2. REVIEW OF LANDSLIDE HAZARD AND RISK ASSESSMENT: INTERNATIONAL DEVELOPMENTS

2.1 INTRODUCTION

Landslides within Australia cause significant economic loss and there are also many instances of injury and loss of life. Across Australia, at least 75 people have been killed and 38 injured by landsliding (Lieba 1996). Recently, on 30th July 1997, at approximately 11.30pm, the Thredbo Landslide occurred, as shown in Plate 2.1, during which 18 lives were lost. In addition to this human tragedy, which is almost unrivalled in the history of Australian natural disasters, this landslide also destroyed two tourist Lodges, a section of a local lane, and the roadside verge of a main regional roadway. Furthermore, this landslide has resulted in considerable economic losses to the local community and associated businesses. In late September 1996, the collapse of a section of an overhanging coastal cliff line at South Point in Cowaramup Bay, south western Western Australia, killed 9 people. On the 30th April 1988, at Coledale (within the study area of this research project) in New South Wales, a section of an embankment on the South Coast Railway slumped and a mud flow developed which inundated a nearby house, killing two residents. A vertical aerial photograph of the Coledale site, immediately following the debris slump-mud flow is shown in Plate 2.2. These and other natural and man-made catastrophes have enhanced the perception of the risk of slope instability and landsliding.

Geotechnical engineers have been drawn only slowly to the modern concepts of risk and hazard assessment. Yet the use of the term ‘risk’ is not new. Recognising the importance of risk in the geotechnical engineering literature, Casagrande wrote about the role of “calculated risk” in his Terzaghi Lecture (Casagrande, 1964). However, major uncertainties and complexities associated with slope instability and landsliding were not fully understood at that time. More than thirty years have passed since that lecture and uncertainties related to landsliding are now recognised to be significant.

Whilst not always as spectacular as earthquakes, floods, hurricanes, or other natural disasters, landslides occur frequently and may cause more property loss than any other geological hazard (Varnes, 1984). Yet it is feasible to map major areas of slope instability and to take measures for avoidance, prevention or remediation of landsliding based on observation, analysis and research. As many of the basic causes of land

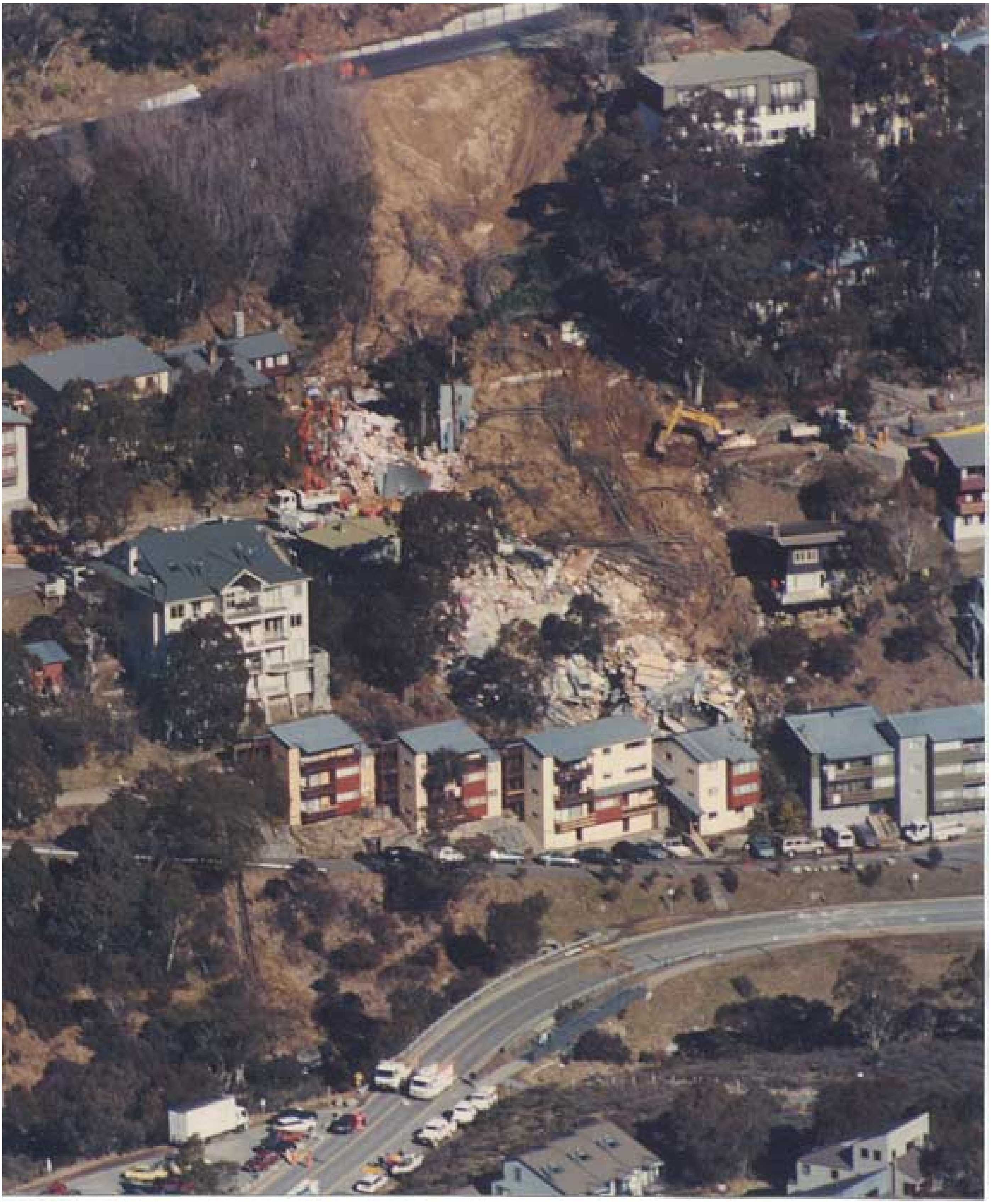


Plate 2.1. Oblique aerial photograph of the Thredbo Landslide, which occurred at approximately 11.30pm on the 30th July 1997. Photograph courtesy of the Canberra Times, picture by Gary Schafer.

Plate 2.2. Vertical aerial photograph of the Coledale Landslide which occurred on the 30th April 1988. Photograph courtesy of the New South Wales Railway Services Authority.

instability are reasonably well understood, it is feasible to approach landslide hazard mitigation from a spatial zonation point of view (Varnes, 1984) as part of an integrated strategy for observation, research, assessment and management.

Avoidance is not always possible, especially in urban areas. For example in Ventnor on the Isle of Wight (Great Britain), and in Wollongong on the south coast of New South Wales (Australia), residential and associated infrastructure development exists on active landslide terrains. Hence, methods of quantifying hazard, both existing and potential, and the attendant risk associated with land instability require investigation and research.

Recent national and international works in the fields of landslide hazard and risk assessment are briefly reviewed in this chapter. Much has been written on these topics over the last 30 years. It is not possible to provide a comprehensive review within the scope of this thesis. It is intended to indicate the directions of current international research and some of the more pertinent theories, and to highlight good examples of hazard and risk assessment. Among the many references in the literature are the proceedings of the International Symposia on Landslides, held every four years, the biannual Bulletins of the International Association of Engineering Geologists, Special Reports 58, 176 and 247 of the United States Transportation Research Board.

There is widespread use of terms such as ‘landslide’, ‘classification’, ‘magnitude’, ‘probability’, ‘hazard’, ‘vulnerability’, ‘damage’, ‘element’, ‘specific risk’ and ‘total risk’. However, their is considerable variation between several disciplines and different authors as to the meanings of these terms. Hence, for clarity and consistency, definition of these terms as preferred by the writer and used in this research project is necessary. In the following sections, reference is made to these key definitions.

2.2 DEFINITION OF TERMS

2.2.1 Landslide

Terzaghi (1950) defined ‘landslide’ and ‘creep’ as follows:

“a landslide is a rapid displacement of a mass of rock, residual soil, or sediments adjoining a slope, in which the centre of gravity of the moving mass advances in a downward and outward direction. A similar movement proceeding at an imperceptible rate is called creep”.

In 1958, the United States Highway Research Board in Special Report 29 adopted a similar definition. This definition was later revised as follows;

"a landslide constitutes the group of slope movements wherein shear failure occurs along a specific surface or combination of surfaces" (Varnes, 1978).

The definition of the term 'landslide' was again revised, by Varnes (1984), as follows;

"the term landslide comprises almost all varieties of mass movements on slopes, including some, such as rockfalls, topples, and debris flows, that involve little or no sliding".

The International Geotechnical Societies UNESCO Working Party on the World Landslide Inventory (WP/WLI) provided a working definition of a landslide as;

"The movement of a mass of rock, earth or debris down a slope" (Cruden, 1991). As an all-encompassing definition and for simplicity and ease of use, this most recent definition is used herein. This definition has also been adopted by Cruden and Varnes (1996).

2.2.2 Landslide morphology and classification

In 1958, the United States Highway Research Board published its Special Report 29, 'Landslides and Engineering Practice'. This report included a classification of landslides that was well received by the profession. Varnes (1978) extended the 1958 Special Report 29 landslide classification to include both extremely slow distributed movements of both rock and soil, termed creep, and also toppling failures and spreading movements. In recognition of the fact that some landslides involve no direct shear surfaces, Varnes titled his 1978 work as: 'Slope Movement, Types and Processes', in preference to the 1958 title: 'Landslide Classification'. Varnes' 1978 classification system has become one of the most widely used systems (WP/WLI 1990). Other classification systems do exist. For example, a different classification system was proposed by Hunt (1984), although he adopted Varnes' 1958 velocity scale (Hutchinson, 1988).

Varnes 1978 system has been revised further (Cruden and Varnes, 1996). This most recent revision streamlines the 1978 system, and incorporates advances in the field of landslide research since 1978. Departures from the previous 1978 system have been minimised. The revised system is consistent with the suggested terminology and methods of the WP/WLI (1990, 1991, 1993, 1994 and 1995).

While a detailed description of Cruden and Varnes 1996 classification is beyond the scope of this thesis, a very brief introduction to it is considered appropriate. The main thrust of the system is still based on the use of two nouns to describe a landslide, eg a rock fall or a debris flow, one for the material involved and the other for the style of movement. In addition to this, the system directs the user to build a descriptive name for the landslide as more information becomes available, based on an ordered nomenclature using a standard glossary of terms. A summary of the classification system by Cruden and Varnes (1996) is presented in Table 2.1. The glossary of terms provided by Cruden and Varnes for forming the names of landslides is given in Table 2.2.

The landsliding material is classified as either 'bedrock' or 'engineering soil'. Engineering soils are subdivided into either debris or earth, the latter being fine grained material in which at least 80% of the particles are smaller than 2mm (Bates and Jackson 1987, in Cruden and Varnes 1996). Debris contains a significant proportion of coarse material; 20 to 80% of the particles are larger than 2mm, and the remainder are less than 2mm. Varnes identified five main types of movement; falls, topples, slides, spreads and flows. He concluded that, more often than not, slope movements involve a combination of one or more of the principal types of movement, either within the various moving parts, or at some stage during the movement of the failed mass.

TYPE OF MOVEMENT	**TYPE OF MATERIAL**		
	BEDROCK	**ENGINEERING SOILS**	
		Predominantly coarse	**Predominantly fine**
FALL	Rock fall	Debris fall	Earth fall
TOPPLE	Rock Topple	Debris topple	Earth topple
SLIDE	Rock slide	Debris slide	Earth slide
SPREAD	Rock spread	Debris spread	Earth spread
FLOW	Rock flow	Debris flow	Earth flow

Table 2.1 Classification of slope movements (Varnes and Cruden 1996).

The name of a landslide can become more elaborate as more information about the movement becomes available. To build up a complete identification of the movement, descriptions are added in front of the two noun classification using a preferred sequence of terms. The sequence suggested by Varnes and Cruden provides a progressive narrowing of the focus of the descriptions, first by time, and then by spatial location, beginning with a view of the whole landslide, continuing with parts of the movement, and finally defining the materials involved. The recommended sequence as shown in Table 2.2 describes activity (state, distribution, and style) followed by descriptions of all movements (first, second, etc, in terms of rate, water content, material and type).

ACTIVITY		
STATE	**DISTRIBUTION**	**STYLE**
Active	Advancing	Complex
Reactivated	Retrogressive	Composite
Suspended	Widening	Multiple
Inactive	Enlarging	Successive
Dormant	Confined	Single
Abandoned	Diminishing	
Stabilised	Moving	
Relict		

DESCRIPTION OF FIRST MOVEMENT			
RATE	**WATER CONTENT**	**MATERIAL**	**TYPE**
Extremely rapid	Dry	Rock	Fall
Very rapid	Moist	Soil	Topple
Rapid	Wet	Earth	Slide
Moderate	Very wet	Debris	Spread
Slow			Flow
Very slow			
Extremely slow			

DESCRIPTION OF SECOND MOVEMENT			
RATE	**WATER CONTENT**	**MATERIAL**	**TYPE**
Extremely rapid	Dry	Rock	Fall
Very rapid	Moist	Soil	Topple
Rapid	Wet	Earth	Slide
Moderate	Very wet	Debris	Spread
Slow			Flow
Very slow			
Extremely slow			

Table 2.2 Glossary for forming names of landslides (Varnes and Cruden 1996).

