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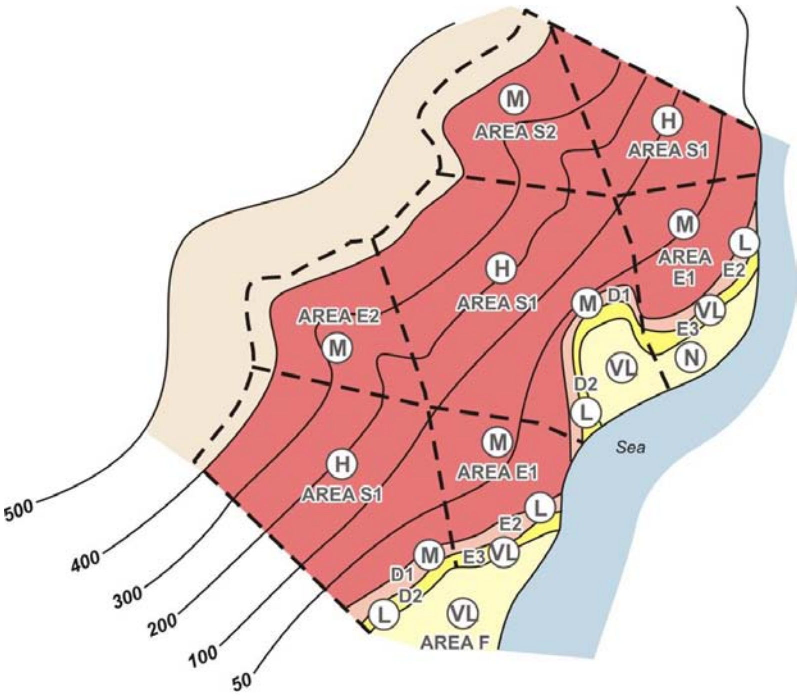

Landslide Risk Management

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COMMENTARY ON

GUIDELINE 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.

C1 INTRODUCTION

There have been examples of landslide susceptibility and hazard zoning in use since the 1970's (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 and the Cartes de Dangers or Gefahrenkarten in Switzerland are carried out at the Canton level but with Federal funding support (Leroi *et al*., 2005).

C2 DEFINITIONS AND TERMINOLOGY

C2.1 DEFINITIONS

The definitions in the Guideline are consistent with International Landslides and Geotechnical Engineering practice.

Some practitioners in Australia have used the term "hazard" without including the frequency of landsliding in the definition. This is contrary to the AGS (2000, 2002) definition and to international practice.

C2.2 LANDSLIDE CLASSIFICATION AND TERMINOLOGY

There is no consensus within the international geotechnical community on which landslide classification system to use. All existing systems are seen to have shortcomings. In recognition of this JTC 1, the Joint Technical Committee on Landslides and Engineered Slopes has established a working committee to develop a new classification system on behalf of ISSMGE, IAEG and ISRM. This will not be completed until late in 2008.

In the meantime it is recommended that the classification and terminology described in Appendix B of AGS (2000, 2002) be used. These are based on Cruden and Varnes (1996), Varnes (1978) and IAEG (1990).

C3 LANDSLIDE RISK MANAGEMENT FRAMEWORK

More details on the use of risk management in landslides are given in the State of the Art papers in The International Conference on Landslide Risk Management, Vancouver, June 2005 (Fell *et al*., 2005; Picarelli *et al.*, 2005; Nadim *et al*., 2005; Hungr *et al*., 2005; Roberds, 2005; Leroi *et al*,. 2005; Cascini *et al.*, 2005 and Wong, 2005); in AGS (2000, 2002, 2007a) and Lee and Jones (2004).

For information on the historical development of landslide risk management, see Einstein (1988, 1997), Fell (1994), IUGS (1997) and Fell and Hartford (1997).

C4 DESCRIPTION OF LANDSLIDE SUSCEPTIBILITY, HAZARD AND RISK ZONING FOR LAND USE PLANNING

C4.1 TYPES OF LANDSLIDE ZONING

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.

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 uphill of the study area but may travel on to it, and landslides downhill of the study area which may retrogressively fail up-slope into it.

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.

Areas which may be affected by travel or regression of the landslides from the source will often be best shown on a separate map. The travel and regression of the landslides is dependent on different factors to those causing the landslides.

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.

Landslide Hazard Zoning

Hazard zoning should be applied to 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 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 it will be possible to give some approximate guidance on the frequency of landslides in the zoning classes.

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 recognised 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

Examples of landslide susceptibility, hazard and zoning maps are attached in Appendix CA. For other examples see Cascini *et al*. (2005) which references a number of zoning schemes. Note that the terms used in these examples are not necessarily consistent between each other or with this guideline.

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 categorised 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 geomorphologic 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

It should be noted that, unless specifically required by the organisation funding the zoning study or by the 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

C6 SELECTION OF THE TYPE AND LEVEL OF LANDSLIDE ZONING

C6.1 SOME GENERAL PRINCIPLES

Some landslide zoning management schemes rely only 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 recognised 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.

The money saved by the planning authority in doing the lower cost susceptibility zoning study may be expended many times over by those in low hazard zones being required to fund unnecessary detailed hazard and risk assessments.

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 proposed 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 an 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 based on susceptibility zoning that does not consider the frequency of the potential landsliding.

It is recognized that the funding available for landside 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 and 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. Reliable zoning cannot be produced if, for instance, a landslide hazard zoning map prepared at a scale of 1:5,000 is based on a 1:25,000 geomorphologic 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 the 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 is 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 into account 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 descriptors generally fall into the following categories:

- Likelihood that landsliding may occur in an area.
- The proportion or percentage of an area which may be susceptible to landsliding or on to which landslides may travel.
- The percentage (proportion) of the total events within the zoned area.
- The likelihood given landslides (e.g. rock falls) occur that they will reach an area being zoned.

Which of these is most appropriate should be determined on a study specific basis. The examples given in Table 4 should be used so far as practical to give some consistency between different zoning studies. It is emphasised that:

(a) Landslide susceptibility does not include a time frame or frequency of landsliding.

