Commentary

Guidelines for landslide susceptibility, hazard and risk zoning for land-use planning

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Purpose of the commentary

The Commentary has been prepared to:

• Provide background notes to explain the reasons for adopting the provisions of the guideline.
• Elaborate on some parts of the guideline
• Provide references for additional reading.

The commentary is not meant to be a textbook on Landslide Susceptibility, Hazard and Risk Zoning.

C. Introduction

There have been examples of landslide susceptibility and hazard zoning in use since the 1970s (e.g. Brabb et al., 1972; Nilsen et al., 1979; Kienholz, 1978). The hazard and risk maps have usually incorporated the estimated frequency of landsliding in a qualitative sense rather than quantitatively. These examples of zoning have generally been used to manage landslide hazard in urban areas by excluding development in some higher hazard areas, and requiring geotechnical engineering assessment of slope stability before development is approved in other areas. In some countries, landslide susceptibility, hazard and risk maps are being introduced across the country. For example the PPR (Plans de Prevention des Riques Naturels Previsibles) in France (Ministère de l’Aménagement du Territoire et de l’Envi-
C4. Description of landslide susceptibility, hazard and risk zoning for land-use planning

C4.1. Types of landslide zoning

C4.1.1. Landslide inventory

Landslide inventories are essentially factual in nature. However in some cases there may be a degree of interpretation because they may be based on geomorphologic attributes seen on air photographs or mapped on the ground.

C4.1.2. Landslide susceptibility zoning

Landslide susceptibility zoning involves a degree of interpretation. Susceptibility zoning involves the spatial distribution and rating of the terrain units according to their propensity to produce landslides. This is dependent on the topography, geology, geotechnical properties, climate, vegetation and anthropogenic factors such as development and clearing of vegetation. It should consider all landsliding which can affect the study area and include landslides which are above the study area but may travel onto it, and landslides below the study area which may retrogressively fail up-slope into it. The scale of susceptibility is usually a relative one.

The travel and regression of the landslides are dependent on different factors to those causing the landslides. Areas which may be affected by travel or regression of the landslides from the source will often be assessed independently.

It should be recognized that the study area may be susceptible to more than one type of Landslide e.g. rock fall and debris flows, and may have a different degree of susceptibility (and in turn hazard) for each of these. In these cases it will often be best to prepare separate susceptibility, and hazard zoning maps for each type of landslide and to combine them to obtain the global landslide hazard map of the area.

There are some differences of viewpoint amongst experts in landslide zoning as to whether susceptibility zoning should include an assessment of the potential travel or regression of landslides from their source. Some feel that this should be considered only in hazard zoning. However, in some situations it will be difficult to assess the frequency of landsliding and land-use zoning may be carried out based on susceptibility zoning. In these cases the important matter of travel or regression would be lost. In view of this travel and regression should be considered in susceptibility zoning.

C4.1.3. Landslide hazard zoning

Hazard zoning should be done for the area in its condition at the time of the zoning study. It should allow for the effects of existing development (such as roads) on the likelihood of landsliding. In some situations the planned development may increase or reduce the likelihood of landsliding. This can be assessed and a post-development hazard zoning map produced.

Hazard zoning may be quantitative or qualitative. It is generally preferable to determine the frequency of landsliding in quantitative terms so the hazard from different sites can be compared, and the risk estimated consequently also in quantitative terms. However in some situations it may not be practical to assess frequencies sufficiently accurately to use quantitative hazard zoning and a qualitative system of describing hazard classes may be adopted. Usually, even for these cases, it will be possible to give some approximate guidance on the frequency of landslides in the zoning classes and this should be done.

C4.1.4. Landslide risk zoning

Risk zoning depends on the elements at risk, their temporal–spatial probability and vulnerability. For new developments, an assessment will have to be made of these factors. For areas with existing development it should be recognized that risks may change with additional development and thus risk maps should be updated on a regular basis. Several risk zoning maps may be developed for a single hazard zoning study to show the effects of different development plans on managing risk.

C4.2. Examples of zoning

For examples of zoning see Cascini et al. (2005) which references a number of zoning schemes. Note that the terms used in these examples are not necessarily consistent with each other or with these guidelines.

C5. Guidance on where landslide mapping is useful for land-use planning

C5.1. General principles

No comments or additional information.

C5.2. Topographical, geological and development situations where landsliding is potentially an issue

The examples given in the guideline are categorized into 5 classes based on:

(a) Where there is a history of landsliding. This is the most obvious class, and the most common reason for deciding that landslide zoning should be carried out.

(b) Where there is no history of sliding but the topography dictates sliding may occur.

If slopes are steep enough they may be susceptible to landsliding for a wide range of geological conditions. If sliding occurs, it is likely to be rapid and pose a hazard to lives of persons below the slopes.

(c) When there is no history of sliding but geological and geomorphological conditions are such that sliding is possible.

The list of conditions is not meant to be complete, and other situations may be known locally to be susceptible to landsliding. It should be noted that in many of the cases listed the areas susceptible to landsliding may be in relatively flat terrain, with sliding occurring on low strength surfaces of rupture.

(d) Where there are constructed features which should they fail, may travel rapidly.

Many of these cases relate to soils which lose a large amount of strength on sliding, and thus, will suffer a large drop in the factor of safety and travel rapidly after failure. The list is not meant to be complete but it is intended to give a reasonable range of examples.

(e) Forestry works and land clearing where landslides may lead to damage to the environment such as in degrading streams and other receiving water bodies.

This is a separate class with the emphasis on environmental consequences.

C5.3. Types of development where landslide zoning for land-use planning will be beneficial

For roads and railways, linear susceptibility, hazard or risk maps may be prepared. These maps have some specificities such as, for instance, the frequency is usually assessed at the road level and not at the landslide source. However, the general mapping principles are the same.

