and status of slope protective measures, site investigation and laboratory test data, which may be needed for assessing the priority of follow-up measures. Physical and social data are needed for all subsequent probability, vulnerability and risk assessment and management. These data should include topographic, geological, seismological and geomorphologic data at various scales. A further requirement is social, economic, cultural, political and environmental factors so as to determine elements at risk for the purpose of vulnerability assessment. Real-time monitoring data on rainfall, earthquake, pore pressure, and displacement of landslides, which may be a trigger for landslide occurrence, or indications of the movement of specific landslides, should be communicated into the database in real-time for the purpose of landslide warning. This information can be acquired at sites by local monitoring units (LMUs), which are directly connected to the central network monitoring, or by remote monitoring units (RMUs), which transmit data to the central network monitor by telemetry (usually radio) links. The individual RMU or LMU systems contain modules for the switching, signal conditioning, power excitation, control, and communications functions required to acquire data from each transducer. RMU and LMU systems can be designed to convert raw data readings to the desired engineering unit, to collect data readings according to a pre-programmed sequence, or to be polled from the central network module. The development of the computer-based automated data analysis systems (ADAS) is generally capable of dealing with a variety of transducer types and instrument monitoring needs.

Once the spatial database has been developed, the manipulation and analysis of the data allow it to be combined in various ways to evaluate what will happen in certain situations. The overlay operation of the GIS coupled with both heuristic and statistical approaches allows us to combine factor maps of site characteristics in a variety of ways to produce susceptibility maps (Gupta and Joshi, 1989; Carrara et al., 1991; van Westen et al., 1997; Chung and Fabbri, 1999). At large and site-specific scales, process models are in use that simulate the spatial distribution of the factor of safety using slope stability models (e.g. Wu and Sidle, 1995; van Westen et al., 1997). Most present applications of GIS to landslide studies are based on map overlaying, which only allows the spatial comparison of different maps at common pixel locations. A relatively new development in the use of GIS for slope instability assessment is the application of the so-called "neighborhood analysis" (e.g. Wu and Sidle, 1995). Neighborhood operations permit evaluation of the neighboring pixels surrounding a central pixel, which can be used to simulate trajectories of paths for slope processes and hydrological response to rainfall as one of the input parameters in infinite slope modeling (Wu and Sidle, 1995). Temporal database information is correlated with historical triggering factors to calculate temporal probabilities for landslide forecasting (Dikau et al., 1996).

However, the above-mentioned specific capabilities desired to perform risk analysis, risk assessment and management in a spatial environment are not all available in a standard off-the-shelf GIS. It is desirable to design a system that would integrate the capabilities of selected components and programs. In designing and developing such a system for landslide risk assessment and management, an architecture consisting of interconnected subsystems is selected. The subsystems encompass aspects of the overall system that share some common property or have similar functionality. Examples of subsystems in the development described herein are third-party software packages as well as original programs and macro languages. Several prototypical architectural frameworks are common in existing systems, and the one adopted for this system may be an interactive interface. This type of interface

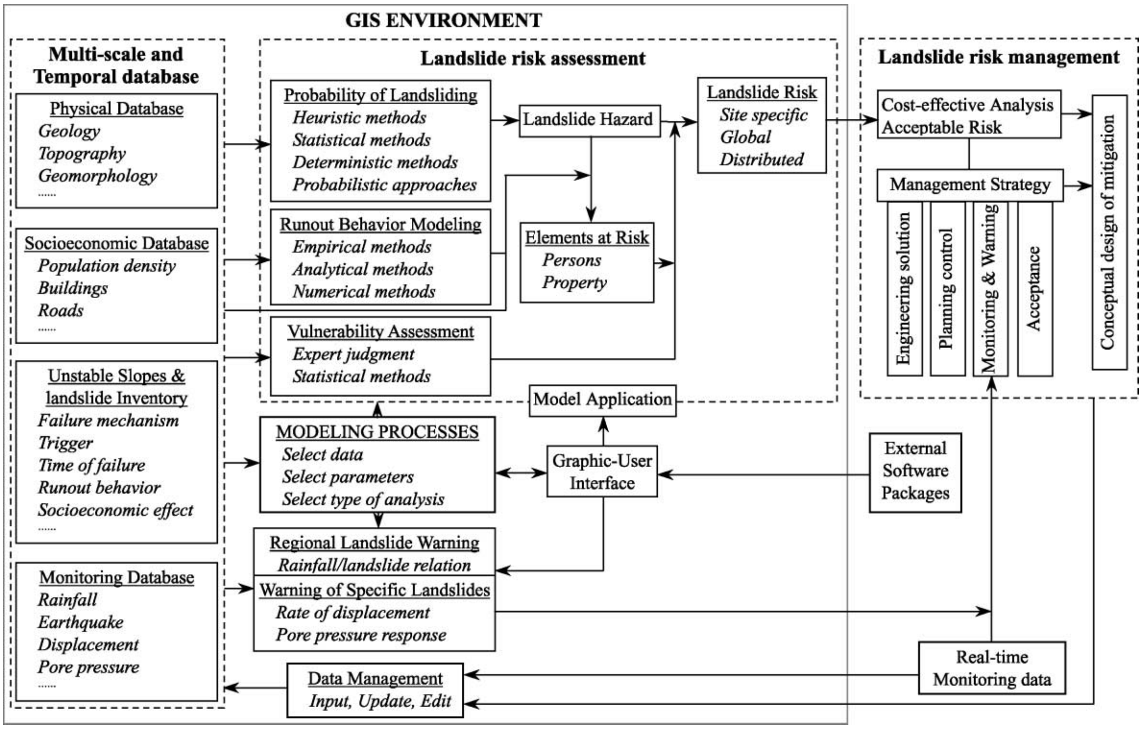

Fig. 4. A GIS-based conceptual integrated system for landslide risk assessment and management.

is dominated by the interactions between external software packages and the system, such that the control of the analysis remains with the user who, in this case, is expected to have some knowledge of both geotechnical engineering and spatial analysis technology. Present knowledge on the regional and local landslide risk assessment indicates that statistical analysis should be available to regional and local landslide susceptibility assessment. For this purpose, commercial statistical software packages can be integrated into the system. For specific slopes, commonly used geotechnical software on slope stability analysis, groundwater modeling, and runout modeling of landslide may be integrated with the system. Based on the geotechnical data available for a specific slope, detailed geotechnical analysis can be performed with the data. Other software for assessing slope performance based on monitoring data, priority classification systems for slopes for the purpose of follow-up measures, should be developed since apparently no commercial software packages are presently available for such purposes.

As shown in Fig. 4, all of the aforementioned techniques can generally be integrated for the purpose of landslide risk assessment and management.

9. Concluding remarks

Significant progress has been made in the field of landslide risk assessment. The availability and quality of historic landslide database cannot be overemphasized since they constitute the basis for all components of landslide risk assessment. Modern technologies, such as GIS and remote communications, should have a wider application in landslide risk assessment and management.

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