(b) The ability to recognize susceptibility to some types of landslide may depend on how long before the zoning study the landslides occurred. For example shallow landslides on steep natural slopes may not be evident a few years after they occur if the area revegetates.

(c) Some types of landslides may have occurred under different climatic conditions than now exist. Others may have exhausted the source material; e.g. shallow slides forming in drainage gullies on steep slopes may remove all the colluvial soil from the gully so that no further sliding will occur.

C7.2.3 Recommended landslide hazard zoning descriptors

Table 5 is meant to be used to assign verbal descriptors to the hazard zoning where the hazard has been quantified. It must not be used in reverse. If the assessed rock fall hazard is “high” by some qualitative method, this should not be interpreted to mean 1 to 10 rock falls/annum/km of cliff.

It should be noted that the “low” and “very low” descriptors for large landslides are most likely to be applied to slopes which have no geomorphic or other evidence of landsliding. It is difficult to assess such low frequencies to existing landslides.

In many cases there will be insufficient data to reliably quantify the hazard. In such cases the available data should be used to make a best estimate and the hazard which is then described as in Table 5 with a suitable qualification on the accuracy of the estimated hazard.

In some situations it may be possible to add to the description of the hazard the temporal occurrence within the year of the landsliding. For example, if the rainfall is monsoonal all landslides may occur within a 4 to 6 month period in the year. This can be useful additional knowledge for those managing the landslide hazard and should be done where practical.

C7.2.4 Recommended landslide risk zoning descriptors

Table C1 summarizes individual life loss risk criteria in use in a number of engineering related disciplines, including landsliding. It can be seen that there is a similarity between most of the criteria. Criteria in AGS (2000, 2002, 2007a) were determined taking many of these examples into account.

Table 6 has been developed taking as the starting point the individual life loss risk criteria of 10^{-6}/annum for acceptable risk and 10^{-5}/annum for tolerable risk, for the person most at risk for new cut and fill slopes suggested in AGS (2000, 2002, 2007a). It has been assumed that "acceptable risks" are "low" and tolerable risks are "moderate". Higher risks are often tolerated for existing slopes than for new slopes but it is considered impractical to adopt different figures for defining the descriptors for new and existing slopes in landslide zoning because of the common mix of existing and new development. Table 6 is meant to be used to assign verbal descriptors to the risk zoning where the risk has been quantified.. If the risk is assessed as "low" by some qualitative method it should not be interpreted to mean the annual probability of death of the person most at risk is assumed to be between 10^{-6}/annum and 10^{-5}/annum.

Whether risks within a zone are tolerable is a matter for the authority managing landslide hazards and regulators.There are no internationally accepted risk criteria for landsliding. It is necessary therefore to develop tolerable loss of life criteria for each situation, taking account of the legal framework of the country and regulatory controls in place. Criteria should be developed in consultation with all the affected parties, including the affected public. Those doing the risk analysis are likely to be most informed about precedents and understand the analyses and their limitations, so it is appropriate they are involved in this process. More information on tolerability of landslide risks is given in Leroi *et al.* (2005), ANCOLD (2003), Lee and Jones (2004), Bonnard *et al.* (2004) and Christian (2004).

Generally it should be possible to define 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.

Table C1: Individual life loss risk criteria. (Leroi *et al.*, 2005).

Organization	Industry	Description	Risk/annum	Reference
Health and Safety Executive, United Kingdom	Land use planning around industries	Broadly acceptable risk. Tolerable limit	10^{-6}/annum, public and workers 10^{-4}/annum public(1) 10^{-3}/annum workers	HSE (2001)
Netherlands Ministry of Housing	Land use planning for industries	Tolerable limit(2)	10^{-5}/annum, existing installation 10^{-6}/annum, proposed installation	Netherlands Ministry of housing (1989), Ale (2001), Vrijling *et al.* (1998)
Department of Urban Affairs and Planning, NSW, Australia	Land use planning for hazardous industries	"acceptable" (tolerable) limits (2)	$5x10^{-7}$/annum hospitals, schools, childcare facilities, old age housing 10^{-6}/annum residential, hotels, motels $5x10^{-6}$/annum commercial developments 10^{-5}/annum sporting complexes	
Australian National Committee on Large Dams	Dams	Tolerable limit	10^{-4}/annum existing dam, public most at risk subject to ALARP 10^{-5}/annum new dam or major augmentation, public most at risk, subject to ALARP.	ANCOLD (2003)
Australian Geomechanics Society guidelines for landslide risk management	Landslides (from engineered and natural slopes)	Suggested tolerable limit	10^{-4}/annum public most at risk, existing slope 10^{-5}/annum, public most at risk, new slope	AGS (2000)
Hong Kong Special Administrative Region Government	Landslides from natural slopes	Tolerable limit	10^{-4}/annum public most at risk, existing slope. 10^{-5}/annum public most at risk, new slope	Ho et al. (2000), ERM (1998), Reeves *et al*. (1999)
Iceland ministry for the environment hazard zoning	Avalanches and landslides	"acceptable" (tolerable) limit	$3x10^{-5}$/annum residential, schools, daycare centres, hospitals, community centres. 10^{-4}/annum commercial buildings $5x10^{-5}$ recreational homes(3)	Iceland Ministry for the environment (2000), Arnalds *et al.* (2002)
Roads and Traffic Authority, NSW Australia	Highway landslide risk	Implied tolerable risk	10^{-3}/annum(4)	Stewart *et al*. (2002), RTA (2001)

Notes:

(1) But for new developments HSE (2001). advise against giving planning permission where individual risks are > 10^{-5}/annum. (2) Based on a temporal spatial probability of 1.0. (3) Assumes temporal spatial probability of 0.75 for residential, 0.4 commercial, 0.05 recreational. (4) Best estimate of societal risk for one person killed, top risk ranking. If slope ranks in this range action is taken to reduce risks within a short period. For the second ranking, societal risk is 10^{-4}/annum, and slope is put on priority remediation list.

The recommended 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 "Likelihood" is the annual probability of the event which causes the property loss. It includes the annual probability of the landslide with allowance for whether it will reach the property. The damages include the cost of stabilization of 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 (2007c).