It should be noted that, in some countries, unless specifically required by the organisation funding the zoning study or regulatory authorities, the impact of landsliding of the road or railway on road or railway users will not usually be considered in the landslide zoning. This is usually considered the responsibility of the road or railway owner, not those developing adjacent land unless the proposed development increases the landslide risk to the infrastructure and its users. The effect of landsliding of the road or railway on the adjacent areas which are being developed will usually be considered in the landslide zoning study.
C6. Selection of the type and level of landslide zoning

C6.1. Some general principles

Some landslide zoning management schemes rely on susceptibility zoning to differentiate between areas where geotechnical assessment of landslide risk will be required for an individual development, and areas where no geotechnical assessment is required. It should be recognized that:

(a) Such schemes are potentially expensive to implement in total cost terms because they do not differentiate areas for which some general development controls are required (such as limiting the height of cuts and fills), but no detailed geotechnical assessment of hazard or risk assessment is needed.

(b) They potentially categorize as equally susceptible areas which have different frequencies of landsliding and as a result different hazards.

Only risk mapping allows assessment of the risks of life-loss and comparison with tolerable life-loss criteria. Early experience is that many of those involved in landslide zonation were not sufficiently aware of the potential for loss of life from landslides and either did not considered life-loss risk, or underestimated its importance.

C6.2. Recommended types and levels of zoning and map scales

Table 1 is intended for use by land-use planners in selecting the type, level and scale of landslide zoning that should be done. It is emphasised that this should be controlled by the use of the landslide zoning. If statutory controls are to be imposed on development applications based on the landslide zoning, then the zoning should be hazard or risk zoning, and at the appropriate large or detailed scale. Zoning boundaries generally cannot be sufficiently accurately defined at the medium or small scale. It is also undesirable to base statutory zoning requirements which may for example impose restrictions on development on susceptibility zoning that does not consider the frequency of the potential landsliding.

It is recognized that the funding available for landslide zoning may be a constraint and this may force the use of smaller scale zoning of susceptibility or hazard. If this is done there should be a realistic understanding of the accuracy of zoning boundaries and of the susceptibility or hazard estimates. These types of zoning should only be used to act as a trigger for more detailed geotechnical assessment of landslide hazard and/or risk, not to impose statutory constraints on development.

C6.3. Definition of the levels of zoning

No comments or additional information.

C7. Landslide zoning map scales and descriptors for susceptibility, hazard and risk zoning

C7.1. Scales for landslide zoning maps and their application

Table 3 summarizes map scales and the landslide susceptibility, hazard and risk mapping to which they are usually applied. The table is based on Soeters and Van Westen (1996), Cascini et al. (2005) and discussions at the JTC 1 Workshop on Landslide Susceptibility, Hazard and Risk Zoning held in Barcelona in September 2006. The following are some comments on the table:

(a) The input data used to produce landslide zoning maps must have the appropriate resolution and quality. Generally speaking, the inputs to the zoning should be at larger scales than the zoning map, not smaller. Reliable zoning cannot be produced if, for instance, a landslide hazard zoning map prepared at a scale of 1:5000 is based on a 1:25,000 geomorphological or topographic maps because the accuracy of boundaries will be potentially misleading.

(b) The use of larger scale zoning maps must be accompanied by a greater detail of input data and understanding of the slope processes involved.

(c) In practice, only limited detail can be shown on small, medium and even large scale maps. Most examples of municipal (local government) landslide hazard or risk zoning maps which assign a hazard or risk classification on an individual property level should be prepared at the detailed level on large scale landslide zoning maps. There are some who believe that even at detailed scale it is not technically or administratively defensible to make site specific decisions based on zoning maps, and that site specific assessment is necessary. Others believe it is possible, provided the zoning process includes ground inspection to define zoning boundaries, as was done by Moon et al. (1992) for debris flow hazard zoning.

(d) The usefulness and reliability of small scale landslide zoning mapping are considered by some to be questionable, even for regional developmental planning.

C7.2. Descriptors of the degree of susceptibility, hazard and risk for use in landslide zoning

C7.2.1. General

The descriptors have been developed based on the experience of the scientific committee taking account of the opinions of the reviewers. There is not necessarily equivalence in risk for the different types of landslide having the same hazard descriptor.

C7.2.2. Examples of landslide susceptibility descriptors

Landslide susceptibility may be assessed based on either qualitative or quantitative way. In the qualitative approaches, the

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<th>Susceptibility descriptors</th>
<th>Rock Falls</th>
<th>Small landslides on natural slopes</th>
<th>Large landslides on natural slopes</th>
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<td>High susceptibility</td>
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<td>Moderate Susceptibility</td>
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<td>Low susceptibility</td>
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<td>Very low susceptibility</td>
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a Spatial probability determined from historic, relative stability indexes, data or analysis taking consideration of the uncertainty in travel distance.

b Based on landslide inventory, geology, topography and geomorphology.

c Usually this is active, dormant and potentially reactivated slides, not first time slides.
descriptors are defined based on the judgement of the person carrying out the analysis. The qualitative approaches can be divided into two types (Aleotti and Chowdhury, 1999): field geomorphologic analysis and the combination or overlaying of index maps with or without weighting. In the geomorphologic approach the assessment is made by the expert in the field, often with the support of aerial photo interpretation. The stability map is derived from the geomorphologic map without a clear indication of the rules that have to lead to the assessment.

As one on the main principles of such type of approach is that the past is the key to the future (Varnes, 1984), in a given region, the areas showing the highest landslide activity in the past may be considered as the most susceptible ones. In that respect, landslide isoleth maps may serve as a guide to landslide susceptibility (Wright et al., 1974). The susceptibility descriptors may be expressed as, for instance, the percentage of the landslide deposits per unit area. Table C.1 gives examples of landslide susceptibility mapping descriptors in relation to the potentially affected area.