For example, the Morrison Avenue Landslide, Site 77, discussed in Chapter 9 could be described, using the Varnes and Cruden (1996) classification system as a Reactivated enlarging composite very slow wet debris slump-very slow wet debris block slide-very slow wet debris flow.

Differences between definitions in Varnes (1978) and Varnes and Cruden (1996) relate to description of the style of activity of a landslide. For example, in 1978, the term 'complex' was used to describe landslides with at least two types of movement in different parts of the mass. On the other hand, in the 1996 proposed definition, it refers to a landslide in which various movements occur in sequence. In 1996, the term 'composite' is used to describe landslides in which different types of movement may occur in different areas of the displaced mass, possibly simultaneously. In 1978, ‘composite’ was a synonym for ‘complex’.

Varnes’ 1978 classification system has been used by the writer while compiling the land instability database for this research project, as discussed in Chapter 5. The 1978 system has been used as it is widely accepted, and, in any case, the 1996 system only became available after preparation of the database was well advanced.

The classification system of Varnes (1978) includes a scale for rate of movement (Table 2.3, columns one and two). According to Cruden and Varnes (1996) this scale represented informal practice in the US at that time. Subsequently, this scale has received wide acceptance. In particular, it has also been adopted with some changes by the WP/WLI (1995). This modified form allowed the scale to span ten orders of magnitude (column 3 of Table 2.3). The fourth column of this table shows the same rate of movement as column 3, at different scales which allow a direct comparison with Varnes’ original 1978 scale. The WP/WLI (1995) rates of movement scale has been included in Cruden and Varnes (1996).

RATE description	**VARNES (1978) rate/period**	**WP/WLI (1995) millimetre/second**	**WP/WLI (1995) rate/period-local**
extremely rapid	> 3 metres/second	> 5 by 10^{3}	> 5 metres/second
very rapid	> 0.3 metres/minute	> 50	> 3 metres/minute
rapid	> 62.5 millimetres/hour	> 0.5	> 1.8 metres/hour
moderate	> 50 millimetres/day	> 5 by 10^{-3}	> 430 millimetres/day
slow	> 4.1 millimetres/day	> 50 by 10^{-6}	> 4.3 millimetres/day
very slow	> 0.164 millimetres/day	> 0.5 by 10^{-6}	> 0.043 millimetres/day
extremely slow	< 0.164 millimetres/day	< 0.5 by 10^{-6}	< 0.043 millimetres/day

Table 2.3 Rate of movement scale, Varnes (1978) versus WP/WLI (1995).

During this research project the scale of movement shown in column 4 has proved to be most convenient when discussing monitored rates of landslide movement at nineteen case study sites. Application of this landslide movement or velocity scale to sites included within the land instability database compiled during this research project is discussed in Chapter 5 and 7. The case study landslide sites are discussed in Chapters 8 and 9.

Landslide velocities within the local experience a range of velocities from extremely slow to extremely rapid. For example, early on Sunday the 29th June 1997, a composite, extremely rapid, wet, rock fall-debris flow occurred during heavy rainfall from the east facing sandstone cliff lines due east of Mount Barrengarry, immediately upslope of the Fitzroy Falls to Kangaroo Valley Road, approximately 40km south west of the study area, as shown in Plate 2.3. Approximately 21,000m³ of rock and debris was involved in the landslide, the toe of which extended to within a few metres upslope of the road.

Plate 2.3. The Mount Barrengarry Landslide occurred in the early morning of the 29th June 1997, during heavy rainfall. The rock fall involved approximately 6000m^3 of Hawkesbury Sandstone bedrock. The ensuing debris flow also involved approximately 15000m^3 of additional colluvium on the slopes below (underlain by Kangaloon Sandstone). The debris flow completely destroyed up to 2Ha of dense forest. The toe of the flow stopped several metres upslope of the Fitzroy Falls to Kangaroo Valley Road.

The terms described below follow mainly the descriptions given in a United Nations Educational, Scientific and Cultural Organisation (UNESCO) review paper, authored by Varnes (1984). Some additional terms have been proposed, more recently, by other workers. Varnes' review was of work undertaken by the International Association of Engineering Geology's Commission on Landslides and other Mass Movements on Slopes (Varnes, 1984). For some terms, such as 'Specific Risk', 'Hazard' and 'Vulnerability', he drew attention to the terminology used by the United Nations Disaster Relief Organisation. Varnes' review was supported in the same year by the United States Geological Survey (Brabb, 1984). Subsequently, Varnes' descriptions have been widely supported (with some variations, discussed here as appropriate) in papers by Einstein (1988), Fell (1994), Hutchinson (1995), Fell et al (1996), Leone et al

(1996) and Turner and Schuster (1996), to name but a few.

Most recently the International Union of Geological Sciences (IUGS) Working Group on Landslides, through its committee on Risk Assessment has proposed some further definitions for terms associated with Quantitative Risk Assessment, or QRA (IUGS, 1997).

2.2.3 Magnitude (M)

The term 'Magnitude', whilst not mentioned by Varnes, is used by Hunt (1984), Fell (1994), Crozier (1995) and Hutchinson (1995). Magnitude as used by Hunt and Crozier refers to the volume of material which may fail, the velocity of movement during failure, and the land area which may be affected. Crozier includes the duration of landsliding. A simple definition of Magnitude as 'the volume in cubic metres of the source landslide' has been adopted for use during this research project, as discussed in Chapter 5. It is also considered appropriate for the local area because landslide velocities are generally slow to extremely slow, even though there is a variety of types of movement. (see Table 2.4 for descriptions of Magnitude ranges)

A simple approximate formula to calculate the volume of displaced material of a landslide has been proposed by the WP/WLI (1990) as:

$$^{1}/_{6}\,\pi \times D_r \times W_r \times L_r, \text{ where;}$$

- D_r = Maximum depth of rupture below original ground surface,
- W_r = Maximum width between flanks of landslide perpendicular to length L_r,
- L_r = Minimum distance from toe of surface of rupture to crown.

In this project, the plan area of each landslide has been determined by computer. For the sake of simplicity, the volume of each landslide has been determined on the basis of the product of this plan area multiplied by an average of the known or estimated depth to the actual or potential slip surface. A description of volume ranges adopted for use in this research project is shown in Table 2.4.

2.2.4 Probability (P)

Estimating the probability of landslide movement is one of the essential factors in assessing landslide hazard, and hence assessing landslide risk. Crozier (1996), suggested that the ultimate goal of comprehensive landslide hazard research should include determining the probability of landslide occurrence as a function of time for any given site. Probability of landslide movement is generally taken as the probability that a particular landslide occurs within a given (stated) period of time and often reference is made to annual probability, implying the likelihood of occurrence within a period of one year. However, failure probabilities may also be calculated without reference to time. It is, therefore essential to, a) distinguish between temporal and spatial probabilities of failure and, b) state the type of probability being reported, ie, the definition adopted in any given instance.

The literature abounds with different methods of assessing the probability of failure or of landsliding. The focus of the probabilities assigned to land instability depends on the scale of the investigation being undertaken. In a regional study, one may not attempt to assess the probability of one particular debris flow impacting a particular structure. Such studies must be concerned with more general probabilities of occurrence, and the probabilities of such occurrences impacting on, say, residential areas.

Recognised methods of assessing the probability of landsliding are discussed in section 2.6. Probability is generally expressed as a number between 0 and 1, with 0 indicating an impossible outcome, and 1 indicating an outcome is certain (AS/NZS 4360:1995). Probability may also be expressed as percentages ranging from 0 to 100.

2.2.5 Hazard (H)

The Risk Management Standard (AS/NZS) 4360:1995 defines a hazard as a "source of potential harm or a situation with a potential to cause loss." In this thesis, hazard (H) is defined as a description of the magnitude (M) and probability (P) of occurrence within a specified period of time and within a given area of a potentially damaging phenomenon (Fell, 1994). Hence, $H = M \times P$. This simple definition has been adopted for its simplicity. The velocity and potential maximum velocity of a landslide is important and should be reported separately from the hazard. The definition of Hazard preferred by the writer is in accordance with the definition of Hazard as proposed by the IUGS (1997). The IUGS does suggest that there may be some value in describing the velocity and differential velocities of the landslide.

This definition is at variance with that of Varnes (1984) and Einstein (1988) as it includes a measure of the volume of the material involved, as opposed to Varnes description that only includes the probability of occurrence. Einstein (1988) suggested a description of hazard to include the term danger, a measure of the geometrical and mechanical character of a landslide. In a report on ground movement in Ventnor (South Wight Borough Council 1995) hazard is described, along the lines of Varnes (1984), as the chance of a potentially damaging ground movement event occurring within the area.

Varnes (1984) and Fell (1995) both referred to natural hazard in the above description. The writer considers that the term ‘hazard’ should not be restricted to natural phenomena. Within the study area of this research project, many landslides have developed in association with man-made fill deposits and cuttings. It is necessary, however, at the time of description of each individual landslide, to differentiate between man-made and natural hazards.

2.2.6 Element (E)

The elements at risk in a given area includes, the population, properties, economic activities, including public services etc. Such that $E_t = \Sigma\ (E_p + E_e +,..., + E_a)$ where E_t is the total combination of elements being considered, and E_p E_e and E_a etc, are the individual elements (Fell, 1995). The level of detail at which various elements are considered depends on the scale of the investigation. For example, one element could be all the houses or the population in a city for a regional assessment, one particular house or family for a local assessment, or even individual rooms, walls or individual people within a house for a site specific investigation.

The writer considers that four elements are appropriate for the scale and purpose of this research. The elements considered appropriate are; land, structures and services, economic activity and human life.

2.2.7 Damage (D)

Damage caused to an element by land instability, or the degree of loss to a given element is reportable, ie, it has happened or is happening, in contrast to damage which may occur in the future, which is discussed below, as vulnerability. Damage is understood during this research project to refer to past and present damage resulting from landslide movement. Hence, there needs to be some measure of damage, subjective or quantitative, from the outset of any risk assessment procedure. Damage can, of course be to human or animal life (injury or death), assets (land, structures and services), and economic activity. The level of element detail required by a particular investigation, will determine the appropriate level of damage detail required.

The AS/NZS 4360 defines the terms consequence, loss and cost which together could be equated to the terms damage and vulnerability. Consequence is defined in the AS/NZS 4360 as the outcome of an event or situation expressed qualitatively or quantitatively, being a loss, injury, disadvantage or gain.

It is not feasible to report all landslides to the international level. The WP/WLI (1990) defined a reportable landslide as one which satisfies at least one of the following:

- is over 1 million cubic metres in volume
- causes casualties
- causes considerable direct or indirect damage.

The last two of these criteria fall into the damage field. Direct effects take place at or near the landslide site, and indirect effects include those which may occur away from or after the event. Indirect effects include, for example, soil erosion, pollution of streams, formation of landslide dams and failure of utilities. The monetary value of damage estimate to be included in the WP/WLI Landslide Report should be in the local currency. The number of deaths and substantial injuries by the direct or indirect effects of the landslide should also be recorded. A substantial injury is defined as that resulting in complete loss of earning capacity of the injured person for over one year.

For reporting damage to a national and international level the WP/WLI proposed a per capita annual Gross Domestic Product, (or person-product) as a currency and culture independent damage measure. To determine this value, the annual GDP of the country is divided by its population. This yields a value, the person product, that represents the average contribution to the GDP per person, per year, for that country. The landslide damage estimate should then be divided by the person product. The result, the number of person years, is an estimate of damage in terms of the effort it will take inhabitants of the country to repair the damage. This type of work is outside the scope of the present research project.

In order to assist in the quantification of hazard and ultimately risk, it is necessary to quantify the damage to individual elements. To achieve this, classification systems are required to systematically and quantitatively record the damage for the individual elements. Such quantification has received very little attention in the literature and is discussed further in chapter 5.

It is worth noting that insurance for damage caused by land instability is not readily available in most countries including Australia.

2.2.8 Vulnerability (V)

Vulnerability is defined (Varnes, 1984) as the potential degree of loss (damage) to a given element or set of elements at risk resulting from the occurrence of a natural phenomenon of a given magnitude. It is expressed on a scale from 0 (no damage) to 1 (total loss). Vulnerability is understood for this research project to refer to potential damage in the future resulting from landslide movement, in contrast to past or present damage.

Fell(1994) suggests the total vulnerability may be determined as a product of several components in the form $V = V_S \times V_T \times V_L$, where V_S is the likelihood of spatial impact, V_T is the likelihood of temporal impact, and V_L is the likelihood of loss of life of an individual occupant in the impacted element.

Leone et al (1996), proposed a framework for structuring the concept of vulnerability. Damage matrices were used to record and classify damage, due to land instability, that occurred to specific elements. Analysis of records allowed classification of the types and magnitudes of damage experienced by the various elements. This data was used in combination with return periods of the landslide events to quantify the vulnerability of elements exposed in potential landslide areas.

2.2.9 Risk (R)

Risk is a concept that requires more than a simple definition, hence the matter is discussed in more detail in section 2.3.2. Lists of definitions of terms associated with risk are growing increasingly longer in the literature. However, several of the most commonly used terms are defined below. These definitions are preferred by the writer.

Risk is defined in the AS/NZS 4360:1995 as “the chance of something happening that will have an impact upon objectives. It is measured in terms of consequences and likelihood.” IUGS (1997) defined risk as “a measure of the probability and severity of an adverse effect to health, property or the environment. Furthermore, IUGS notes as follows;

“risk is often estimated by the product of probability × consequences. However, a more general interpretation of risk involves a comparison of the probability and consequences in a non product form.”