C7.2.5 Recommended approach

No comments or additional information

C8 METHODS FOR LANDSLIDE ZONING FOR LAND USE PLANNING

C8.1 THE PURPOSE OF THIS SECTION

No comments or additional information.

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 landslide inventories

GIS-based landslide inventories can be quite simple or they can include extensive and detailed information compiled over longer periods of time in related tables and associated spatial data, typically in vector format.

Table C2 gives a generic example of the fields which may be included in an inventory.

The compilation and use of standard parameters for storage and reporting fields in landslide inventories has been the subject of an ongoing project initiated by Geoscience Australia. This work is addressing landslide inventory structure and includes generic categories whilst employing complex relational database structure. The project aims to establish a nationally consistent system of data collection to ensure a sound knowledge base for natural disasters such as landslides and facilitate better disaster mitigation. It is recommended that the future outcomes from this project to be published in Oschuwoski *et al*. be considered as a new guide for the development of landslide inventories.

Table C2: Generic Primary Landslide Inventory Fields. (courtesy of A Miner and P Flentje).

Field ID	Field Name	Data Type	Number Format	General Description of Field Contents
1	Inventory Number	Number	Single	Unique landslide site reference code
2	Landslide Type	Text	n/a	Cruden and Varnes (1996) basic landslide type (i.e, slide, flow, fall or as described elsewhere in this guideline Falls, shallow landslides, large landslides and small built environment failures)
3	Detailed Landslide Classification	Text	n/a	Cruden and Varnes (1996) full landslide classification
4	Reported By	Text	n/a	Name of person reporting landslide
5	Contact Details	Text	n/a	Contact details of reporter
6	Date Reported	Text	n/a	Date landslide reported
7	Date and Time of Landslide	Date/ Time	n/a	Date and time of landslide. Perhaps in related table with one to many relationship
8	Magnitude of displacement (m)	Number	Single	Distance travelled by landslide
9	Street Number	Text	n/a	Physical Street Number
10	Street Name	Text	n/a	Physical Street Name
11	Suburb	Text	n/a	Local Government suburb

12	City	Text	n/a	City or Country region
13	State	Text	n/a	State
14	Post Code	Number	Integer	Australian Post Code
15	Jurisdiction	Text	n/a	Organisation or individual responsible for land management of site
16	GDA1994 Easting	Number	Long Integer	GDA1994 Easting grid position to centre of landslide
17	GDA 1994 Northing	Number	Long Integer	GDA 1994 Northing grid position to centre of landslide
18	Method of Spatial Data Capture	Text	n/a	Field mapping, surveying, old reports, API etc
19	Positional Accuracy	Text	n/a	An estimate of positional accuracy such as +/- 20m or similar
20	Landslide Width across the slope (m)	Number	Single	Maximum width across the slope in metres
21	Landslide Length up/down the slope (m)	Number	Single	Maximum length up/down slope in metres
22	Landslide Depth (m)	Number	Single	Maximum thickness of landslide profile perpendicular to surface of rupture in metres
23	Volume	Number	Single	WP/WLI (1990) landslide volume calculation
24	Location	Text	n/a	Describe physical location of landslide to aid geographic positioning
25	Site Description	Text	n/a	Physical description of site to aid visualisation and detail positioning
26	Landslide Trigger	Text	n/a	Describe trigger if known (i.e rainfall intensity/duration; seismic Magnitude and location etc)
27	References	Text	n/a	Reference listing of Investigation Reports and other material pertaining to this landslide
28	Current Site	Number	Byte	Is this site still a current site or has it been superseded, see comments
29	Comments	Text	n/a	Addendum to any of the above and or additional comments
30	Ground slope	Number	Byte	Local area average ground slope
31	Geological Setting	Text	n/a	Geological Province
32	Bedrock Geology	Text	n/a	Geological formation - name of underlying bedrock units
33	Slide Geometry	Text	n/a	Generalised description of slide profile, if known.
34	Slide Material	Text	n/a	Description of bulk of material being displaced
35	Depth to Bedrock	Number	Single	Depth to bedrock (m)
36	Depth to Basal Failure Plane	Number	Single	Depth to basal failure plane (m)
37	What is the Relationship to Rainfall?	Text	n/a	What is the relationship between movement and rainfall if known?
38	Strength Parameters	Text	n/a	Reference to or list any geotechnical parameters either tested or back analysed
39	Houses Damaged	Number	Double	Number of houses damaged
40	Houses Destroyed	Number	Double	Number of houses destroyed
41	Person Injured	Number	Double	Number of persons injured
42	Person Killed	Number	Double	Number of persons killed
43	Infrastructure Damaged	Text	n/a	Description of infrastructure damaged
44	Infrastructure Destroyed	Text	n/a	Description of infrastructure destroyed
45	Environmental impact	Text	n/a	Description of environmental impact
46	Economic Loss	Text	n/a	Description of economic loss caused by landslide and date with references
47	Geotechnical Investigation Type	Number	List select	Type/Level of Geotechnical Investigation with references
48	Cost of Geotechnical Investigation	Number	Double	Cost of Geotechnical Investigation with references

(b) GIS based modelling of landslide susceptibility and hazard

With the available data in place various methods can be applied to establish inter-relationships and ultimately to establish levels of susceptibility and hazard. Key vector data sets typically used in landslide zoning studies include landslide polygons, geology, geomorphologic 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, condition analysis and discriminate analysis etc.

These indirect methods involve qualitative or quantitative modelling 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 and 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 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 approach is based on the observed relationships between each factor and the past distribution of landslides. Hence susceptibility and hazard zoning is conducted in a largely objective manner whereby factors and their interrelationships are evaluated on a statistical basis. Various methods exist for the development of the rules for and relationships between variables and these include bivariate analysis, multivariate analysis, Boolean approaches using logistic regression, Bayesian methods using weights of evidence and neural networks (Soeters and van Westen, 1996). 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 (e.g. Bishop, Sarma etc) and less commonly finite element and 3-D 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, meta-stable 1.0 to 1.1 etc). See for example, Savage *et al*. (2004) and Baum *et al*. (2005). The variability of input data can be further used to calculate probability of failure in conjunction with return periods of triggers (Soeters and van Western, 1996).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 considered in relation to the subsequent use of the 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 a 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.