Rock fall susceptibility may also be described in terms of the density of scars on a rock slope from which falls have occurred, or the number of rocks which has fallen from at a slope. Relative susceptibility may be described as the proportion of the total number of scars or rocks within a section of the slope.

For small shallow landslides the susceptibility may also be expressed as the number of slides per square kilometre. In the index maps, the expert selects the critical instability parameters, assigns to each of them a weighted value that it is expected be proportionate to the relative contribution to the slope failure. The following operations should be carried out (Soeters and van Westen, 1996):

(a) subdivide each parameter into a number of relevant classes
(b) assign a weighted value to each class
(c) assign a weighted value to each of the parameter map
(d) overlay weighted maps and obtain scores of each terrain unit
(e) classify the obtained scores in susceptibility classes

The outputs of the quantitative susceptibility assessment may be either relative or absolute. Data treatment techniques evaluate first of all the relative significance of the parameters and then correlate different combinations of parameters with the spatial distribution of the existing landslides in order to obtain the best match. An important step is the conversion of categorical parameters into numerical ones and ranking them according to their contribution to the instability (Carrara, 1983). Susceptibility scores obtained with these techniques are usually reclassified to obtain susceptibility classes (i.e. high, medium and low susceptibility).

Absolute susceptibility is usually assessed with deterministic approaches such as slope stability models. The susceptibility may be expressed as the safety factor which calculation requires the knowledge of the geometry of the slope, the soil/rock strength properties and groundwater conditions. The safety factor of each slope or terrain unit is assigned to a susceptibility class (Gökceoğlu and Aksoy, 1996). In practice for natural slopes it is not practical to assess factors of risk zones in individual risk terms. However there may be some situations where a large number of deaths may result from a single landslide event. In these cases consideration of individual risks may not properly reflect societal aversion to such an event and societal risk criteria may require consideration. Leroi et al. (2005) present a discussion on societal risk and include examples of societal risk criteria.

The descriptors for risk zoning for property loss criteria shown in Table 7 have been developed after considerable discussion and trialling of different versions. It has been developed mostly for use with residential dwellings. The damages include the cost of stabilizing the site to allow reconstruction of the residence so they can exceed the value of the property. For guidance on the use of this table refer to AGS (2007a).
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_C8.2. The importance of understanding slope processes and the geotechnical characteristics of the landsliding_

It should be recognized that landslide zoning is a multidisciplinary exercise. Zoning carried out by persons who do not have the required knowledge and experience, or without sufficient detail of geotechnical investigations is likely to be inaccurate and may be totally misleading.

_C8.3. Application of GIS-Based techniques to landslide zoning_

(a) GIS-based modeling of landslide susceptibility and hazard

With the available data in place, various methods can be applied to establish inter-relationships and to ultimately establish levels of susceptibility and hazard. Key vector data sets typically used in landslide zoning studies include landslide polygons, geology, geomorphological and or terrain units, cadastre, road, rail and utilities, land-use and vegetation. Other data that can be imported given the required spatial data elements may include borehole information, soil strength parameters, pore water pressures, rainfall etc. The key grid or raster data is the digital elevation model (DEM). GIS software can derive numerous data sets useful in landslide zoning from the DEM such as slope, aspect, flow accumulation, soil moisture indices, distance to streams and curvature to name only a few.

A GIS model can be used to combine a set of input maps or factors using a function to produce an output map. The function can take many forms including linear regression, multiple regression, conditional analysis and discriminate analysis etc. These indirect methods involve qualitative or quantitative modeling and analysis techniques of various types (Soeters and Van Westen, 1996):

(i) Heuristic analysis.

In heuristic methods the expert opinion of the person carrying out the zoning is used to assess the susceptibility and hazard. These methods combine the mapping of the landslides and their geomorphologic setting as the main input factors for assessing the hazard. Two main types of heuristic analysis can be distinguished: geomorphic analysis and qualitative map combination.

In geomorphic analysis the susceptibility or hazard is determined directly by the person carrying out the study based on individual experience and the use of reasoning by analogy. The decision rules are therefore difficult to formulate because they vary from place to place.

In qualitative map combination the person carrying out the study uses expert knowledge to assign weighting values to a series of input parameters. These are summed according to these weights, leading to susceptibility and hazard classes. These methods are common, but it is difficult to determine the weighting of the input parameters.

(ii) Knowledge based analysis.

Knowledge based analysis or heuristic ‘data mining’ is the science of computer modeling of a learning process (Quinlan, 1993). The data mining learning process extracts patterns from the databases of landslides (Flentje et al., 2007). Pixels with attributed characteristics (from the input data layers) matching those for known landslides are used to define classes of landslide...
zoning. The percentage distributions of landslides within the zones are then used to help define the zones.

(iii) Statistical analysis.
The statistical or probabilistic approach is based on the observed relationships between each factor and the past distribution of landslides. This approach usually involves the mapping of the existing landslides, the mapping of a set of factors that are supposed be directly or indirectly linked to the stability of the slopes, and the establishment of the statistical relationships between these factors and the instability process. Hence susceptibility or hazard zoning is conducted in a largely objective manner whereby factors and their inter-relationships are evaluated on a statistical basis. Various methods exist for the development of the rules for and relationships between variables and these include bi-variate analysis (Brabb et al., 1972), multi-variate analysis, particularly the discriminant analysis (Neuland, 1976; Carrara, 1983; Carrara et al., 1995), Boolean approaches using logistic regression (Atkinson and Massari, 1998; Dai and Lee, 2001; Ayalew and Yamagishi, 2005), Bayesian methods using weights of evidence and neural networks (Gómez and Kavzoglu, 2005; Lee et al., 2006). Limitations with such methods result from data quality such as errors in mapping, incomplete inventory and poor resolution of some data sets as the models are essentially data trained. In addition, the results of such models are not readily transferable from region to region.