The term ‘risque’, as used by the French in the comprehensive ZERMOS/POS/PER (Porcher and Guillope-1979, in Varnes, 1984) project of landslide hazard zonation and attendant government regulation, is equivalent to the English word ‘hazard’ (Varnes, 1984).

2.2.10 Specific Risk, (R_S)

Specific Risk is the expected degree of loss (experienced by a given element) due to a particular natural phenomenon (Varnes, 1984). It is considered as the product of hazard and vulnerability, eg, $R_S = H \times V$.

Proposed descriptions and ranges of values for magnitude, probability, hazard, vulnerability and specific risk are shown in Table 2.4 (Fell, 1994). These value ranges have been proposed in the context of ‘small urban residential subdivisions’. The ranges proposed represent a compilation of data from many sources and may help to encourage consistency amongst potential users. However, no explanation was provided for the numerical scaling.

2.2.11 Total Risk (R_t)

Total Risk is the expected number of lives lost, persons injured, damage to property, or disruption to economic activity due to a particular natural phenomenon. It is therefore the product of specific risk (R_s), and elements at risk (E), Varnes (1984). Thus:

$$(R_t) = \Sigma\,(E \times R_s) = \Sigma\,(E \times H \times V)$$

When discussing risk, one must be specific whether reference is to lives lost, or to the monetary cost of damage or to both, eg, monetary value may be assigned to the loss of each life.

2.2.12 Risk Analysis

Risk Analysis is defined in AS/NZS 4360 as “a systematic use of available information to determine how often specified events may occur and the magnitude of their likely consequences.”

2.2.13 Risk Assessment

Risk Assessment is defined in the AS/NZS 4360 as “the process used to determine risk management priorities by evaluating and comparing the level of risk against predetermined standards, target risk levels or other criteria.”

2.2.14 Risk Management

Risk Management is defined in the AS/NZS 4360 as “the systematic application of management policies, procedures and practices to the tasks of identifying, analysing, assessing, treating and monitoring risk.”

Magnitude *M*		
M	Description	Volume (m^3)
7	Extremely large	> 5000000
6	Very large	1000000 - 5000000
5	Large	250000 - 1000000
4	Medium - large	50000 - 250000
3	Medium	5000 - 50000
2.5	Small	500 - 5000
2	Very small	50 - 500
1	Extremely small	< 50

Probability *P*		
P	Description	Annual *P*
12	Extremely high	~ 1
8	Very high	~ 0.2
5	High	~ 0.05
3	Medium	~ 0.01
2	Low	~ 0.001
1	Very low	~ 0.0001
0.5	Extremely low	~ 0.00001

Hazard *H* =*M* x *P*	
H	Description
≥ 30	Extremely high
≥ 20 H < 30	Very high
≥ 10 H < 20	High
≥ 7 H < 10	Medium
≥ 3 H < 7	Low
≥ 2	Very low

Vulnerability *V*	
V	Description
≥ 0.9	Very high
≥ 0.5 *V* < 0.9	High
≥ 0.1 *V* < 0.5	Medium
≥ 0.05 *V* < 0.1	Low
≥ 0.05	Very low

Specific Risk *Rs*	
Rs	Description
≥ 0.1	Very high
≥ 0.02 *Rs* < 0.1	High
≥ 0.005 *Rs* < 0.02	Medium
≥ 0.001 *Rs* < 0.005	Low
≥ 0.0001 *Rs* < 0.001	Very low
< 0.00001	Extremely low

Table 2.4. Qualitative risk assessment terminology for Magnitude, Probability, Hazard, Vulnerability and Specific Risk (Fell, 1994). [a] for property loss, not loss of life.

2.3 DEFINITION OF BASIC PRINCIPLES

2.3.1 Landslide Hazard Zonation and Hazard Assessment

Landslide Hazard Zonation applies generally to the division of the land surface into categories and the ranking of these categories according to the levels of actual or potential hazard from landslides. Varnes (1984) pointed out that at least three fundamental assumptions were common to zonation studies. Hutchinson (1995), revised Varnes' three assumptions and added a fourth. These four assumptions are summarised below.

1) The past and present is considered to provide a key to the future. In some ways this is a reversal of the 'Theory of the Earth' (Hutton, 1788), which suggests that understanding present geological environments provides the key to understanding past environments and their deposits. Varnes suggests that natural slope failures in the future are most likely to occur in geological, geomorphological and hydrological situations that have led to past and present failures. However, the absence of past and present landslides at a given location, can not be taken to mean that landslides will not occur at that location in the future.
2) The main conditions that cause landsliding are controlled by physical factors and are therefore, in principal, identifiable. With our present technology, and variable resources available for different projects, some of these conditions and factors can be recognised and evaluated.
3) Degrees of landslide hazard can be identified on the basis of identifying and evaluating the causes of, or factors contributing to landsliding.
4) Various types of landsliding can generally be recognised and classified, both morphologically, geologically and geotechnically.

2.3.2 Landslide Risk Analysis, Assessment, and Management

Workers in the field of geotechnical engineering and engineering geology have for a long time recognised the need to have a consistent strategy for evaluating risk (Whitman, 1984). This need for a consistent strategy has arisen due to the dialogue that occurs between the engineer and all the other bodies that may possibly become involved in any given engineering project. This has lead to the development of both probabilistic and quantitative risk assessment.

A total land instability risk management procedure must encompass; a) the entire development of a project from the initial identification of the scope, b) characterisation of the site, c) hazard identification and mapping, d) determining elements at risk and e) assessing damage and vulnerability, f) assessing the consequences of the various failures occurring, g) assessing risk, and h) finally making recommendations for management of that risk by a range of proposed actions or alternatives.

The Australian Standard/New Zealand Standard (AS/NZS) 4360:1995 presented a five level Risk Management Process. This process is quite general given the broad audience to which the standard has been targeted. A similar five level approach to risk assessment and management, employing maps, was discussed at length by Einstein (1988). A more recent revision of Einstein's 1988 procedure was summarised by Wu, Tang and Einstein (1996). This 1996 procedure is discussed under the banner of decision making under uncertainty. Yet another risk management process has recently been outlined by Fell and Hartford (1997) which subdivided the process into three phases, ie, risk analysis, risk assessment and risk management. Such approaches to risk management have considerable merit. A complex procedure can be undertaken in an ordered sequence and an open and iterative line of communication can be developed between all those involved in the process. A multi-layered approach to risk management is shown in Figure 2.1.

One way of dealing with landslide hazard and risk, is avoidance. For example, one may not use particular sites for development. However, this strategy is not always feasible, due to the presence of existing development. Often there are also economic, political and social pressures to develop sloping land of marginal stability. Hence, methods of quantifying hazard, both existing and potential, and of assessing the attendant risk associated with land instability are very useful tools for land management. This includes the selection and scale of remedial and preventative measures for different sites.

Given that risk assessment is a desirable tool for land management and decision making, one is faced with the vexing question:

"what are acceptable levels of hazard and risk ?"

While procedures for quantitative risk assessment have been developed during the last few decades, they have not been widely adopted for landslide work. A consensus on

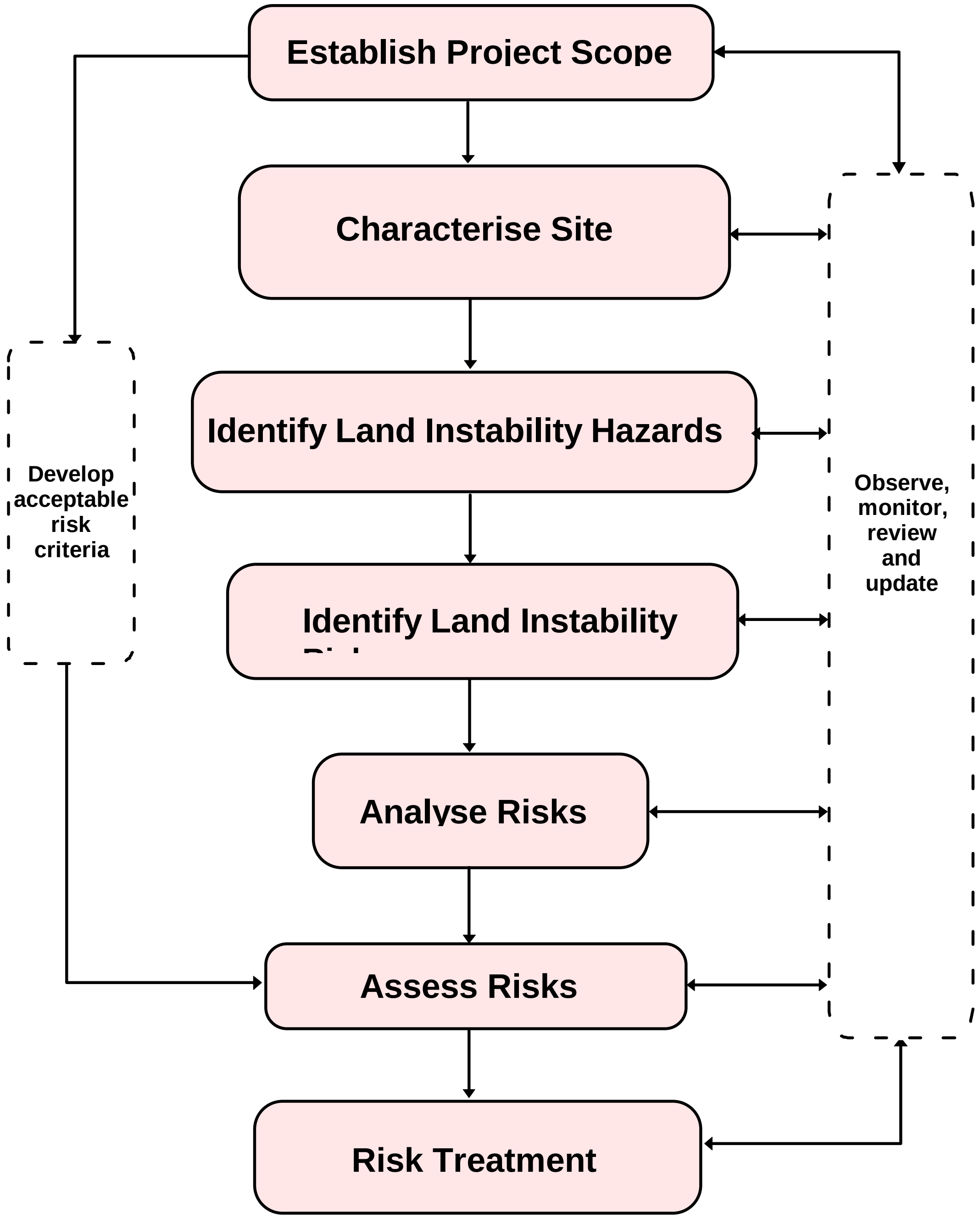


Figure 2.1. Proposed Risk Management Process, an overview.

acceptable hazard is difficult to achieve. In an effort to interpret engineering practice concerning acceptable geotechnical risk, Whitman (1984) presented a diagram which is now well known and is shown in Figure 2.2. This diagram considers the order of magnitude of risk for various engineering projects. For instance acceptable risk, expressed as a probability of occurrence, for slope stability is shown in this diagram as having an order of magnitude of 10^{-2} (a value the writer considers to be to high), for the loss of one life. In contrast, for dams the order of magnitude of risk expressed again as a failure probability is shown as 10^{-4} for the loss of 10 to 100 lives. There is some literature available concerning acceptable risk values for some different activities within our society as summarised in Table 2.5. However, there are no established criteria backed by a government or a national or international technical society (Fell and Hartford, 1997).

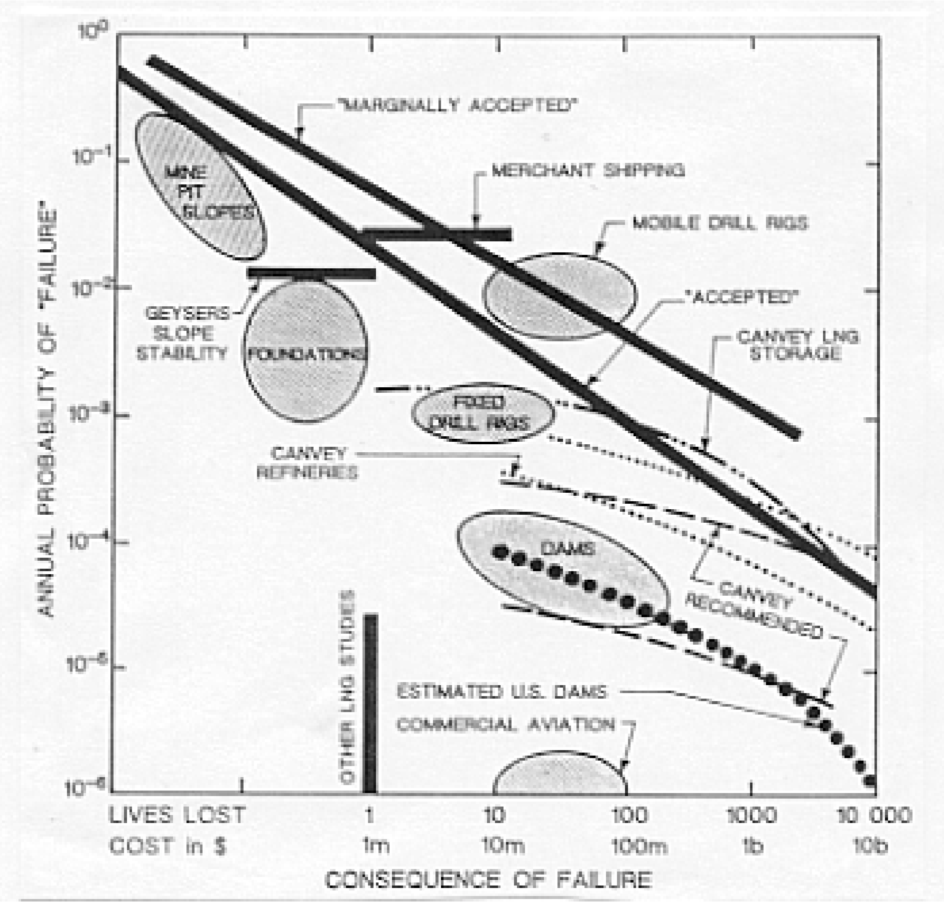


Figure 2.2. Risk for selected engineering projects, Whitman (1984). Note slope stability at 10^{-2}.