(d) The need for calibration of GIS modelling.

The need to field check iterations of the GIS modelling output is critical in producing a 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 an appropriate scale and resolution is considered to be possibly the most significant task undertaken in any GIS-based inventory compilation and modelling 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 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 may not be able to 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 sophisticated 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 (or equivalent in GIS terms). It is unnecessary and impossible to distinguish between landslide scarp features and resulting mass 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 m^2. Smaller landslides are represented by a dot. Minor and lateral scarps may be distinguished as well as upslope deformations such as tension cracks or minor landslides. Landslides are classified. Original mass, volume and averaged velocity is recorded from direct information 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 scale 1: larger than 1:5,000 for site specific or local zoning.
The minimum area covered by an inventoried mapped landslide is 100 m^2. 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 lithological 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 from 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 their area.

C8.5 LANDSLIDE SUSCEPTIBILITY ZONING

C8.5.1 Landslide characterization and travel distance and velocity

Table C3 (a) to (d) provides more detail on the activities required 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. For advanced methods, intermediate and basic mehods 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 the larger scale of 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 sophisticated 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: Evans and Hungr (1993), Hungr *et al*. (2005), Corominas (1996), Hunter and Fell (2003).
- Numerical methods for assessing travel distance: Hungr (1995), McDougall and Hungr (2004), Hungr *et al.* (2005).
- GIS based methods: 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 Hungr *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. The DAN Program (Hungr, 1995, McDougall and Hungr, 2005) is available for use commercially but requires calibration on failed slopes in the study area before being used in a forecasting mode. 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.

Table C3: Details of some activities which may be used to characterise, and evaluate the spatial distribution of potential landslides and their relationship to topography, geology and geomorphology.

(a) Rock Falls

Characterisation method	Activity	References
Basic	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.	
Intermediate	**The same activities as Basic plus**	Romana (1988) Selby (1980) Rouiller *et al*. (1998) Hungr, *et al*. (1999) Picarelli, *et al*. (2005) Moon, *et al*. (2005)
	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 Use magnitude-frequency relationship techniques.	
Sophisticated	**The same activities as Intermediate plus**	Hoek and Bray (1981) Goodman and Shi (1985)
	Detailed mapping of geological structure and relate field performance to analysis of stability using planar, wedge and toppling analyses.	

(b) Small Landslides

Basic	Map historic landslides from air photography, preferably photographs taken at different times some years apart and using some surface mapping.	Nilsen *et al.* (1979) Brabb (1984) Evans and King (1998) Dai and Lee (2002)
	Relate landslide occurrence to topography (e.g. slope, elevation, aspect) and lithology using simple correlation of single variables and judgement.	
Intermediate	**The same activities as Basic plus**	Van Westen (1994) Carrara *et al.* (1995) Baynes and Lee (1998)
	Carry out more detailed surface mapping of the incidence of landslides and geomorphology mapping using air photographs and/or by surface mapping.	
	Relate landslide occurrence to topography, geology, type and depth of soils and geomorphology using statistical analysis techniques..	
Sophisticated	**The same activities as Intermediate plus**	Baum *et al.* (2005)
	Detailed surface mapping and aerial photo interpretation, geotechnical and hydrological investigations. Relate landsliding with coupled slope stability models implemented in a GIS.	

(c) Large Landslides

Basic	Map landslides from aerial photography and/or surface mapping. Prepare an inventory of landsliding.	Crandell *et al.* (1979) Cascini *et al.* (2005) Hungr *et al.* (2005)
	Relate landslide occurrence to topography (e.g. slope, elevation, aspect) and lithology using simple correlation of single variables and judgement.	
Intermediate	**The same activities as Basic plus**	Dikau, *et al.* (1996)
	Carry out more detailed geological and geomorphology mapping using air photographs and/or by surface mapping, distinguishing the activity of landsliding qualitatively.	
	Relate landslide occurrence to topography, geology, type and depth and geotechnical characteristics of soil and geomorphology using statistical analysis techniques.	
Sophisticated	**The same activities as Intermediate plus**	Wu and Abdel-Latif, 2000 Corominas and Satacana, 2003
	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.	

(d) Cuts, fills and retaining walls in roads and railways and in urban development

Basic	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.	
Intermediate	**The same activities as Basic plus**	Budetta (2004) MacGregor *et al.* (2007)
	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.	
Sophisticated	**The same activities as Intermediate plus**	
	Include in the inventory details of slope angles, geotechnical properties of typical slopes, drainage and groundwater conditions for the failed slopes and the population.	

C8.5.2 Preparation of landslide susceptibility map

Landslide susceptibility zoning maps may be developed from landslide inventories and geomorphologic 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 analysing 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. Triggering events include ground 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 Cascini *et al*. (2005), Lee and Jones (2004), and Chacon *et al*. (2006).

C8.6 LANDSLIDE HAZARD ZONING

C8.6.1 Frequency Assessment

(IUGS, 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.

Methods of determining frequency include:

- Historical records. When the complete series of landsliding events is 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.
- 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 landslides 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).
- Geomorphologic 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. For example the frequency of large landslide events having long recurrence periods may be obtained 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) 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 analyse 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 geomorphology data: Baynes and Lee (1998), Wieczorek (1984), McCalpin (1984),Carrara *et al.* (1995), Palmquist and Bible (1980), Fell *et al.* (1996).
- For assessing historic data to produce magnitude –frequency curves. Fell *et al.* (1996), Bunce *et al.* (1997), Hungr *et al*. (1999), Remondo *et al.* (2005), Coe *et al*. (2004), Picarelli *et al.* (2005), Moon *et al.* (2005), Evans *et al*. (2005).
- 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), Gonzalez –Diez *et al*. (1999), Corominas *et al.* (2005)
- For relating landslide frequency to rainfall and other factors: Picarelli *et al.* (2005), Strunk (1992), Wilson and Wieczorek (1995), Crozier (1997), Finlay *et al.* (1997), DUTI (1983), Soeters and van Westen (1996), Baum *et al*. (2005).
- For relating the frequency of rock falls and small slides on natural slopes to seismic loading: Wieczorek (1996), Keefer (1984), Schuster *et al.* (1992), Cascini *et al.* (2005), Harp and Jibson (1995,1996), Jibson *et al.* (1998)
- 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 and 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.* (2007).