(iv) Deterministic analysis.
Deterministic methods apply classical slope stability theory and principles such as infinite slope, limit equilibrium and finite element techniques. These models require standard soil parameter inputs such as soil thickness, soil strength, groundwater pressures, slope geometry etc. The resultant map details the average factor of safety and boundaries while susceptibility and hazard classes can be set according to factor of safety ranges (i.e. unstable <1.0, metastable 1.0 to 1.1 etc). One-dimensional deterministic slope stability models have been used to calculate average safety factors of the slopes (Van Westen and Terlien, 1996; Zhou et al., 2003) in which an hydrological model may also be incorporated (Montgomery and Dietrich, 1994; Montgomery et al., 1998). Three-dimensional deterministic modeling integrated in a GIS have been performed by Xie et al. (2004). Deterministic distributed models require maps that give the spatial distribution of the input data. The variability of input data can be further used to calculate probability of failure in conjunction with return periods of triggers (Savage et al., 2004; Baum et al., 2005). The main problem with these methods is the oversimplification of the geological and geotechnical model, and difficulties in predicting groundwater pore pressures and their relationship to rainfall and/or snow melt.

These methods of data analysis are applicable to non-GIS-based systems but the use of GIS greatly assists the process. 

(c). Spatial data and scale in GIS
Scale in GIS is related to the subsequent use of the output data. Landslide inventory maps, susceptibility and hazard zoning maps will be used by Local Governments and Government Authorities etc. to make important land management decisions at large scale, often down to the cadastral land parcel scale. Data queries and decisions based on data mandate the integrity of the data to be rigorous at that scale. Hence the scale at which input data is collected should relate to the required scale of the output.

A main issue related to the scale is the size of the mapping unit. This unit is defined as the proportion of land surface which contains a set of ground conditions that differ from the adjacent units across definable boundaries (Hansen, 1984). Several mapping units may be defined (Guzzetti et al., 1999): grid cells, terrain units, unique-condition units, slope units and topographic units. If the sample unit covers a large area (i.e. 200 × 200 m) it will become a difficult task to characterize each unit by a single value of a given factor. As the size of the unit becomes smaller it gets easier for one observation to represent the terrain, but then the number of units may become too large to be manageable.

(d). The need for calibration of GIS modeling
The need to field check iterations of the GIS modeling output is critical in producing a high quality zoning map that reflects, as best one can, the reality in the field. Calibration of this model is essential in any project. The significance of compiling the best possible input data to any GIS application cannot be overstated. Time and resources devoted to the assembly of comprehensive, accurate, high quality data which is captured at appropriate scale and resolution are considered to be one of, if not the most significant task undertaken in any GIS-based inventory compilation and modeling project. The use of GIS is not a substitute for the involvement of geotechnical professionals with the skills required to carry out landslide zoning. GIS is a tool to assist them to do the zoning efficiently.

C8.4. Landslide inventory
It should be noted that the landslide inventory is often the basis for all the zoning, and it is important that this activity is done thoroughly. For precipitation-induced rock falls, slides from cuts, fills and retaining walls the data will usually need to cover 10, 20 or more years so a number of significant rainfall events can be sampled in the inventory if it is to be used as the basis for frequency assessment. In many cases it will not be possible to create a good inventory from past records, so the inventory has limitations. These can be overcome with time if those responsible establish a system for gathering data which can then be incorporated in later zoning studies.

For small landslides in natural slopes, the quality of the inventory will be enhanced by carrying out surface as well as aerial photograph-based interpretation. Even experienced aerial photo interpreters cannot see slides which have been hidden by vegetation. Basic small or medium scale landslide inventory mapping at regional or local level may be followed by intermediate or advanced mapping of higher susceptibility areas. The inventory should be mapped at a larger scale than the susceptibility, hazard or risk zoning maps. Different information can be mapped depending on the scale. For example:

(a) Inventory scale: 1:50,000 to 1:100,000 for regional zoning. The minimum area covered by an inventoried landslide is 4 ha. Smaller landslides may be represented by a dot. It is unnecessary and impossible to distinguish between landslide scarps or visible materials or deposit. Landslides are only classified. Data about activity are simplified to active, dormant. Data about damages are simplified.

(b) Landslide inventory at scale 1:10,000 to 1:25,000 for local zoning. The minimum area covered by an inventoried and mapped landslide is 1600 m². Smaller landslides are represented by a dot. Minor and larger scarps may be distinguished as well as up-slope deformations such as tension cracks or minor landslides. Landslides are classified. Original mass, volume and averaged velocity is recorded from direct observation or expert assessment. Activity should be described using WP/WLI (1993). Data about damages if they are available are simplified to: no data, minor and major.

(c) Landslide inventory at a scale greater than 1:5000 for site specific or local zoning.

The minimum area covered by an inventoried mapped landslide is 100 m². Smaller landslides are represented by dots. Mapped landslides may be divided into its components: scarp, rupture surface and mass or deposit. Rupture surface is digitized as a polygon comprising visible (scarps) and hidden sides covered by the mass. Landslides are classified. Mass volume and average velocity is estimated and recorded. GIS analysis may be used to obtain the total area of each landslide type in each lithology unit of the mapped zone so the distribution of landslide
rupture surface by lithology units is obtained. Activity should be described using WP/WLI (1993). Data about damages are recorded if available with mention of economic losses or qualitative description of losses, number of days, weeks or months of interrupted services or catastrophic losses. Human losses are also detailed with number of injured and dead persons. Historical data or record of temporal distribution of landslides, triggering rainfall and earthquake magnitudes may also be added to the inventory. The inventory may also record landslide features relating to slope deformations associated to early stage of landslide development such as inclined trees, inclined fences and deformed structures, tension cracks on element at risk such as roads, walls, houses, pavements, etc. and tension cracks on slopes.

For landslides from cuts and fills, and rock fall, even the most basic inventory of landslides can be valuable in estimating landslide frequency. This can be set up in GIS or simply as a spreadsheet with such data as the location, classification, volume, travel distance and state of activity, and date of occurrence.