Some Australian local government councils accept development on Medium Risk or lower risk (AGS, 1985) sites, but will usually not accept development on High or Very High Risk sites. In comparison with Table 2.4, this suggests that these councils

Cause	Risk (× 10^{-6})
Building Hazards	
Structural failure, U.K. (Construction industry and Information Association	0.14
Building Fire (Australian Government statistics)	4
Natural Hazards (USA)	
Hurricane (1901-1972)	0.4
Tornado (1953-1971)	0.4
Lightning (1969)	0.5
Earthquake (California), Kletz 1976	2
General accidents (USA, 1979)	
Railway travel	4
Electrocution	6
Ait travel	9
Water transport	9
Poisoning	20
Drowning	30
Fires and burns	40
Falls	90
Road accidents	300
Occupations (UK) (Royal Society Study Group,	
Clothing manufacturing	5
Vehicle manufacturing	15
Chemical and allied industries	85
Shipbuilding and marine engineering	105
Agriculture	110
Construction industries	150
Railways	180
Coal mining	210
Quarying	295
Mining (non-coal)	750
Offshore oil and gas (1967-1976)	1650
Deep sea fishing (1959-1968)	2800
Sports (Royal Society Study Group 1983)	
Cave exploration (USA,1970-1978)	45
Gliding (USA, 1970-1978)	400
Scuba diving (USA, 1970-1978)	420
Power boat racing (USA, 1970-1978)	800
Hang gliding (USA, 1977-1979)	1500
Parachuting (USA, 1978)	1900
All causes UK, 1977 (Kletz 1982)	
Whole population	12000
Woman aged 30	600
Man aged 30	1000
Woman aged 60	10000
Man aged 60	20000

Table 2.5. Risk statistics, probability of early deaths per person per year for persons exposed voluntarily or involuntarily to various hazards (Read 1989).

will accept development on sites with a specific risk of property loss less than 0.02, but not on sites with a specific risk greater or equal to 0.02. These values do not consider the probability of loss of life.

Leighton (1976, in Brabb 1984) discusses the concept of landslide risk in the relative context of government action, where unacceptable risk is defined as the level above which specific action by the government is deemed necessary to protect life and property, whereas, acceptable risk is the level below which no specific action by the government is deemed necessary.

Starr (1969) suggests that societal activities fall into two categories, those in which the individual participates on a voluntary basis, and those in which the participation is involuntary. In the case of voluntary activities, the individual uses his or her own value systems to evaluate his or her own experiences. Involuntary activities differ in that the criteria and options are determined not by the individuals affected, but by a controlling body. Obviously, acceptable risks will be different for the two categories.

Evaluation of the acceptability of risk, must be based on social, financial and economic decisions. Risk assessment procedures form a basis for an informed and logical comparison of risk management procedures, including remedial, or corrective measures.

2.4 LAND INSTABILITY HAZARD AND RISK ASSESSMENT PROCEDURES INVOLVING MAPS

2.4.1 Introduction

Due to the complex requirements of risk management (which includes hazard assessment), the writer favours a staged approach to risk management for application to the study area of this research project. A staged approach, comprising 7 levels has been outlined previously in Figure 2.1. The writer proposes the use of computer based maps and databases to facilitate site characterisation and hazard identification, and spreadsheets and databases for risk identification, analysis and assessment, as summarised in Figure 2.3.

A multi-layered approach as is necessitated by the multi-disciplinary requirements of this work involving knowledge and application of geomorphology, engineering geology, geotechnical engineering, computing and management. This approach also serves as a framework for discussion of significant works that have been undertaken in landslide mitigation. The seven levels which comprise this procedure are described below.

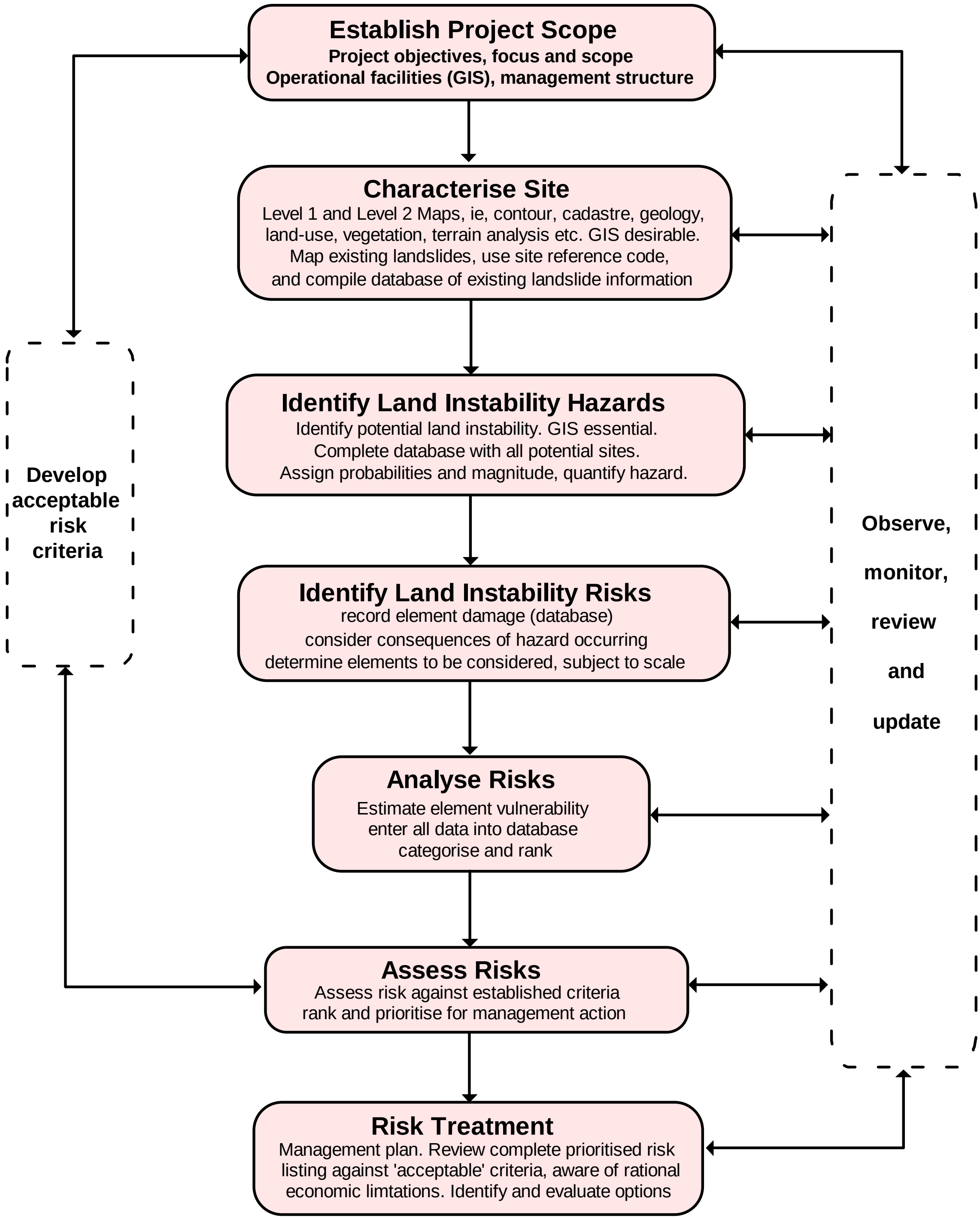


Figure 2.3. Detailed view of the proposed Risk Management Process showing use of maps, spreadsheets and databases.

2.4.2 Establish the Scope of the Project

The terms of reference for the project require clear definition at the outset. This should include the scope of work that is expected to be undertaken, the management structure under which the work is to operate, and the framework under which the risk management results will be required to operate.

Risk criteria must be determined first. Such risk criteria must be developed in agreement with management and the engineering judgement of the geotechnical professionals. It is acknowledged that such criteria will represent compromises based on social, economic and political forces. However, the criteria must follow acceptable, and legally defendable levels of risk. Expectations of those persons involved in the project or affected by it must be aired at this stage.

2.4.3 Observe, monitor, record, review and update

These components are essential features of the procedure which will develop effectively with ongoing communication between all the parties involved in the project. These features will promote a review of the risk management procedure at all stages of its development and all of the inputs which may affect its results.

2.4.4 Characterise the site

2.4.4.1 Level 1 maps

Basic site information may be available on 'State of Nature or Level 1 Maps' (Einstein, 1988) which comprise of basic information regarding the existing state of the study area, for example; topography (contour information), some geological maps (surface, bedrock, structural), cadastral and land use maps. This style of information is largely descriptive (Varnes, 1984) and does not include any synthesis or interpretation of the data presented on the maps beyond cartographic requirements. Geological maps may possibly include interpretive data between areas of known outcrop, borehole locations etc. If this is the case, it should be stated that the maps contain such interpretative data, and as such they would be regarded as Level 2 maps.

2.4.4.2 Level 2 - Factor Maps and Landslide Databases

Local area judgement regarding those factors that contribute to land instability represents quite a challenge for hazard assessment. Only some Level 1 maps are Factor

Maps (topography and geology). All Level 2 maps are Factor Maps, and are largely interpretative. They include maps such as vegetation maps, interpretative geology maps, terrain analysis maps, geomorphological maps, slope maps, some geotechnical parameter maps such as hydrology maps and existing landslide maps which require considerable interpretative judgement. Existing landslide maps are often called landslide inventories (Cruden 1996). It is important to note that level 1 and 2 maps do not include any forecasting of future or potential hazards.

To facilitate a better understanding of the change in Factor of Safety of a slope up to the time of failure, Terzaghi (1950) plotted the Factor of Safety versus time, conceptually, for Turtle Mountain after the Great Frank Alberta Slide in 1903. This concept was also discussed by Popescu (1994), as shown in Figure 2.4. The potential forms of this curve are unlimited, however, it serves here to point out that seldom can a landslide be attributed to a single causal factor. The triggering factor can be identified as that which initiated the failure, but clearly, other preparatory causes contributed to the onset of the failure.

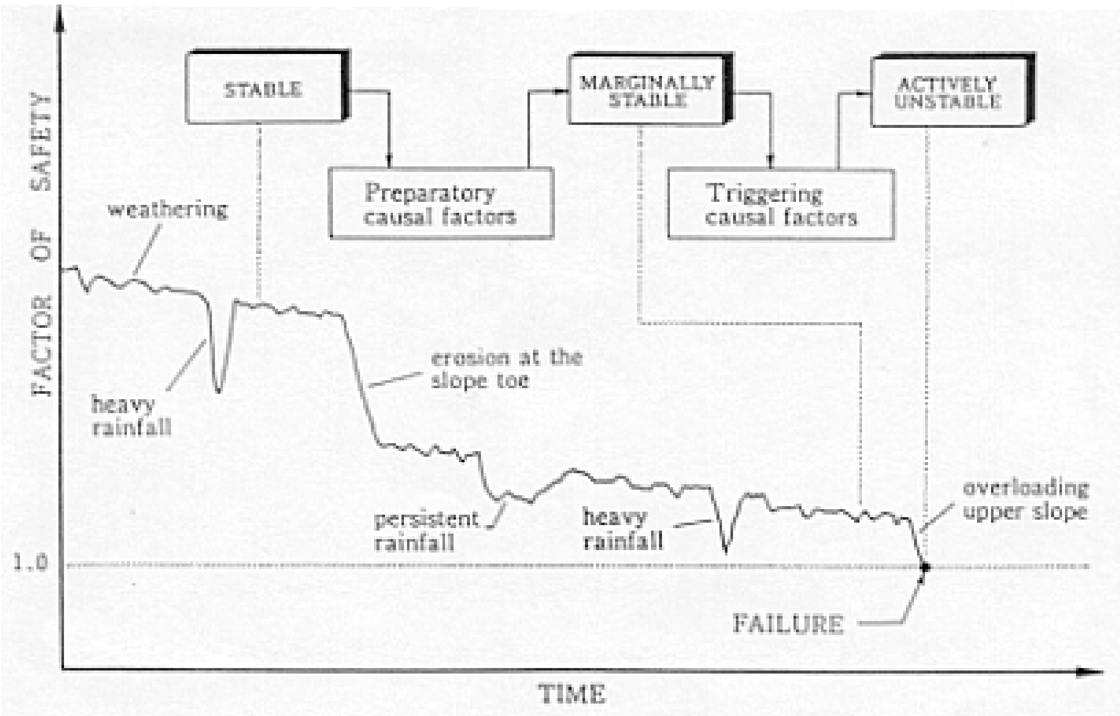


Figure 2.4. Conceptual representation of the decrease of a slopes Factor of Safety with time (Popescu, 1996, after Terzaghi, 1950).