(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*., 2007) 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 hour 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*., 2007; Walker, 2007).

(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 Keefer (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*. (2005).

(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 and 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). Australian examples include the Shire of Lillydale (1993) mapping which was at an intermediate level and classifies hazard (called risk in the scheme documents) into low, low (basalt), medium M1, medium M2 and high. There are other areas classified as not susceptible to landsliding. Depending on the classification, development may proceed without detailed geotechnical assessment or with geotechnical assessment. The scheme is described in Moon *et al*. (1992).

Part of that Shire was also subjected to a sophisticated level study of debris flow hazard. This is described in Moon *et al*. (1992) and in Fell and Hartford (1997) who extended the scheme to risk zoning.

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.

C8.7.2 Temporal spatial probability and vulnerability

Some useful references include Roberds (2005), Van Westen (2004), Wong (2005) and AGS (2000, 2002, 2007c).

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 scarps 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 dependant 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 type. 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

Examples are given in Cascini *et al.* (2005), Bell and Glade (2004), Lee and Jones (2004) Michael-Leiba *et al.* (2003) and Corominas *et al.* (2005).

C9 RELIABILITY OF LANDSLIDE ZONING FOR LAND USE PLANNING

C9.1 POTENTIAL SOURCES OF ERROR

The inability of sophisticated 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

Cascini *et al.* (2005), Remondo *et al.* (2003), Ardizzione *et al.* (2002) and Irigaray *et al.* (1999) give examples of validation.

COMMENTARY ON GUIDELINE FOR LANDSLIDE SUSCEPTIBILITY, HAZARD AND RISK ZONING FOR LAND USE PLANNING

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.