Those responsible for landslide risk management are strongly encouraged to develop a landslide inventory if one does not yet exist for the area for which they are responsible.

C8.5. Landslide susceptibility zoning

C8.5.1. Landslide characterization and travel distance and velocity

Table C.3(a) to (d) provides more detail on the activities to characterise the landslides for the four main classes of landslides, and lists suggested useful references. In most cases where intermediate methods are being used basic methods will also be used, and for advanced methods, intermediate and basic will also be used. Note that much of these activities will be carried out in GIS and the terms used here are generic. It should be noted that the more advanced the characterization method, then the larger scale the mapping and level of detail of information and understanding of slope processes is required. Some general references on mapping procedures include Van Westen (1994, 2004), and Guzzetti et al. (1999).

It should be recognized that even at the intermediate and advanced levels it is difficult to accurately define landslide susceptibility from terrain and geotechnical characteristics. This uncertainty should be borne in mind when carrying the information forward into preparing hazard and risk zoning.

Some useful references for assessing travel distance include:

- Empirical methods for assessing travel distance of soil and rock slides which become debris flows and debris slides involve different approaches. They may be based on geometrical relations between the slope and the landslide deposits (Nicoliotti and Sorriso Valvo, 1991; Evans and Hung, 1993; Corominas, 1996; Hunter and Fell, 2003; and Hung et al., 2005) or on volume change-methods (Cannon, 1993; Fannin and Wise, 2001).
- Dynamic and numerical methods for assessing travel distance have been prepared for rockfalls (Bozzolo and Paminii, 1986; Pfeiffer and Bowen, 1981; Agliardi and Crosta, 2003), debris flows (Takahashi, 1991; Hung, 1995; Laigle and Coussot, 1997; McDougall and Hungr, 2004), flowslides (Hutchinson, 1986), and rock avalanches (Soussa and Voight, 1991; Hung, 1995; Eberhardt et al., 2004).
- GIS-based methods for predicting flow paths (Glaze and Baloga, 2003) and travel distances (Dorren and Seijmonsbergen, 2003).

The landslide velocity can be estimated from the potential energy and assumed friction losses using the sliding block model as described in Hung et al. (2005).

Care should be exercised when defining travel distance based on the location of ancient landslide deposits. The source of pre-historic landslides cannot always be properly located and travel distance estimation may be subjected to significant error. It should be noted that there is not yet available a commercial computer program with sufficient documentation or guidance on selection of input parameters to reliably model travel distance and velocities. Because of this, empirical methods are the most widely used. These have a significant model uncertainty which should be allowed for in developing the susceptibility maps for landslides which will travel beyond the source landslide.

C8.5.2. Preparation of landslide susceptibility map

Landslide susceptibility zoning maps may be developed from landslide inventories and geomorphological maps produced from aerial photos, satellite images, and field work. A relative susceptibility is allocated in a subjective manner by the person doing the study. This often leads to a map which is very subjective and difficult to justify or reproduce systematically.

A more objective way of developing susceptibility zoning is by correlating statistically a set of factors (such as geological–morphological factors) with slope instability from the landslide inventory. The relative contribution of the factors generating slope failures is assessed and the land surface is classified into domains of different susceptibility levels. Finally, the results of the classification are checked by analyzing whether the spatial distribution of the existing landslides (landslide inventory) takes place in the classes rated as the most unstable.

It should be kept in mind that the aim of susceptibility mapping should be to include the maximum number of landslides in the highest susceptibility classes whilst trying to achieve the minimum spatial area for these classes.

At large scale, detailed susceptibility maps may be founded on geotechnical models such as the infinite slope with parallel plane failure, provide the landslides in the area are shallow translational slides in rocks or soils (i.e. consistent with infinite slopes). An assessment of geotechnical and pore water pressure parameters is necessary in order to use this approach. The safety factor may be established in a GIS in pixel cells and the results referred to susceptibility depending on the calculated factor of safety. Given the complexity of geotechnical conditions in slopes these methods are unreliable unless calibrated by correlating with the landslide inventory.

Slope failure is caused by the concurrence of permanent conditioning and triggering factors. Permanent factors are terrain attributes (i.e. lithology, soil types and depths, slope, watershed size, vegetation cover, among others) that evolve slowly (i.e. by weathering or erosion) to bring the slopes to a marginally stable state. Triggers include shaking due to earthquakes or rise of groundwater levels and/or pressures due to infiltration of rainfall or snow melt. Only permanent conditioning factors are mapped to assess landslide susceptibility while the recurrence period of the triggers is usually used to assess the landslide hazard.

Some examples of susceptibility mapping are given in LCPC-CFG (2000), Cascini et al. (2005), Lee and Jones (2004), and Chacón et al. (2006).

C8.6. Landslide hazard zoning

C8.6.1. Frequency assessment

IIUGS (1997) advise that the frequency of landsliding may be expressed in terms of

- The number of landslides of certain characteristics that may occur in the study area in a given span of time (generally per year, but the period of reference might be different if required).
- The probability of a particular slope experiencing landsliding in a given period.
- The driving forces exceeding the resistant forces in probability or reliability terms, with a frequency of occurrence being determined by considering the annual probability of the critical pore water pressures (or critical ground peak acceleration) being exceeded in the analysis.

This should be done for each type of landslide which has been identified and characterized as affecting the area being zoned. Frequency is usually determined from the assessment of the recurrence intervals (the average time between events of the same magnitude) of the landslides. If the variation of recurrence interval is plotted against magnitude of the event, a magnitude–frequency curve is obtained.
Historical records. When complete series of landsliding events are available, recurrence intervals can be obtained by assuming that future occurrence of landslides will be similar to the past occurrence. Landslides have to be inventoried over at least several decades to produce a valid estimate of landslide frequency and the stability of temporal series has to be checked.