Terzaghi (1950) divided landslide causes into external causes, which result in an increase of the shearing stress (for example, unfavourable erosion across the toe of a slope), and internal causes, which result in a decrease of the shearing resistance (ie, progressive movement along the shear plane reducing the available strength along the shear surface from a peak value to a residual one). Many workers have discussed this field of research including Varnes (1978 and 1984) and Brabb (1984). Siddle et al (1991), referred to extrinsic and intrinsic factors, while Hutchinson (1992) discussed underlying, long term or preparatory and local or shorter-term triggering factors. Popescu (1994, and 1996) noted that the great variety of slope movements reflects the diversity of conditions that cause the slope to become unstable and the processes that trigger the movement. He suggested, that it is more appropriate to discuss causal factors, a term proposed to include conditions and processes.

Due to the complexity of landslide causes, the Working Party on the World Landslide Inventory considered it appropriate to adopt a simple classification system for landslide causal factors. The system is based on making a distinction between ground conditions, and processes. Ground conditions specify the slope system, the setting on which a process can act to trigger a failure. This system, shown here as Figure 2.5 classifies landslide causal factors according to their effect, preparatory or triggering, and their origin, ground conditions and geomorphological, physical or man made processes.

The factors mapped may be assigned purely a spatial distribution, hence gaining a binary yes/no, or 0/1 value, indicating the presence or absence of the given factor. Alternatively, the value may be assigned as a weight of say 0 to 5, depending on the severity of its occurrence, or its significance as a causal factor. The weight applied may be assigned according to judgement if it cannot be determined quantitatively.

An interesting Level 2 type of map, Terrain Classification (Finlayson, 1984), has been adopted in Hong Kong (Brand, 1988). Terrain Classification differentiates and classifies areas of ground with different characteristics. It is also most convenient, for as well as being an integral component of hazard assessment, it also provides convenient land units upon which hazard and subsequent risk can be assessed. The alternative method upon which to spatially assess hazard zones is to use grid patterns. The grids used are commonly between 50m and 350m across (Brand 1988, Carrara et al 1991), that is 2500 - 125,000 m^2, (0.25 - 12.5 Ha). The advantage of using a grid pattern is that

1. GROUND CONDITIONS

(1) Plastic weak material
(2) Sensitive material
(3) Collapsible material
(4) Weathered material
(5) Sheared material
(6) Jointed or fissured material
(7) Adversely oriented mass discontinuities (including bedding, schistosity, cleavage)
(8) Adversely oriented structural discontinuities (including faults, unconformities, flexural shears, sedimentary contacts)
(9) Contrast in permeability and its effects on ground water
(10) Contrast in stiffness (stiff, dense material over plastic material)

2. GEOMORPHOLOGICAL PROCESSES

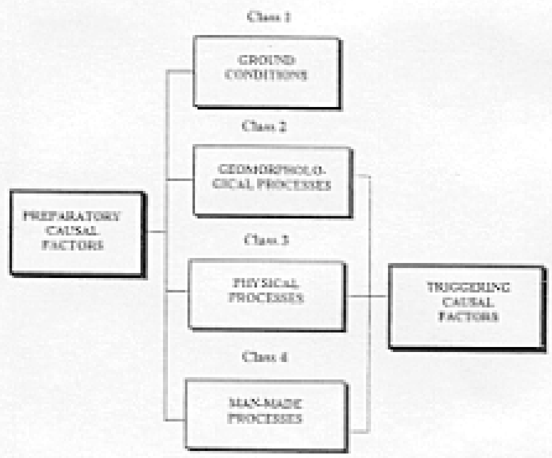
(1) Tectonic uplift
(2) Volcanic uplift
(3) Glacial rebound
(4) Fluvial erosion of the slope toe
(5) Wave erosion of the slope toe
(6) Glacial erosion of the slope toe
(7) Erosion of the lateral margins
(8) Subterranean erosion (solution, piping)
(9) Deposition loading of the slope or its crest
(10) Vegetation removal (by erosion, forest fire, drought)

3. PHYSICAL PROCESSES

(1) Intense, short period rainfall
(2) Rapid melt of deep snow
(3) Prolonged high precipitation
(4) Rapid drawdown following floods, high tides or breaching of natural dams
(5) Earthquake
(6) Volcanic eruption
(7) Breaching of crater lakes
(8) Thawing of permafrost
(9) Freeze and thaw weathering
(10) Shrink and swell weathering of expansive soils

4. MAN-MADE PROCESSES

(1) Excavation of the slope or its toe
(2) Loading of the slope or its crest
(3) Drawdown (of reservoirs)
(4) Irrigation
(5) Defective maintenance of drainage systems
(6) Water leakage from services (water supplies, sewers, stormwater drains)
(7) Vegetation removal (deforestation)
(8) Mining and quarrying (open pits or underground galleries)
(9) Creation of dumps of very loose waste
(10) Artificial vibration (including traffic, pile driving, heavy machinery)



Types of causal factors of landslides

Figure 2.5. A classification system for landslide causal factors. For example, preparatory causes 1.4, triggering cause 3.1 (Popescu 1996, adopted by WP/WLI).

whilst they can be prepared manually, they can be rapidly and easily computer generated. The clear disadvantage of grids is that the boundaries may, and usually will transgress landforms. Terrain units, however, require manual delineation and are, to a degree, subjective. The detail achieved is dependant on the map scale employed, which is clearly shown in Figure 2.6 (after Shih-Chiao Chang, 1992).

(a) (b)

Figure 2.6. Definition of terrain units at different scales. With larger map scale contours are more accurate, and more land units are recognisable; (a) 1:25000 scale, (b) 1:5000 scale (after Shih-Chia Chang, 1992).

Use of State of Nature (Level 1) and Factor Maps (Level 2) to produce Hazard Maps (Level 3) by Brand (1988) and Bhandari et al (1994) is discussed in section 2.4.5.

Landslide databases may be brief tabulated summaries or detailed computer based inventories summarising many aspects of the landslides within a particular study area. The databases may be simple (Pitsis 1992) or complex (WP/WLI 1990, 1991, 1993a, 1993b, 1994, Raviskanthan and Perera 1994, Cruden 1996) and are now contributing significant detail to landslide research and investigations. A landslide inventory to develop tenable criteria for landslide zonation has been suggested by Chandra (1996). Tabulated or computer database summaries of landslides can add enormous amounts of detail to the map based inventories (Cruden 1996) and hence, are useful at all scales of investigation, from the local level, through to regional, national and international. An analogy may be drawn to the early recordings and compilation of earthquake databases, which led to the recognition of the Pacific “rim of fire”, and further supporting evidence confirming the theory of plate tectonics.

If the information gathering and storage process can be computer-based then immense benefits are achieved through approaches incorporating the use of Geographic Information Systems (Carrara et al 1991, Raviskanthan and Perera 1994, Chowdhury and Flentje 1996, Kienholz and Krummenacher 1996, Flentje and Chowdhury 1997, Rosenbaum and Popescu 1996). GIS computer packages are well suited to linking spatial information with database text based information. This linking can be in a spatial analysis and reporting style, for example complex overlays of two or more ‘map layers’, and/or in a cartographic, map presentation sense, dependant on the requirements of the users.

The writer firmly believes in keeping technical maps simple within practical limits, to maintain their readability, broaden their appeal and hence usefulness. Therefore accompanying databases, conceptually linked to individual map features, can become very powerful tools for hazard assessment and risk management. Computer based databases can be easily updated and modified with time to keep pace with current and developing knowledge.

2.4.5 Identify Land Instability Hazard

Landslide hazard, in particular existing landslide hazard, is best communicated through maps. In landslide hazard zonation maps, both existing and potential hazards may be shown, often with the use of different colours for varying types and/or levels of hazard. These maps have been called landslide susceptibility maps (Einstein 1988). Hazard maps may be prepared, as the definition of hazard may suggest, on the basis of the magnitude of the landslides within the map area, and the probability of their (specific) occurrence, or based on the probability of the occurrence of landslides.

As noted above, establishing the probability of landslide movement is one of the essential factors in assigning landslide hazard. This may be done by any one of the four methods described in section 2.6, that is;

- conventional deterministic approach
- probabilistic approaches
- calculated probabilities
- historical failure probabilities
- relationship between rainfall and failure probabilities
- probabilities based on engineering judgement

Furthermore, this may be achieved in the first instance with the use of basic statistical percentages, representing prior probabilities, which could be updated during later work, on the basis of more detailed investigations of specific indicators, which in turn may lead to the use of more specific posterior probabilities.

Many procedures have been described in the literature to produce hazard maps, some using the results obtained in Level 1 and Level 2 investigations. Hazard maps in California have been reported, amongst others, by Blanc and Cleveland (1968), Brabb Pampeyan and Bonilla (1972). The percentage of landslide occurrences in different geological formations was estimated and then combined with slope inclination data to produce such maps. Radbruch-Hall et al (1982), using the same technique, completed a landslide overview map of the United States on a scale of 1:7,500,000. In Australia, Bowman (1972) produced a five level stability zoning scheme, based on geology, slope angle and existing landslides (section 3.9 and 3.10) for the study area of this research project, that is the local government area of the Wollongong City Council.

The ZERMOS project, commenced in France in 1974 has become one of the most comprehensive and developed systems in France. This system considers numerous factors, slightly different with each application, to produce maps delineating Zones Exposed to Risks of Soil Movement (ZERMOS). The ZERMOS map of the Moyenne Vesubie region, France, 1:25000 scale prepared by Meneroud and Calvino (1976) shows four zones of instability defined on the basis of five factors; lithology, geological structure, slope, morphology and hydrology. The ZERMOS map prepared by Landry (1979) at Poligny in the area of Lonsle-Saunier identifies seven classes of hazard on the basis of factors like geological origin of the soil and sub soil, slope angle, drainage, and local history of landsliding. The geomorphological and process aspects of landslide hazard zonation, typical of the ZERMOS procedures, have been extended by Kienholz (1977) on 1:10,000 maps of the Grindelwald area in Switzerland.

In general, the ZERMOS maps show three levels of hazard, indicated by a) green - (V) - nil or very slight hazard, b) orange - (O) - slight to moderate hazard, and c) red - (R) - high degree of hazard. Two distinctions of hazard are permitted within V (V1 and V2), three in O, (O1 O2 and O3), and two in R, (R1 and R2). Thus seven classes, are the maximum number allowed in the ZERMOS maps. Various kinds of movement are shown by black symbols (ie rock falls, various landslides, subsidence, particular geological horizons etc). The maps are accompanied by text conforming to a pattern, which explain further detail which cannot be shown on the maps.

In a paper summarising some risk assessment work used by the Geotechnical Control Office in Hong Kong, Brand (1988) discusses the Geotechnical Area Studies Programme (GASP), under which a terrain evaluation approach has been used for a geotechnical assessment of the whole territory. A series of user orientated maps was produced at regional (1:20000) scale and district (1:2500) scales. In particular the Geotechnical Land Use Map (GLUM) series, classifies the land into four zones of geotechnical difficulty.

In the 1:20000 scale maps, the smallest mappable area was approximately 1.0 Ha, and the land was classified on the basis of three attributes, determined from level 1 and level 2 factors and some related maps;

- slope gradient (6 classes), measured along the gradient of the greatest slope to allow determination of most limiting value,
- terrain component and morphology (25 classes), physical appearance of slope and general shape of slope profile (straight, concave or convex),
- erosion and instability (14 classes), surface condition of terrain on basis of major forms of denudation, including landslips and evidence of instability.

In the 1:2500 scale maps, the smallest mappable area was approximately 0.3 Ha, and the land was classified on the basis of seven attributes determined from level 1 and level 2 factors and some related maps;

- slope gradient (6 classes), as for the regional studies,
- terrain component (21 classes), physical appearance of terrain,
- terrain morphology (15 classes), general shape and distinguishes insitu terrain, and terrain of colluvial and alluvial origin
- erosion and instability (17 classes), as for the regional studies,
- slope condition (9 classes), distinguishes man made influence for cuts and fills,
- hydrology (4 classes), hydrological features which influence instability,
- vegetation (8 classes), broad vegetation type.

On the basis of these attributes, the land is classified into four GLUM classes; Low, Moderate, High and Extreme Geotechnical Limitations. In the 5 level system being discussed here, the GLUM map series is considered by the writer to be a Level 3 map. In a comparative exercise, Styles et al (1984), evaluated the district GASP data in the context of slope stability. Of 1400 potential failure surfaces, nearly all with a factor of safety less than 1.4 had been assigned GLUM classes of III and IV (ie land subject to high or extreme geotechnical limitations). Hence, the district GLUM maps may be considered as hazard maps depicting potential failure zones, although no consideration of probability is given. An additional map entitled 'GLEAM' was produced and is discussed briefly in section 2.4.7, below.