C13 REFERENCES

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APPENDIX CA - EXAMPLES OF LANDSLIDE ZONING MAPPING

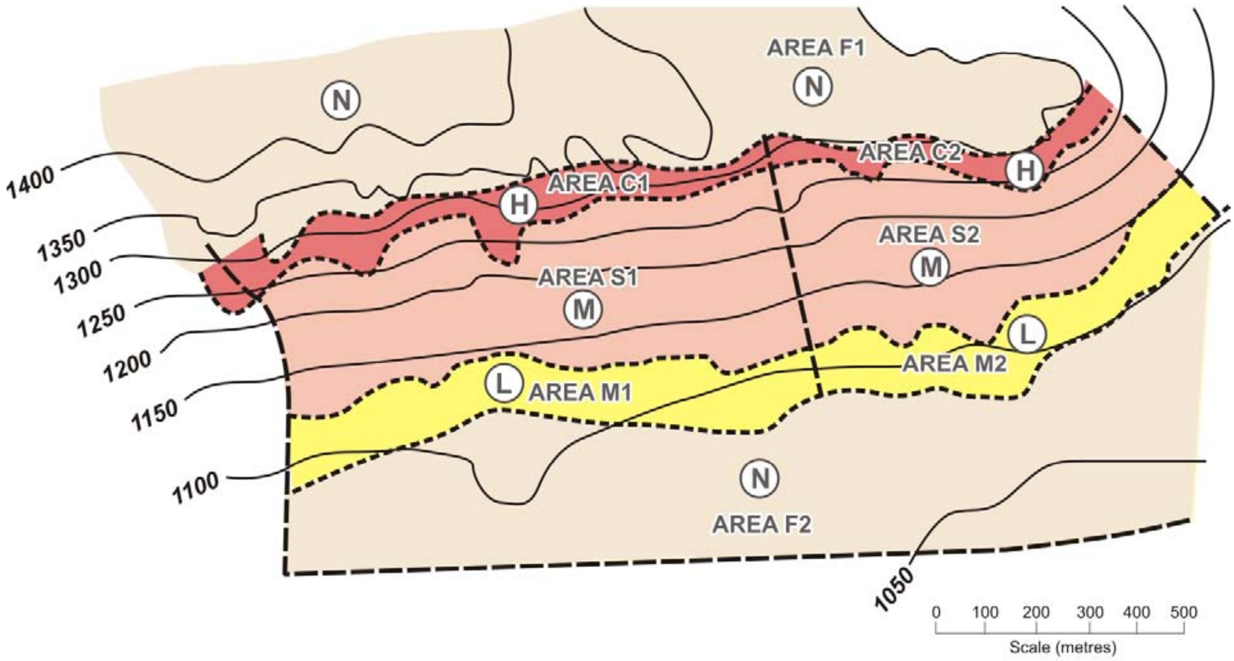

Figure 2A Rockfall Susceptibility

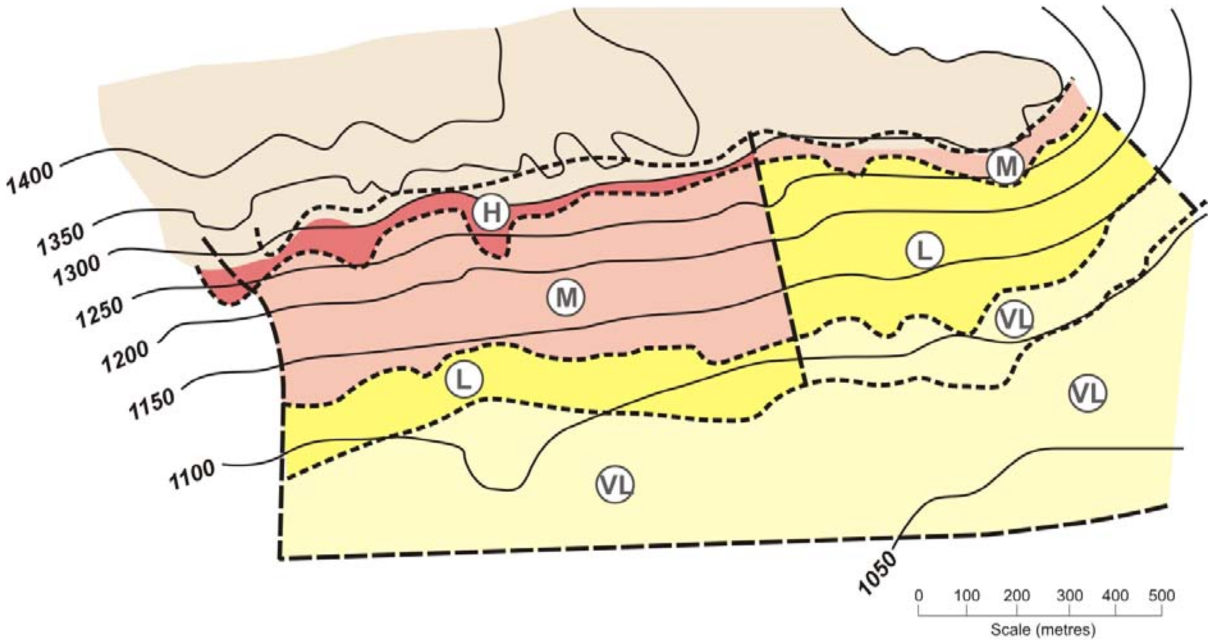

Figure 2B Rockfall Hazard

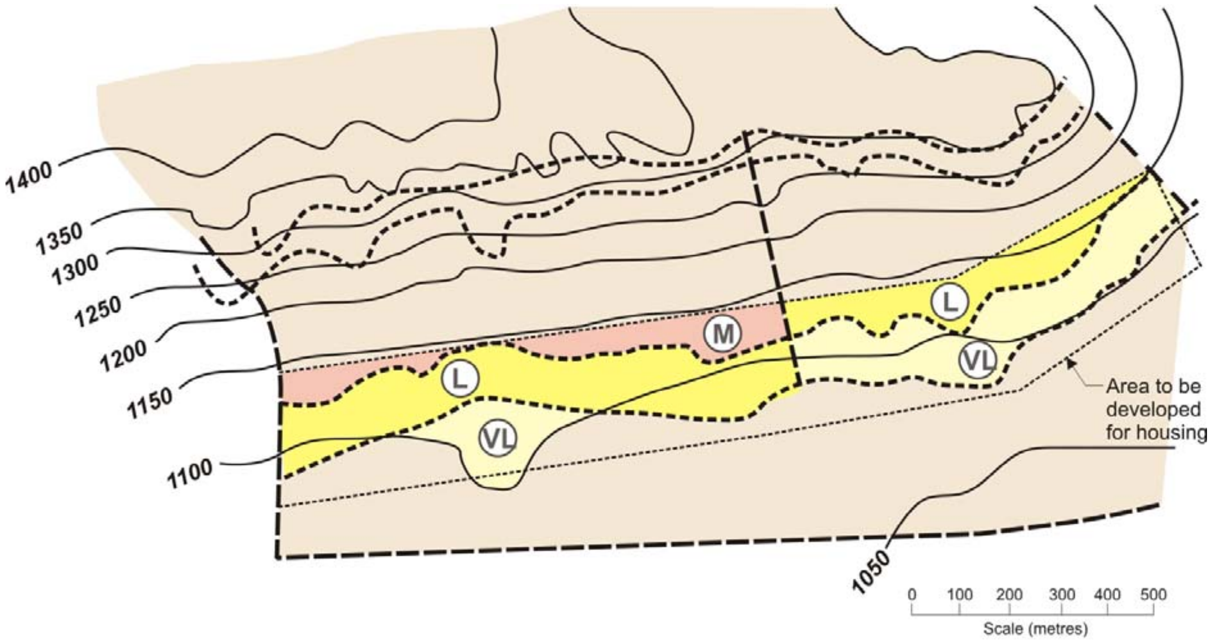

Figure 2C Rockfall Risk

LEGEND

Mapping Area	Landslide Classification	Landslide Susceptibility (1)	Landslide Hazard (2)	Landslide Risk for Life Loss (3)
C1	Rock falls from cliff	High	High	Negligible (4)
C2	Rock falls from cliff	High	Moderate	Negligible (4)
S1	Rock fall travel path	Moderate	Moderate	Moderate (5)
S2	Rock fall travel path	Moderate	Low	Low (5)
M1	Rock fall deposition zone	Low	Low	Low (5)
M2	Rock fall deposition area	Low	Very Low	Very low (5)
F1	Area above cliff	Not susceptible	No hazard	No risk
F2	Area beyond rock fall deposition zone	Negligible	Negligible	Negligible

Notes

(1) Likelihood that rock falls will reach the area if they occur.

(2) The number of rock falls per annum/ km of cliff which will reach this area. The frequency of rock falls is an order of magnitude lower for areas, C2, S2 and M2 than for C1, S1 and M1.

(3) Accounting for the landslide hazard and the persons within the area.

(4) Because there are no elements at risk.

(5) Within the area to be developed for housing, otherwise negligible.

(6) H=high; M=moderate; L=low; VL=very low; N=negligible.