### Methods of determining frequency include:

- **Historical records.** When complete series of landsliding events are available, recurrence intervals can be obtained by assuming that future occurrence of landslides will be similar to the past occurrence. Landslides have to be inventoried over at least several decades to produce a valid estimate of landslide frequency and the stability of temporal series has to be checked.

### Table C.3

<table>
<thead>
<tr>
<th>Characterization method</th>
<th>Activity</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>(a) Rock Falls</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic</td>
<td>Map historic rock fall scars and record the number, spatial distribution, volume of fallen rocks below the source of the rock falls. Relate rock fall occurrence to presence of fallen blocks and talus deposits. The same activities as Basic plus Map geomorphic indicators (cracks, partially detached blocks). Develop frequency–magnitude relationships from the historic data Relate rock fall activity to Slope Mass Rating, Rock Mass Strength or use techniques such as Matterock Prepare landslide magnitude–frequency relations</td>
<td>Moon et al. (2005) Romana (1988), Selby (1980), Rouiller et al. (1998) Hungr et al. (1999), Guzzetti et al. (2003), Picarelli et al. (2005)</td>
</tr>
<tr>
<td>Intermediate</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The same activities as Intermediate plus</td>
<td>Hoek and Bray (1981), Goodman and Shi (1985), Bauer et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>Detailed mapping of geological structure (i.e. with laser scanner techniques) and relate field performance to analysis of stability using planar, wedge and topping analyses.</td>
<td></td>
</tr>
<tr>
<td>Advanced</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>The same activities as Intermediate plus</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Detailed mapping of geological structure (i.e. with laser scanner techniques) and relate field performance to analysis of stability using planar, wedge and topping analyses.</td>
<td></td>
</tr>
<tr>
<td><strong>(b) Small landslides</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic</td>
<td>Map historic landslides from air photography, preferably photographs taken at different times some years apart, and using some surface mapping. Prepare isopleth maps Relate landslide occurrence to topography (e.g. slope, elevation, aspect) and lithology using simple correlation of single variables and judgement.</td>
<td>Evans and King (1998), Dai and Lee (2001) Wright (1974) Nilsen et al. (1979), Brabb (1984)</td>
</tr>
<tr>
<td></td>
<td>Carry out more detailed surface mapping of the incidence of landslides, and geomorphology mapping using air photographs, remote sensors and/or by surface mapping. Relate landslide occurrence to topography, geology, type and depth of soils and geomorphology using statistical analysis techniques. Prepare landslide magnitude–frequency relations.</td>
<td>Guzzetti et al. (2002), Reid and Page (2002), Guthrie and Evans (2004)</td>
</tr>
<tr>
<td>Advanced</td>
<td>The same activities as Intermediate plus</td>
<td>Baum et al. (2005), Xie et al. (2003)</td>
</tr>
<tr>
<td></td>
<td>Detailed surface mapping and aerial photo interpretation, geotechnical and hydrological investigations. Relate landsliding with coupled slope stability models implemented in a GIS.</td>
<td></td>
</tr>
<tr>
<td><strong>(c) Large landslides</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic</td>
<td>Map landslides from aerial photography and/or surface mapping. Prepare an inventory of landsliding. Relate landslide occurrence to topography (e.g. slope, elevation, aspect) and lithology using simple correlation of single variables and judgement.</td>
<td>Crandell et al. (1979), Rohn et al. (2004), Cascini et al. (2005), Hungr et al. (2005)</td>
</tr>
<tr>
<td>Intermediate</td>
<td>The same activities as Basic plus</td>
<td>Dikau et al. (1996), Parise (2003), Van Westen and Getahun (2003), McKean and Roering (2004)</td>
</tr>
<tr>
<td></td>
<td>Carry out more detailed geological and geomorphology mapping using air photographs, remote sensors and/or by surface mapping, distinguishing the activity of landsliding qualitatively and identifying active processes leading to instability. Relate landslide occurrence to topography, geology, type and depth and geotechnical characteristics of soil and geomorphology using statistical analysis techniques. Obtain series of reactivation events.</td>
<td>Corominas and Moya (1999)</td>
</tr>
<tr>
<td></td>
<td>Detailed surface and air photo mapping, geotechnical and hydrological investigations. Some analyses of stability may be carried out. Analysis of historic and survey data to assess activity.</td>
<td></td>
</tr>
<tr>
<td><strong>(d) Cuts, fills and retaining walls in roads and railways and in urban development</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Basic</td>
<td>Make an inventory of the classification, volume, location and date of occurrence of landslides from local government records, newspaper articles and consultants files. Collect data on the population of slopes including the number, height, geology, type of wall construction. Relate these to the length of roads and the number of properties on which they have occurred to assess susceptibility. The same activities as Basic plus</td>
<td>MacGregor et al. (2007)</td>
</tr>
<tr>
<td>Intermediate</td>
<td>Include in the inventory the height of cuts, fills and retaining walls, slope angles, basic geology (lithology, depth of soil) and possibly basic geomorphology (e.g. are slides located in gullies, planar slopes or convex slopes); types of retaining walls for failed slopes and the population. Relate rock fall activity to Slope Mass Rating, Rock Mass Strength</td>
<td>Romana (1988), Pierson et al., 1990, Budetta (2004)</td>
</tr>
</tbody>
</table>
| Advanced                | The same activities as Intermediate plus | ]
• Sequences of aerial photographs and/or satellite images. Average frequency of landslides may be obtained dividing the number of new landslides identified or the retreat of a cliff in metres by the years separating the images.

• Silent witnesses. They are features that are a direct consequence of the landslide phenomenon such as tree impacts produced by fallen blocks or organic soils buried by the slide deposits. They provide the age of the landslide event with a precision that depends on the method used to date the feature.

• Correlation with landslide triggering events. Rain storms and earthquakes are the most common landslide triggering mechanisms. Once the critical rainfall and/or earthquake magnitude capable to trigger landslides has been assessed in a region, the recurrence intervals of the slides are assumed to be that of their triggers.