In addition to the conventional line-drawn maps produced from the Regional GASP Studies, computer generated maps are also available as a product of the Geotechnical Terrain Classification System (GEOTECHS). GEOTECHS records data on 53,200 two hectare grid cells referenced to the Hong Kong metric survey grid. For each grid cell, nine natural attributes are recorded; slope gradient, terrain component, erosion and instability, aspect, relief, superficial and bedrock geology, existing land use, vegetation, and average annual rainfall (Brand 1988). GEOTECHS facilitates the rapid production of computer generated plots which assist in the correlation of terrain attributes and other data on a Territory wide basis. It also permits the development of planning and engineering strategies.

The development of 1:10000 scale graded Landslide Hazard and Zoning maps in Sri Lanka has been reported by Bhandari, Herath and Thayalan (1994), Raviskanthan (1994) and Bhandari (1994). The work reported by these authors follows the Landslide Hazard Mapping Project by the National Building Research Organisation (NBRO). The procedure involved the use of a Geographic Information Systems computer package for computer based mapping and integration of "state-of-the-nature" or "factor maps" (Bhandari et al, 1994) to produce graded Landslide Hazard Maps. The "factor maps" included; landslides, geology, colluvium and residual soils, slope, landform, land use and management, hydrology, infrastructure and human settlements The map gradations employed follow those of Zollinger (1976), where zones with practical development guidelines are proposed. For mapping at scales larger than 1:1000, grading on the basis of numerical probability was proposed.

Kienholz and Krummenacher (1996) discuss a procedure for generating a landslide hazard-index map of potentially unstable areas. This procedure involves established slope stability analyses in combination with a GIS computer package. This procedure is intended for use at regional planning map scales of approximately 1:25000, as opposed to local planning maps at scales of say 1:5000. Input parameters required include; slope topography, parameters of soil strength, depth and shape of potential slip surface and the hydrological regime. This method was assessed in several areas in Switzerland where the input parameters were available. In these tests for validation, in the Kleine Schliere area, 86% of the pixels were classified correctly. Validation of this method included good areas of correlation with existing maps, but a heavy reliance on existing factor maps which often proved to be insufficiently detailed.

Existing landslide maps (Level 2 maps) are very useful as they may also comprise the most basic Level 3 Hazard Map when combined with a landslide database that provides further definition of each mapped landslide feature. In some areas, virtually all of the study region is occupied by landslides. The landslide map, with the necessary subdivision or zoning of activity, becomes the landslide hazard map.

An example of such a situation exists on the south coast of the Isle of Wight, England, in an area known as the Undercliff. The Undercliff has a population of approximately 6000 people, and includes the towns of Ventnor, Bonchurch and St. Lawrence. The landslides are the largest known in southern England, and as such this area probably comprises the largest urban landslide problem in England (Hutchinson 1991). It is also an area which has been studied extensively.

Detailed assessments of ground movement problems in the Ventnor Undercliff have been carried out since 1988 when the Department of the Environment (DoE) commissioned a study of Ventnor. This study was part of their planning and research program, which was required to incorporate land instability problems within the planning system. The findings of the Ventnor study (DoE 1991) and an extension study commissioned by the South Wight Borough Council (1995) which covers St. Lawrence and the Undercliff towards Niton included the following;

- determining the nature and extent of the landslide problems,
- understanding the past and present behaviour of separate parts of the Undercliff,
- formulating a range of management strategies to reduce the impact of future movement.

The program of work comprised a thorough review of available records, reports and documents followed by a program of detailed field investigation, involving geomorphological and geological mapping, assessment of ground movement rates, a survey of damage caused by ground movement, and a review of local building practice.

The 1995 report is supported by three sets of 1:2500 scale maps, entitled Geomorphology, Ground Behaviour and Planning Guidance. The earlier Ventnor study (DoE 1991) contained an additional set of Land Use maps. Each of the three sets contain five maps which cover most of the Undercliff. The base information on each map includes, cadastre, structures (residential, commercial, and some civil), and contours. Three different sets of maps were generated as outlined below;

- Geomorphology maps are of the terrain classification type with some further ground subdivisions based on differentiation of surficial or underlying geology.
- Ground Behaviour Maps identify the nature of the landslide hazard. This has been achieved through the assessment of landslide activity within contrasting geomorphological units. In essence, the maps describe the nature, magnitude and frequency of the mass movement processes which have operated over the last 200 years or more, and their impact on the community. These maps show clearly that the potential problems resulting from ground movement vary from place to place, as all structures are shown on the map bases (and at least some land use maps do exist).
- Planning Guidance Maps follow on from the Ground Behaviour Maps as they recognise areas which are likely to be suitable for development, along with areas which may be suitable subject to further investigation, and other areas which are subject to significant constraints making them unsuitable for development. Guidance is provided on the maps regarding the geotechnical information requirements for planning applications in different areas.

2.4.6 Identification, Analysis and Assessment of Land Instability Risks

Identification of the risks which may arise from an occurrence of the land instability hazard requires an understanding of the elements at risk in the path of or as a result of the land instability, and an assessment of the vulnerability of each element.

As a minimum, these risks need to be tabulated in order to provide a comprehensive overview. This overview will allow the risks to be ranked in order of priority and compared with pre-determined risk criteria. Risks may arise from potential hazards as well as from existing hazards, and hence must be considered. However, those arising from existing hazards may be a convenient point from which to start identifying risks.

As noted previously, Risk Analysis is defined as “a systematic use of available information to determine how often specified events may occur and the magnitude of their likely consequences.” Risk Assessment is defined as “the process used to determine risk management priorities by evaluating and comparing the level of risk against predetermined standards, target risk levels or other criteria."

Quantifying risk is a very complex task, and is compounded further by the procedures involved in mapping risk. In 1988, Einstein stated that risk mapping has been done only to a limited extent. The writer can add that, following the definition of risk in this thesis, even now (1997) risk mapping is still rarely undertaken, with some recent notable exceptions. Some of these exceptions are referred to in this section, while several additional works of note are discussed in section 2.5.

Total Risk, as defined previously, is the product of specific risk (Rs), and elements at risk (E) ;

Total Risk = $Rt = E \times Rs = E \times (H \times V)$

On the basis of the Level 1 through Level 3 maps and the data on which these maps are based, and the equations discussed above, levels of risk may be determined formally. Such an assessment of risk may be;

- fully quantitative, with minimum subjective judgement, or,
- quantitative values based on some objective data and some engineering judgement or,
- largely qualitative indicating relative levels of risk based primarily on subjective judgement.

A simple empirical approach to determine and map relative landslide risk in clay slopes of northern Tasmania was developed by Stevenson (1977 and 1978). Stevenson considered five factors;

- clay type (P) - Plasticity Index of the clay,
- water pressure factor (W) - maximum pore pressure head in relation to slip surface,
- slope angle (S) - overall slope inclination of segment in question,
- slope complexity (C) - simple slope, old eroded failure, or new failure, and,
- land use type (U) - woodland, cleared pasture or urban land.

Unlike traditional deterministic stability analysis which is used for detailed studies of individual sites, this method of Stevenson's was applied over large areas for mapping purposes.

Stevenson proposed the following equation for the degree of risk (denoted by R);

$R = (2P + 2W)(S + 2C)(U)$

Despite the difference between Varnes definition of risk, and the definition preferred by the writer, it is reasonable to accept the conclusions of Varnes (1984) that Stevenson's approach is analogous to Varnes's definition of risk, $R = H \times V$. The first two terms on the right of the equation represent hazard, and the last term represents vulnerability.

Several areas in Tasmania have been examined by various authors. From these studies it may be concluded that the value of R which indicates failure is about 60. Stevenson suggested that such a crude method should not be overtaxed, and hence values above 50 should be treated as a warning of potential instability. In addition, he stressed that relative magnitudes are important and not absolute values.

Work by Mears (1977) regarding debris flows in drainage basins in Colorado (United States of America) is a different example of risk mapping. Mears assumed a debris flow velocity of 4.5m per second for an area extending 0 - 90m below the mouth of the canyons and a velocity of 3m per second for an area 90 - 180m below the mouth of the canyons. Using these velocities and an assumed unit weight of 2 grams per cm^3 for the debris flow material, two zones of potential impact pressure were designated on the map. Rainfall statistics and historical information on the occurrence of debris flows suggested a return period of 50 years, or an annual probability of 2 percent. Flow arrest and mitigation structures were estimated at $10,000 annually, well below the $40,000 estimated damage cost of the real debris flow event of 1977.

This work included the probability of the occurrence of the event, the area potentially affected, the impact pressures of debris, and a cost-benefit analysis of arresting structures. An important component of risk that is missing from this work is the vulnerability of people and structures should the event occur. However, the base map does show the cadastre and location of structures allowing some consideration of the risk to these later elements, which would be appropriate in an even more focussed study.

Anbalagan (1992) and then Anbalagan and Singh (1996) have developed hazard and risk assessment maps for a well defined mountainous regions within the western part of Himalayan belt of northern India. The definitions of hazard and risk used by Anbalagan and Singh follow those of Varnes (1984). A flow chart by Anbalagan and Singh showing their general procedure for risk assessment mapping is included here as

Figure 2.7. Their qualitative landslide hazard zonation maps are prepared at a scale of 1:25000 and 1:50000 on the basis of an estimated significance of causative factors (slope facet, geology, slope geometry, relative relief, land use and land cover). The basis of subdivision are the geomorphological land units, rather than a grid network as shown in Figure 2.8. The five qualitative hazard zones are 1) very low, 2) low, 3) medium, 4) high and 5) very high.

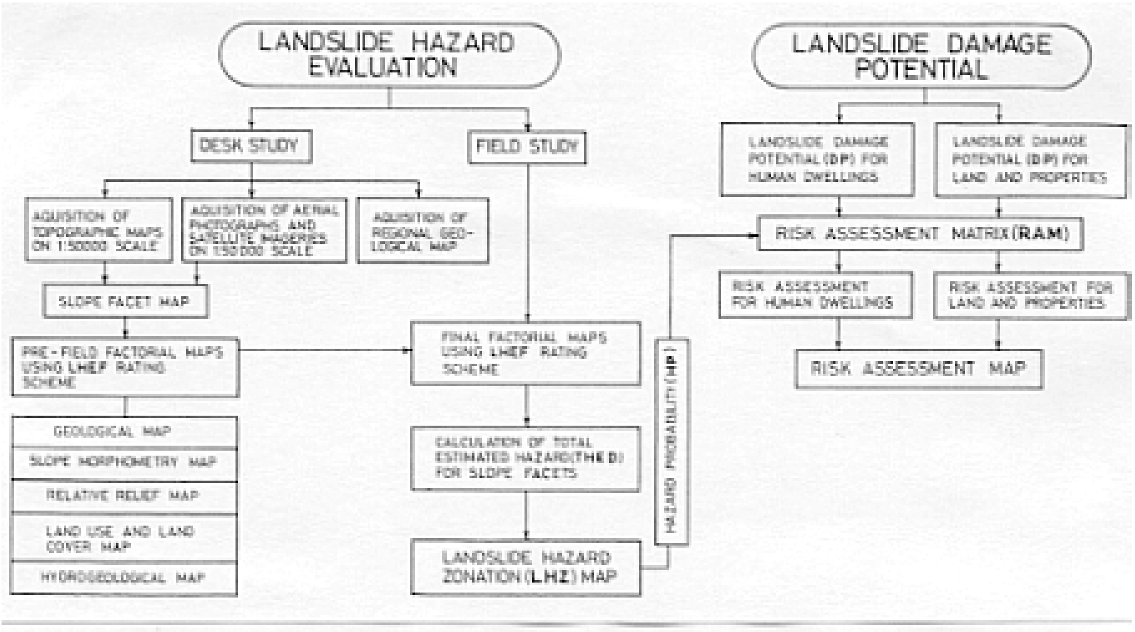


Figure 2.7. Anbalagan and Singh (1996), general procedure for risk assessment mapping developed in the Himalayas.