Figure CA1 Example of landslide zoning for rock fall

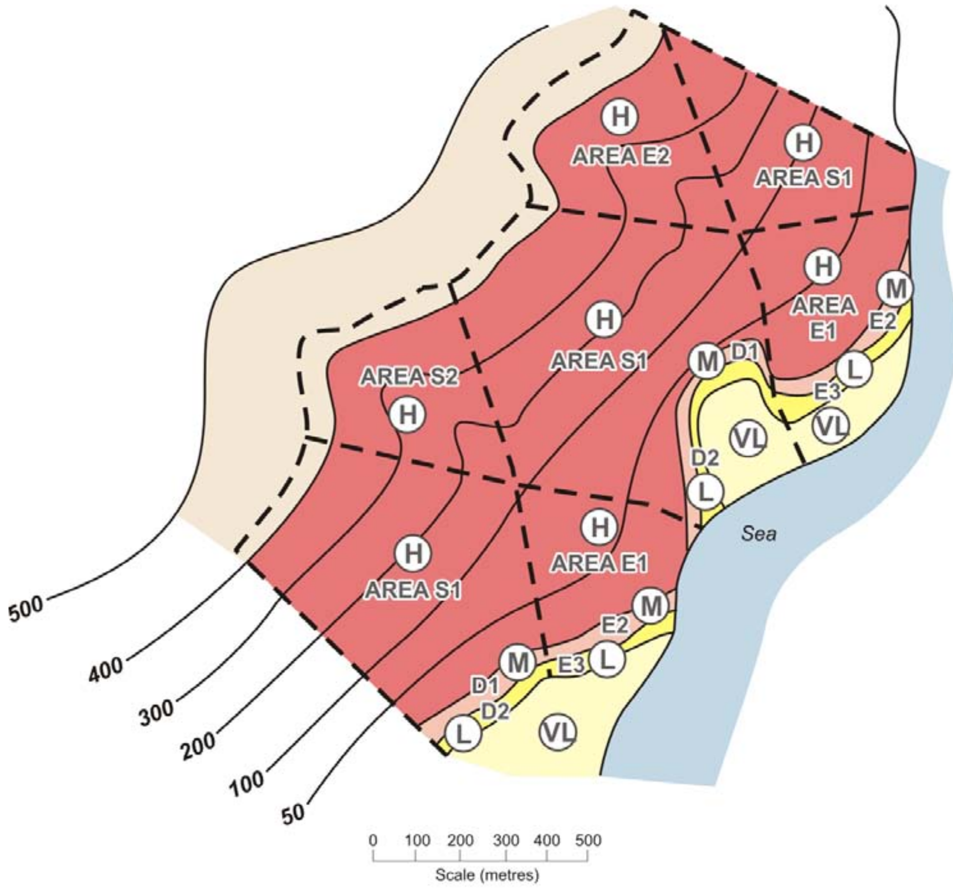

Figure 3A Small Slide Susceptibility

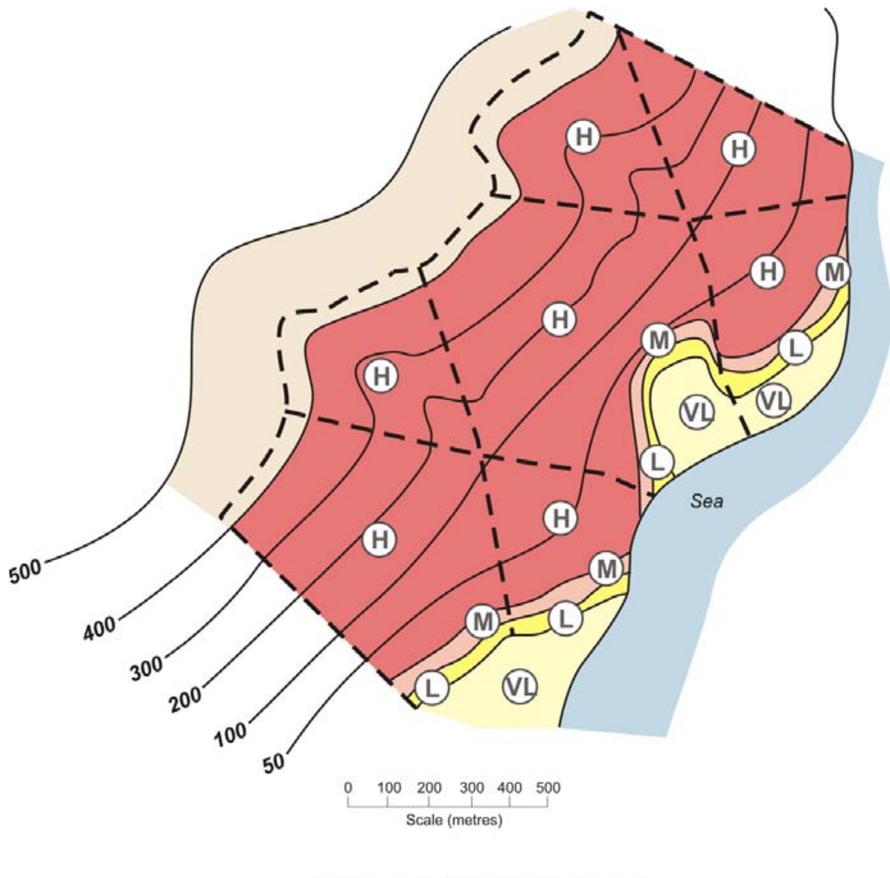

Figure 3B Small Slide Hazard

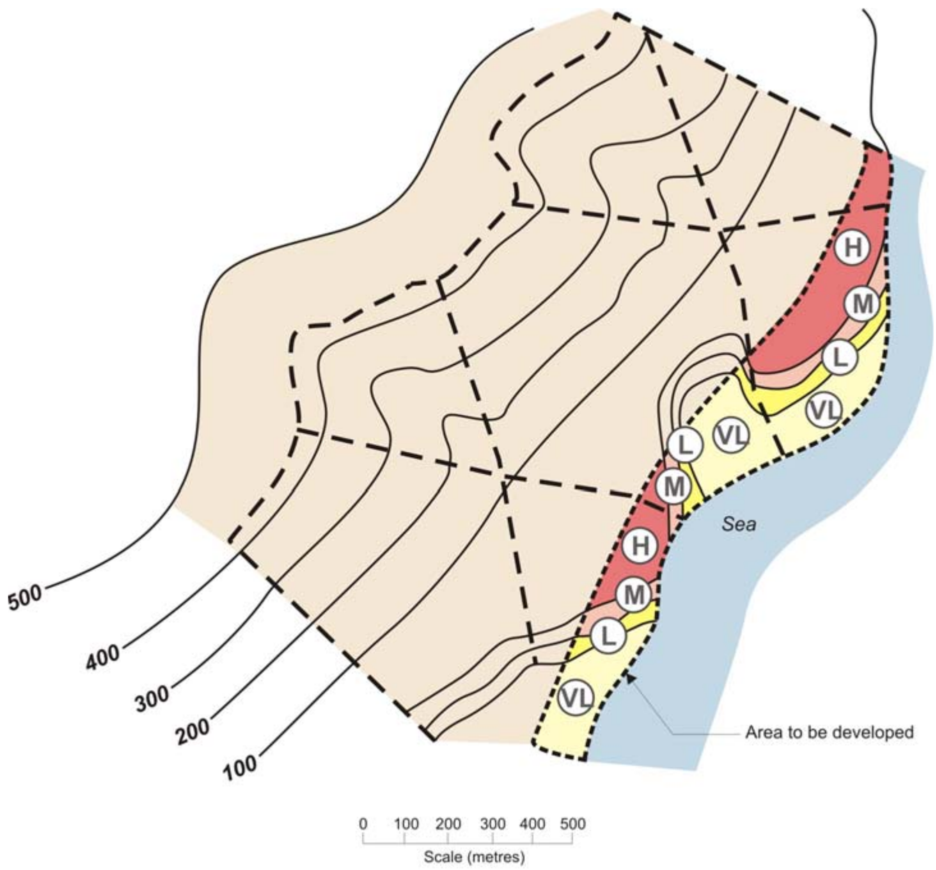

Figure 3C Small Slide Risk

LEGEND

Mapping Area	Landslide Classification	Landslide Susceptibility (1)	Landslide Hazard (2)	Landslide Risk for Life Loss (3)
S1	Rapid earth slides and debris flows up to 200m ^{3}	High	High	Negligible (4)
S2	Rapid earth slides and debris flows up to 2000m ^{3}	Moderate	Moderate	Negligible (4)
D1	Debris flow deposition areas	Moderate	Moderate	Moderate (5)
D2	Debris flow deposition areas	Low	Low	Low (5)
E1	Debris flow deposition areas-fan deposits	Moderate	Moderate	High (5)
E2	Debris flow deposition areas-fan deposits	Low	Low	Moderate (5)
E3	Debris flow deposition areas-fan deposits	Very low	Very low	Low (5)
F	Outside area affected by landsliding	Very low	Very low to negligible	Low to Very low (5)

Notes
(1) Number of small slides per square km
(2) Number of small slides per square km/annum
(3) Accounting for the landslide hazard and the persons within the area.
(4) Because there are no elements at risk.
(5) Within the area to be developed for housing, otherwise negligible