• Proxy data. They are data used to study the landslide, for which no direct information is available. Proxy data may be, for instance, pollen deposited on the surface of the landslide at any time after its emplacement, lichen colonization of the landslide deposits, or fauna assemblages that lived in a pond generated by the landslide movement, etc. These elements can be dated with a variety of techniques (Lang et al., 1999).

• Geomorphological features which are associated with the degree of landslide activity (presence of ground cracks, fresh scarps, tilted structures).

• Subjective (degree of belief) assessment. If there is little or no historical data it is necessary to estimate frequencies based upon the experience of the person(s) doing the zoning. This is usually done by considering the likely response of the slope to a range of triggering events, such as the 1 in 1; 1 in 10; 1 in 100 AEP rainfall and combining the frequency of the triggering event to the probability, given the trigger occurs, the slope will fail. This should be summed over the full range of trigger frequencies.

Assessing the recurrence periods of the landslide events will usually require using different and complementary methods. The frequency of the small size landslides may be obtained from the statistical treatment of the historical records. The frequency of large landslide events having long recurrence periods may be obtained for example from a series of dated old landslide deposits.

Landslides of different types and sizes do not normally have the same frequency (annual probability) of occurrence. Small landslide events often occur more frequently than large ones. Different landslide types and mechanics of sliding have different triggers (e.g. rainfalls of different intensity, duration, and antecedent conditions; earthquakes of different magnitude and peak ground acceleration) taking place with different recurrence periods. Because of this, to quantify hazard, an appropriate magnitude–frequency relationship should in principle be established for every landslide type in the study area. In practice the data available is often limited and this can only be done approximately.

Preliminary landslide hazard zoning maps are often prepared from simple geomorphological maps showing the types of landslides and a qualitative estimation of their activity (i.e. active, dormant or inactive). More elaborated maps are based on the quantitative, or at least semi-quantitative, assessment of frequency–magnitude relationship for different landslide types.

Deterministic approaches for estimating frequency by correlation with rainfall have been mostly performed at a site level (large scale). Recent developments in coupling hydrological and slope stability models have allowed the preparation of landslide hazard maps at a local level. These approaches require data of high quality: detailed DTM, relatively uniform ground conditions, landslide types easy to analyze and a well established relationship between precipitation regime and groundwater level changes (e.g. Baum et al., 2005). This is usually only possible for shallow landslides which generally fit these conditions. The frequency of landsliding can be linked to the frequency of the precipitation. The complex geotechnical nature of slopes makes it impractical to use these methods without calibration against field performance with landslide inventories in the study area.

Some useful references on frequency assessment include:


• For assessing historic data to produce magnitude–frequency curves. Fell et al. (1996), Bunce et al. (1997), Hurgr et al. (1999), Dussage Peiser et al. (2002); Chau et al. (2003); Malamud et al. (2004); Remondo et al. (2005), Coe et al. (2004), Picarelli et al. (2005), Moon et al. (2005), Evans et al. (2005).

• For assessing remote sensing images data (aerial photographs, satellite images) to produce magnitude–frequency curves. Cardinali et al. (2002), Reid and Page (2002), Guthrie and Evans (2004), Guzzetti et al. (2006).

• For assessing proxy data: Gardner (1980), Bull et al. (1994), Lang et al. (1999), Schuster et al. (1992), Van Steijn (1996), Alexandrowicz and Alexandrowicz (1999), González-Díez et al. (1999), Corominas et al. (2005); Stoffel et al. (2005); Irmler et al. (2006).


• For assessing the susceptibility of slopes to liquefaction and flow failure: Youd et al. (2001), Hunter and Fell (2003).

It should be noted that:

(a) The assessment of frequency of sliding from geomorphology is very subjective and approximate, even if experienced geomorphologists are involved. It should be supported with historic data so far as possible. In principle, the method should work best for frequent sliding where fresh slide scarps and other features will be evident. However, such features may be covered within weeks by farming and construction activity.

(b) Most methods for relating landslide frequency to rainfall indicate when landsliding in an area may occur, not whether a particular slope may slide. The figures from these analyses must be adjusted for the population of slopes to allow estimation of the frequency of sliding. This is discussed in Picarelli et al. (2005) and in MacGregor et al. (in preparation).

(c) The incidence of landsliding of slopes to rainfall is usually non-linear. For smaller slides from natural slopes and cuts and fills there is often a “threshold” rainfall below which little or no landsliding will occur, and then a greater frequency of sliding for increasing rainfall. This is evident in the data for failures from cuts, fills and retaining walls in Hong Kong (Finlay et al., 1997), MacGregor et al. (in preparation) for cuts and fills in Pittwater shire, Sydney; and in small shallow slides from steep natural slopes (Kim et al., 1992).

(d) For larger landslides it is often the combination of rainfall intensity and antecedent rainfall over a period which causes landslides to become active. Leroueil (2001) provides several examples.

(e) When relating the frequency of landsliding to rainfall it should not be assumed that 24 h rainfall is the critical duration. The effect of shorter duration high intensity rainfall should be assessed if the rainfall data is available. However, pluviograph data is seldom available. The effect of antecedent rainfall should
be assessed at least qualitatively (e.g. MacGregor et al., in preparation).

(f) The frequency of seismically induced landsliding is related to the peak ground acceleration at the site, and the magnitude of the earthquake. Studies by Keef er (1984), Harp and Jibson (1995, 1996) and Jibson et al. (1998) have shown that there is a critical magnitude and peak ground acceleration (or distance from the earthquake epicentre) above which landsliding will occur. This varies for different classes of landslide. Pre-earthquake rainfall and water tables influence the response of slopes to earthquakes.

(g) Newmark type displacement analysis is described in Newmark (1965) and Fell et al., 2005a,b.