The qualitative risk maps of Anbalagan and Singh classify risk into two categories, injuries and loss of life, and loss of land and properties. Risk Assessment matrices have been developed for human dwellings (a convenient and logical indicator of human life according to Anbalagan and Singh) and land categories. These risk

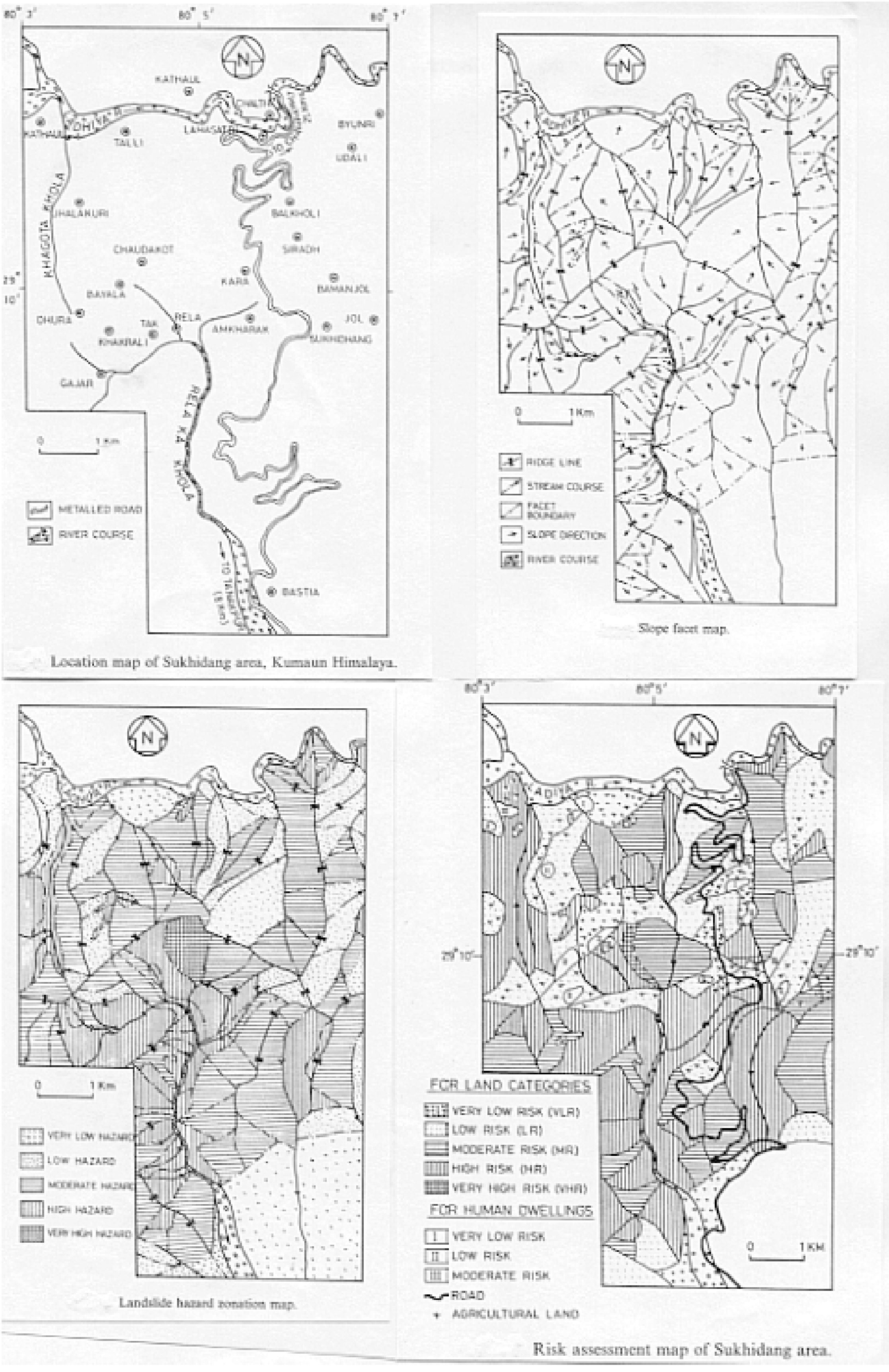


Figure 2.8. Sukhidang area, Kumaun Himalaya, India. Hazard and Risk are assessed on the basis of factor maps, which are not shown. The slope facet map delineates the areas upon which assessments are based, Anbalagan and Singh (1996).

matrices place a five level division of damage potential (very low to very high) against the mapped hazard potential to produce levels of risk, as shown in Figure 2.9.

Damage potential for land categories

Land category	Damage potential (DP)
Barren	Very low DP
Sparsely vegetated	Low DP
Moderately vegetated/ agricultural land	Moderate DP
Thickly vegetated	High DP
Very thickly vegetated	Very High DP

Risk assessment matrix (RAM) for land categories

Damage potential (DP)	Hazard probability (HP)				
	VLHP	LHP	MHP	HHP	VHHP
VLDP	VLR	VLR	LR	LR	LR
LDP	VLR	VLR	LR	MR	MR
MDP	LR	LR	MR	HR	HR
HDP	LR	LR	HR	HR	VHR
VHDP	LR	LR	HR	VHR	VHR

Damage potential (DP) for human dwellings

No. of dwellings likely to be damaged	Type of DP
<2	Very low DP
2–5	Low DP
5–10	Moderate DP
10–50	High DP
>50	Very high DP

Risk assessment matrix (RAM) for human dwellings

Damage potential (DP)	Hazard probability (HP)				
	VLHP	LHP	MHP	HHP	VHHP
VLDP	VLR	VLR	LR	LR	LR
LDP	VLR	LR	LR	MR	MR
MDP	LR	LR	MR	HR	HR
HDP	LR	MR	HR	VHR	VHR
VHDP	LR	MR	HR	VHR	VHR

VLR, very low risk; LR, low risk; MR, moderate risk; HR, high risk; VHR, very high risk.

Damage potential (DP) for roads

Length of damange (m)	Status of damage potential
<100	Very low DP
101–500	Low DP
501–1000	Moderate DP
1001–2000	High DP
>2000	Very high DP

Figure 2.9. Damage potential tables and associated risk assessment matrices, Anbalagan and Singh (1996).

In the approach adopted by Anbalagan and Singh, risk mapping requires the production of a landslide hazard map. The risk boundaries are then mapped whilst considering various factors, including;

- topography of the area, particularly the slope facet in which the hazard exists, and each adjoining facet,
- nature of the failure, and
- geological factors controlling the nature of failure.

For assessment and mapping of risk the precise nature of the specific risk and of the element(s) must be considered. This information must also be included when assessing and communicating the total risk.

As noted previously, the identified risks need to be tabulated. This allows the risks to be ranked in order of priority and compared with pre-determined risk criteria. It is the writer’s opinion that risk due to land instability should be tabulated in a matrix style of presentation, rather than in a comprehensive map format, within the subject area considered by this research project. The matrix would include hazard and risk identification, and quantitative measures of magnitude, probability of occurrence, elements at risk, damage and vulnerability. Quantitative, or at least semi-quantitative assessment can be made for each risk situation, and ranked in order of priority. Such prioritised lists could be compared for different risk ‘events’. This process would lead to logical, justifiable decisions regarding the management of risk.

2.4.7 Landslide Risk Treatment

As noted above, the primary significance of a qualitative or quantitative description of risk is not in the potential production of risk maps, but in the decisions and actions (managerial and technical) that may follow risk assessment. These actions should be based on a prioritised list of risks. However it has to be noted that such ranking, although technically based, may have social or political bias. The extent of such bias is, of course, an area of research outside the scope of this thesis.

A major benefit of geotechnical risk evaluation is that remedial measures can be planned and implemented on a logical basis. This has been highlighted in a study of ground collapse due to subsurface mining in England (Cole et al, 1993).

According to Einstein, 1988, the following types of decisions under uncertainty may be considered;

- passive regulatory measures including prohibition or restricting development,
- active countermeasures such as subsurface drainage, retaining structures, reinforcement etc,
- warning devices, such as early warning systems used in New South Wales by the Railway Services Authority and
- gathering additional information and research studies such as this research project.

In discussing the United States experience, Schuster (1991) states that four mitigative approaches are common. These measures, listed below are similar to those stated above;

- restriction of development within landslide prone areas,
- Codes for excavating, grading, landscaping, and construction,
- use of physical measures to prevent or control landslides,

- landslide warning systems.

Following the study of the Undercliff, on the Isle of Wight in England, commissioned by the South Wight Borough Council (1995), a landslide management Strategy has been promoted by that council. The strategy aims to;

- reduce the likelihood of future movement by controlling the factors that cause ground movement and,
- limit the impact of future movement through the adoption of appropriate planning and building controls.

The strategy involves a variety of approaches to address the ground movement problems by;

- improving ground conditions through the control of water in the ground and coast protection measures,
- preventing unsuitable development through planning control and building control,
- monitoring ground movement and weather conditions at automatic and manual recording stations, and
- raising professional and public awareness through displays and meetings.

This strategy has been neatly summarised in a flow chart included here as Figure 2.10, overleaf.

Varnes (1984) summarises an experience in Los Angeles which attests to the success of regulatory control of construction in urban areas in relation to land instability. Following heavy rains and severe damage in that city in 1951/52, a grading ordinance was developed and adopted. Further storm damage in 1957/58 and 1962 demonstrated the need for stricter control. New regulations were written and adopted. Comparisons were made between damage caused in these earlier years to that caused in 1963-69, whereby it was found that 18 times more total damage (a significant proportion being in relation to slope movements) was experienced by those sites constructed before 1952. This program required three essential elements;

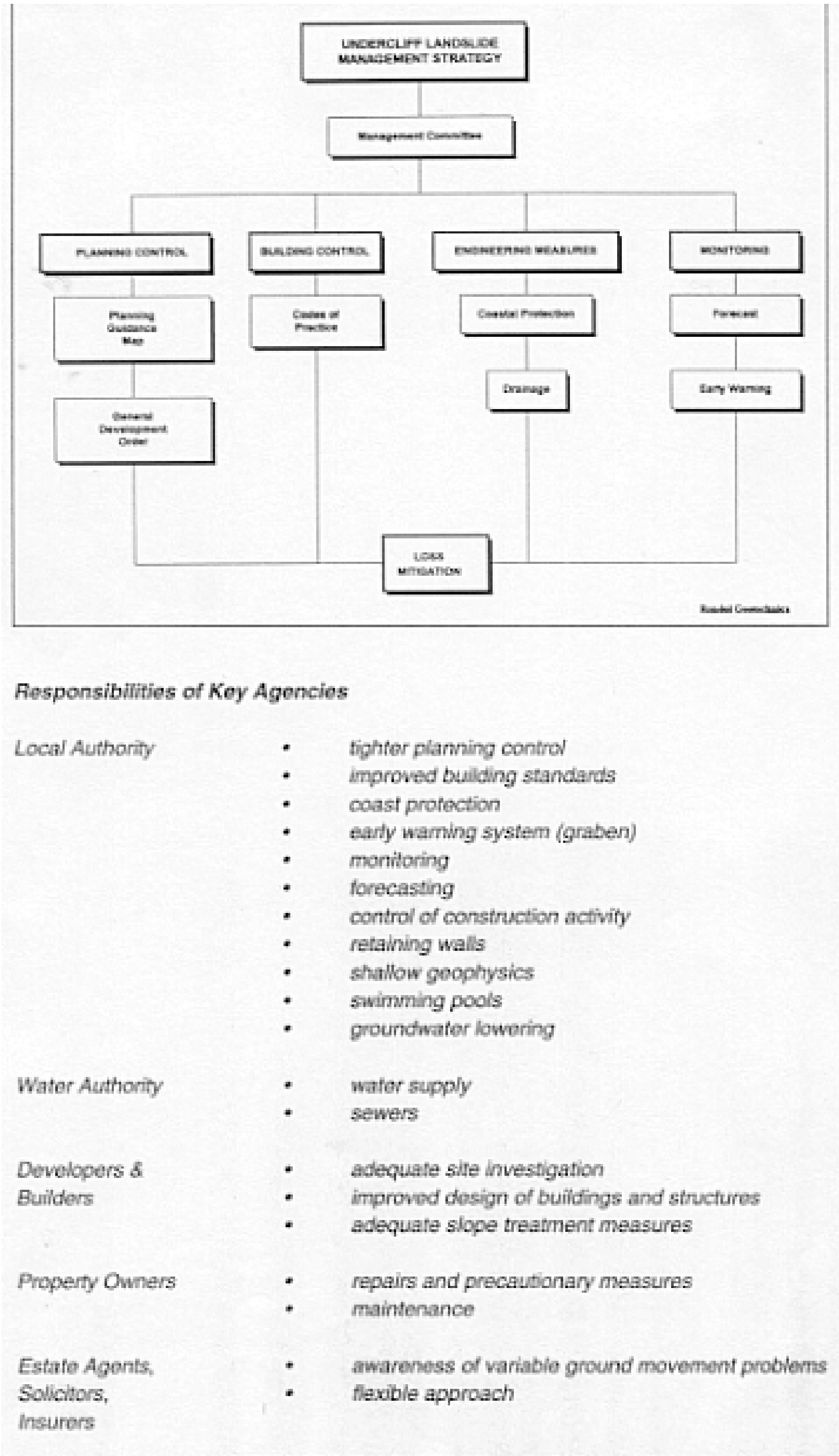


Figure 2.10. Landslide management strategy for the Undercliff, Isle of Wight, England. Strategy aims to reduce and limit the likelihood of future movement by adopting four approaches (South Wight Borough Council, 1995).

- a local government organisation which is concerned about good risk management, has the will to use resources for it and the technical capabilities required for implementation,
- a database of technical information concerning hazards and a technical community able to further build on this information,
- a community that recognises the need for appropriate regulation.

A decree issued in France in 1970, Plans d´occupation des sols (POS, plans of occupation of land) required protection against geologic hazard. Whilst the ZERMOS plans do not have regulatory force, Porcher and Guillope (1979), developed 1:5000 scale POS plans with specific land use recommendations. In 1982, PER (Plans d´exposition aux risques, plans showing risk) plans were developed in response to a 1982 law concerning the indemnification of victims of natural catastrophes.

In Hong Kong, the General Limitations and Engineering Appraisal Maps (GLEAM) produced for Regional Studies (that is, on the basis of 1:20000 map data) were designed specifically for planning evaluation, to aid in the identification of parcels of land suitable for future development. These maps extend and synthesise the guidance given by the other maps (Engineering geology, physical constraints, GLUM etc). GLEAM identifies four development planning zones;

- zones with good potential for development,
- zones with minor (local) geotechnical constraints on development,
- zones with major geotechnical constraints on development,
- zones of existing development.

In New South Wales, Australia, the Lake Macquarie City Council (southern suburbs of Newcastle area) have developed relative landslide susceptibility maps (Fell and Flentje 1991). Some of these zones have development limitations attached. These development limitations are concerned with potential new subdivisions, major development, building application development and minor development. For some of the zones with steeper slopes there are recommendations for Hillside Construction. It has been recommended that all sites be considered in the light of the Australian Geomechanics Classification of Risk of Slope Instability (AGS 1985).