(6) H=high; M=moderate; L=low; VL=very low; N=negligible.

Figure CA2: Example of landslide mapping for small landslides.

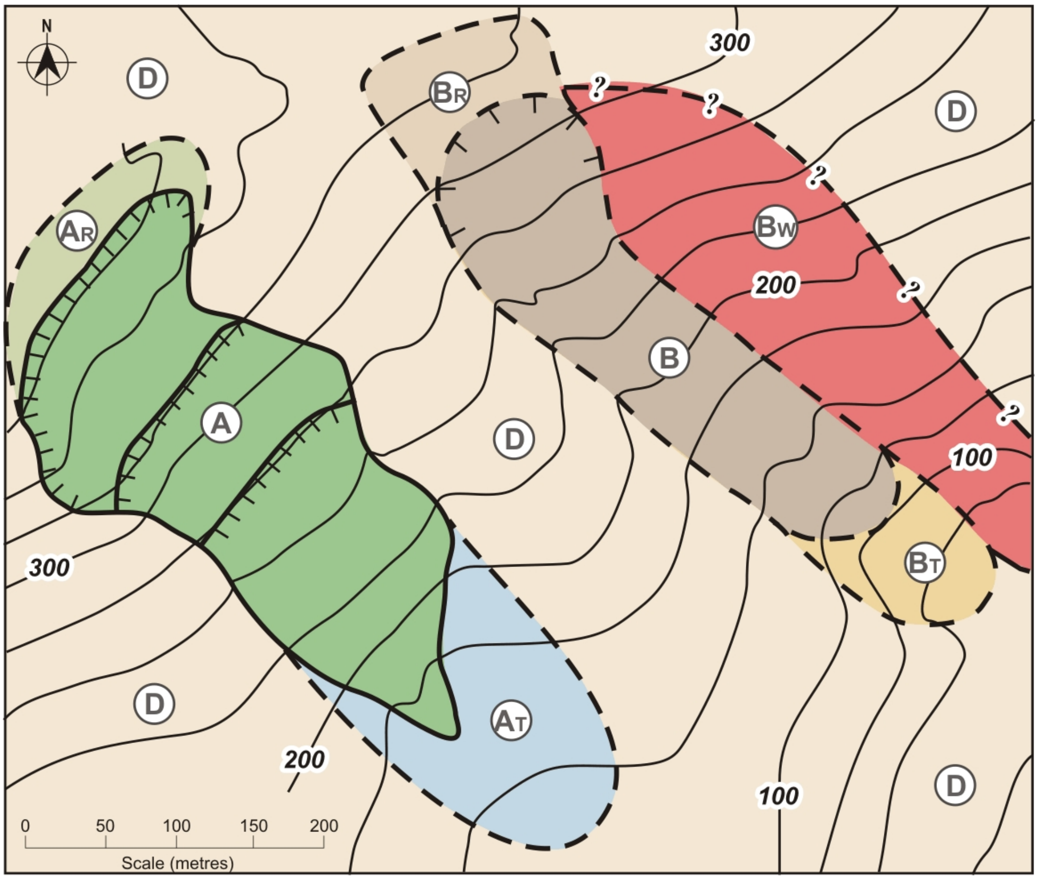

Figure 4 Large Slide

LEGEND

Mapping Area	Landslide Classification	Landslide Susceptibility (1)	Landslide Hazard (2)	Landslide Risk for Property Loss (3),(4)
A	Active very slow earth slide	High	Very high	Very high
A_T	Slope onto which 'A' may travel	Moderate	High	High
A_R	Slope into which 'A' may retrogress	Moderate	Moderate	Moderate
B	Inactive earth slide	Moderate	High	High
B_T	Slope onto which 'B' may travel	Low	Moderate	Moderate
B_R	Slope into which 'B' may retrogress	Low	Low	Low
B_W	Slope into which 'B' may widen	Low	Low	Low
D	Slopes with no geomorphologic characteristics of landsliding	Not susceptible	Very low	Very low

Notes (1) Likelihood large landsides may occur in this area given the topography, geology and geomorphology
(2) Annual probability of active sliding
(3) Accounting for the landslide hazard and the persons within the area. It is assumed that the whole area is available for development
(4) Life loss risk is very low for all areas because of the very low slide velocity

Figure CA3: Example of landslide mapping for large landsliding.