(h) The assessment of the frequency of collapse of coastal cliffs is related to coastal erosion processes which may control the frequency of landsliding. This is a specialist area and should be assessed by a multi-discipline team including engineering geologist, rock mechanics engineer and coastal engineer. Similarly, for mapping of coastal sand dunes subject to erosion by the sea a team consisting of geotechnical engineer, engineering geologist and coastal engineer is required.

Because of the complex interaction between the mechanical behaviour of geo-materials and triggering factors it is recommended that a geotechnical engineer familiar with the mechanics of slopes be involved in frequency estimation for zoning studies.

C8.6.2. Intensity assessment

Hungr (1997) defined landslide intensity as a set of spatially distributed parameters describing the destructiveness of the landslide. These parameters are varied, with the maximum movement velocity the most accepted one, although total displacement, differential displacement, depth of moving mass, depth of deposited mass and depth of erosion are alternative parameters. Keeping in mind the design of protective structures, other derived parameters such as peak discharge per unit width, kinetic energy per unit area, maximum thrust or impact pressure may be also considered.

Landslide movements can range from imperceptible creep displacements of large and small masses to both large and very fast rock avalanches. The likelihood of damage to structures and the potential for life-loss will vary because of this. Intensity is the measure of the damaging capability of the landslide. In slow-moving landslides, persons are not usually endangered while damages to buildings and infrastructures might be high although, in some cases, only evidenced after long periods of time. By contrast, rapid movements of small and large masses may have catastrophic consequences for both persons and structures. For this reason it is desirable to describe the intensity of the landslides in the zoning study.

The same landslide may result in different intensity values along the path (for instance, the kinetic energy of a rock fall changes continuously along its trajectory).

There is therefore, no unique definition for intensity and those carrying out the zoning will have to decide which definition is most appropriate for the study. Useful references include Hungr (1997), Lateltin (1997), Hungr et al. (2005), Cascini et al. (2005) and Copons et al. (2004).

C8.6.3. Preparation of landslide hazard zoning map

Examples of hazard zoning mapping are given in Cascini et al. (2005), Wong (2005), and Corominas et al. (2003).

C8.7. Landslide risk zoning

C8.7.1. Elements at risk

The elements at risk are the population, buildings and engineering works, economic activities, public services utilities, infrastructure and environmental features in the area potentially affected by the landslide hazard. These need to be assessed for existing and proposed development.

C8.6.2. Temporal spatial probability and vulnerability


Elements at risk may be damaged in multiple ways (Leone et al., 1996; Glade et al., 2005; Van Westen et al., 2005). In large landslides, there are sensitive areas where damage will be more likely (or much higher), no matter what the total landslide displacement or the released energy will be. This occurs, for instance, in the landslide boundaries, such as the head or sides, or at local scars where tensile stresses develop with the result of cracks, surface ground depletion and local rotation. Similarly, large differential deformations are expected in the landslide toe where thrusting and bulging of the ground surface might take place.

The resistance of a building is dependent on the landslide mechanism. It might be sufficient to resist the impact of a falling block but it can be insufficient to avoid development of tension cracks due to differential displacements produced by a translational slide. It may be concluded that, for a similar structure or building, the expected damage will depend on: (i) the landslide type (rock fall, debris flow, slide, etc); (ii) the hazard intensity and (iii) the relative location of the vulnerable element in relation to the landslide trajectory or to the position inside the landslide affected area.

The vulnerability of lives and properties are often different. For instance, a house may have a similar high vulnerability to both slow-moving and rapid landslides, while a person living in it may have a low to negligible vulnerability in the first case. It is recommended that vulnerability of the elements at risk be estimated for each landslide type, and hazard intensity. In order to make reliable estimation of the vulnerability of the elements at risk, it is indispensable to carry out the analysis of the performance of structures during past landslide events and the inventory of the observed damages (Faella and Nigro, 2003).

Vulnerability mapping can be performed with the aid of approaches which, depending on both the scale and the intended map application, may be either qualitative or quantitative. A qualitative approach, coupled with engineering judgement, uses descriptors to express a qualitative measure of the expected degree of loss (Cascini et al., 2005). However, qualitative approaches, as recommended by AGS (2000), are only applicable to consideration of risk to property. Quantitative approaches, like that proposed by AGS (2000, 2002, 2007a) for life-loss situations and Remondo et al. (2005), need data on both landslide phenomenon and vulnerable element characteristics (Leone et al., 1996).

Mostly this is empirical data. It should be noted that any errors introduced by uncertainty in vulnerability estimates are usually far outweighed by the uncertainty in frequency estimates.

C8.7.3. Preparation of landslide risk zoning maps


C9. Reliability of landslide zoning for land-use planning

C9.1. Potential sources of error

The inability of advanced methods to model slopes in zoning studies is discussed further in Picarelli et al. (2005) and Fell et al. (2000). Where used they should be calibrated against landslide inventories and empirical methods.

C9.2. Validation of mapping

Bulut et al. (2000), Remondo et al. (2003), Ardizzione et al. (2002) and Irigaray et al. (1999) give examples of validation.
C10. Application of landslide zoning for land-use planning

C10.1. General principles

The importance of carrying out the zoning at an appropriate level and scale cannot be over-emphasised.

C10.2. Typical development controls applied to landslide zoning

No comments or additional information.

C11. How to brief and select a geotechnical professional to undertake a mapping study

C11.1. Preparation of a brief

No comments or additional information.

C11.2. Selection of a consultant for the mapping

No comments or additional information.

C11.3. Provide all relevant data

No comments or additional information.

C12. Method for development of the guidelines, and acknowledgements

It is emphasised that the guidelines have been subject to extensive review internationally.

Acknowledgements

The draft of this Commentary has received comments and suggestions from the participants of the workshop held in Barcelona in 2006 and other experts mentioned in the preface of this issue. All of them are gratefully acknowledged.

References