The Wollongong City Council has a series of confidential maps, for their internal use only, which distinguish between landslip areas, suspect landslip areas and other areas not affected by land slip. These maps are used to determine whether geotechnical reports (concerning land instability) are required for development and or building applications.

2.5 OTHER EXAMPLES OF RISK ASSESSMENT PROCEDURES

2.5.1 The Umbria Region of Central Italy, Carrara et al (1991)

Carrara (1991) discusses the use of GIS techniques and statistical models in evaluating landslide hazard for a small drainage basin of the Tescio River (a tributary of the Tiber River), in the Umbria Region of Central Italy, near the town of Assisi. The area is statistically similar, in some respects, to the study area of this project, as shown in Table 2.6.

Feature	Tescio River basin	Northern Wollongong Escarpment
Area	60 km^2	85 km^2
Rainfall (annual)	1100 mm	1200mm
Number of landslides	243	319
Landslides per km^2	4.05	3.75

Table 2.6. Comparison of Tescio River basin of Central Italy with the subject area of this research project, the Northern Wollongong Escarpment

However, the major causes and processes of slope instability in the two areas are quite different. In Wollongong, the process is dominated by rainfall induced pore pressure and low intrinsic shear strength. In contrast, Carrara (1991) noted that the landslides in the Tescio River basin are frequently related to the process of stream erosion.

Mapping work in the Tescio River basin was carried out at scales of 1:25000 (contours) and 1:10000 (geology). Contour lines were prepared for the study area during the project by the research team, and after rigorous checking and validation, a high fidelity digital terrain model (DTM) at 25m by 25m spacing was produced. Landslide mapping and land use mapping were determined from air photograph interpretation, and systematic ground surveys. Subsequently, additional parameters were estimated in the field and from the geology map, or automatically obtained from the elevation model, namely bedding, altitude, slope aspect, and the stratigraphic relations between permeable and impermeable rock units.

The land characteristics are based on morphologically meaningful terrain units, as opposed the use of grid cells, which Carrara et al (1978), used in previous research. Forty morphological, geological and vegetational attributes for each land or slope unit were determined or calculated. After analysis by means of a statistical package, the values for 15 variables (determined from the initial forty attributes) were used in a discriminant analysis. Scores were determined for each land unit, and subsequently grouped into unstable and stable.

To test the predictive performance of this model, the 266 slope units of the basin were randomly split into two groups. One was used to trial the model, the other being reserved for validation. The percent of cases correctly classified varied from 75% to 82%, depending on the variables used.

2.5.2 Australian Example 1 - The Australian Geomechanics Society (AGS) 1985 Classification of Risk of Slope Instability.

The classification of risk of slope instability by geotechnical engineering consultants in relation to residential development within local government areas is typically required by local councils to follow the guidelines published by the Australian Geomechanics Society (AGS, 1985) The complete paper titled “Geotechnical Risk Associated with Hillside Development” is included in Appendix 1. This article also includes guidelines for hillside construction, with examples of both good and poor hillside construction practice. Appendix 1 also includes the Wollongong City Councils current policy relating to the Development of Land which may be subject to Instability.

With respect to the definitions used in this thesis, the terminology used in this article is a mixture of classification, magnitude, probability, hazard and vulnerability in no specific order. The system is entirely qualitative and primarily subjective, with insufficient guidelines to encourage consistent outcomes when used by different geotechnical engineers or engineering geologists.

No quantitative values of risk are suggested. Concepts including an ‘element’ and its ‘vulnerability’ are not considered. The implications for development are summarised on the basis of suggested required levels of geotechnical investigation and relative levels of risk. Furthermore, consideration is not given to reviewing the classification of sites that may have had remedial works installed.

In spite of these drawbacks, the AGS system is widely used by geotechnical consultants, and accepted by many local government councils in Victoria and coastal New South Wales. The reason is that subjective judgement can be exercised without any investigation at all and, for some relatively small projects, this is very convenient. Some Sydney councils, the Lake Macquarie City Council (southern suburbs of Newcastle) and the Wollongong City Council accept development on sites classified as medium, low or very low risk. Development of sites classified as high and very high risk is not considered acceptable unless remedial works are proposed. Following the installation of remedial works, consultants may lower the risk classification level to medium, low or very low.

The AGS classification system has however, been instrumental in educating councils (Fell, 1992) and geotechnical practitioners to the concept of risk assessment. This has led to a reduction in arbitrary requests, usually by local government councils, to proclaim sites as either stable or unstable.

2.5.3 Australian Example 2 - The New South Wales (Australia) Rail Service Authorities Geotechnical Risk Assessment Guidelines.

Within the state government of New South Wales, the Rail Service Authority (RSA) manages a rail network of approximately 4000km of railway line. This rail network has approximately 1000 active problem sites from a geotechnical perspective. Since the double fatality at Coledale in 1988, approximately $90,000,000 has been spent on remedial stabilisation works by the RSA (pers com D. Christie, RSA, 1997).

The Geotechnical Services Department of the Railway Services Authority, considers risk primarily in relation to safety of structures and the public and staff travelling in trains or of those who are located adjacent to the railway line. The assessment of geotechnical risk of a site relates the estimate of the probability of an event affecting the track in adverse climatic conditions, (and other significant conditions), with the assessment of potential consequences of that event (RSA 1995). Relative risk assessment categories are defined. The RSA considers that an individual should not be exposed to a risk greater than 1 times 10^{-6} for a single rail journey, and that one site should not pose a risk to the rail network greater than one times 10^{-5} (pers com D. Christie, RSA, 1997).

The RSA uses a matrix to assess risk as shown in Figure 2.11. This matrix is

DEFINITION OF RISK CATEGORY

1. **Very High to Extreme Risk**

- Track is closed or is impassable as a result of a Geotechnical Event.

or - A Geotechnical Event, which would be anticipated to result in loss of life and/or extreme damage and disruption, is imminent and the situation is too dangerous to allow trains to pass. Traffic stopped.

2. **High Risk**

- Moderate probability of an event occurring which would reasonably be anticipated to result in loss of life of public, passengers and staff, and to cause extensive damage and disruption.

or - High probability of an event occurring which would result in appreciable damage and disruption occurring where loss of life is possible but not expected.

*Note: Safety action or hazard management, is necessary for problems identified as high risk, to reduce the probability of the event occurring or the consequences of that event. Such action which includes maintenance, speed limits & surveillance may effectively reduce the risk provided the action is continued.

3. Moderate Risk

- Moderate probability of an event occurring which would cause appreciable damage and disruption where loss of life is possible but not expected. (3.1)

or - High probability of an event occurring which would result in minor damage to structures and facilities but neither loss of life nor serious injury would be expected. (3.2)

or - Low probability of an event occurring which would result in loss of life and extensive damage to structures. (3.3)

*Note: Problems identified in this category would have the risk reduced effectively by introducing safety action such as speed limit, maintenance and surveillance.

4. Low Risk

Moderate of low probability of an event which would result in minor damage to structures and facilities but neither loss of life nor serious injury is expected.

5. Very Low Risk

- Problem has been rectified and is being monitored.
- Old problems identified and is being monitored.
- Not a risk.

RISK ASSESSMENT MATRIX

CONSEQUENCE of the event of affecting the track	**Probability of event affecting the track, in the short term (12 months)** *(Assessment is necessary of probability of event occurring and affecting the track)*			
	HIGH Event is anticipated (H)	MODERATE Event is probable (M)	LOW Event is probable but not expected (L)	VERY LOW Event is possible
Extreme E - Loss of life expected - extensive damage and disruption	1	2	3 Priority 3	4
Severe S - loss of life is possible, not expected - appreciable damage and disruption	2	3 Priority 1	4 Priority 1	5
Moderate MC - loss of life or serious injury not expected - minor damage to structures and facilities	3 Priority 2	4 Priority 2	5	
Minor	4	5		

Safety Action reduce the risk by reducing the consequence of the event affecting the track.

The probability of event affecting the track is assessed from a visual inspection of the site assuming that adverse weather conditions will prevail and taking into account past performance.

DEFINITION OF CATEGORIES OF CONSEQUENCES RESULTING FROM GEOTECHNICAL EVENT

Extreme:

- Loss of life (reasonable to anticipate)
- Extensive damage to structure/& facilities
- Serious indirect loss/disruption
- Prolonged loss of essential service; no alternatives, possible restoration extremely difficult/costly

SEVERE:

- Loss of life possible but not expected
- Serious injury anticipated
- Appreciable damage to structures and public private facilities
- Short term loss of service
- Restoration practicable

MODERATE:

- Neither loss of life nor serious injury is expected
- Minor damage to structures and facilities
- Negligible disruption
- Restoration simple, straight forwards/failure can be tolerated

GEOTECHNICAL RISK - EXAMPLES OF ASSESSMENT FOR RAIL OPERATION

High Risk (2)

1. High embankment constructed on side fill. Mechanism is identified as slide which could occur rapidly taking track and leaving it unsupported. Track maintenance has little impact in reducing risk.

2. High narrow cutting consisting of massive rock which has been identified as having potential failure mechanisms which could produce boulders which could crush a train or cause serious impact.

Moderate Risk

1. Cutting consisting of weathered rock which has been identified as a potential failure onto the track into which the train might plough and become derailed.

2. Moderately high embankment constructed on gently sloping ground, mechanism identified has been perceived as slow or comprising small increments and track can be maintained. Lack of maintenance would lead to derailment condition.

Low Risk

1. A rock cutting which has been identified as potentially failing or has failed and all the debris from the failure falls clear of the line.

2. An embankment constructed on gently sloping ground which is experiencing instability of the slope face and which only effects an access road or embankment shoulder with no affects to the track geometry.

3. An embankment which has been washed away due to over topping in flood conditions and which has been repaired by filling with rock spall fill.

Figure 2.11. Railway Geotechnical Services, Railway Services Authority of New South Wales, Australia, Geotechnical Risk Assessment matrix, with definitions of terms and example assessments (Railway Geotechnical Services, 1995).

based on a subjective determination of the probability of an event affecting the track in a twelve month period, versus a subjective measure of consequence (damage/loss of life). The procedure then considers the probability of an event (or hazard) assuming the potential event (with magnitude) is reported, with the vulnerability of the track, personnel and operations (the elements being considered).

The system contains the necessary elements for a relative risk ranking. A ranking on the basis of this system is regularly updated for all the 1000 problem sites.

2.5.4 Australian Example 3 - Kalorama, Victoria, Finlay 1996.

Kalorama is located in the Dandenong Ranges, south east of Melbourne city centre in the state of Victoria. The area, recently studied by Finlay during his PhD research had largely been classified as “high risk” in a slope stability zoning study carried out for the Lilydale Council by Coffey Partners International (Fell 1996). Finlay’s work involved the preparation of a geomorphological map during walkover inspections using existing contour information, and a fresh review of previous landsliding in the area. This review allowed identification of some sites subject to significant landsliding in the years 1850, 1891 and 1934.

Two approaches were used in this study. The first involved assessment using a generalised qualitative system which identifies a number of factors. The second was more site specific and incorporated a scoring system. This scoring system assigned weighted scores based on the following;

- history of landsliding,
- observations of landslide failure surfaces in exposures,
- the shape of the land (scarps, benches, hummocky ground, concave - convex),
- observations of groundwater, and
- human activity, for example, slope disturbance.

The scoring system was introduced to assist in assigning relative probabilities between geomorphological zones with subtle differences. The relative scores were then calibrated into probabilities by relating them to the history of sliding. The probability of debris sliding in the various zones, determined by this method, ranged from 10^{-1} to less than 5×10^{-3}.

The results achieved by both approaches are similar. Both approaches draw heavily on the presence of historic or previous landsliding. Fell stated that the scoring system was introduced to assist in assigning relative probabilities between geomorphological zones which have subtle differences with each other.

2.6 ASSESSING THE PROBABILITY OF LANDSLIDING

2.6.1 Conventional Deterministic Approach for slope stability analysis

Based on an appropriate geotechnical model and taking into account the local geological framework, it is usual to define the performance function of a slope in terms of the factor of safety, F. The factor of safety of a potential sliding mass may be defined very simply as the ratio of resisting forces to disturbing forces or a ratio of the corresponding moments for translational or rotational modes of failure respectively. More appropriately, however, it is often defined as the ratio of actual to mobilised shear strength at any location along a slip surface.

There are numerous methods of slope stability analysis applicable to slip surfaces of circular or arbitrary shape. Methods involving the subdivision of a sloping mass into vertical slices are most widely accepted. These include Bishop simplified method, Janbu method, Spencer Method, Morgenstern and Price method and Sarma method. In one of Sarma's methods the potential sliding mass can be subdivided into non-vertical slices or segments for purposes of analysis. In most other limit equilibrium methods only vertical slices are considered.

Some of these methods are more rigorous than others although all the methods are based on the concept of 'limit equilibrium'. In simpler methods, the interslice or sidewall forces are ignored while developing the expression for the factor of safety from the equilibrium equations. In the so called 'rigorous' methods both force and moment equilibrium are satisfied and the interslice forces are taken into consideration. Several of these methods are available as part of the software used during the analyses of three case study sites of land instability in Chapter 9 of this thesis The software used for these analyses is SLOPE W SLOPE/W Version 3.0 computer program by GEO-Slope International Limited.

Natural slopes often tend to fail along slip surfaces parallel to the ground surface. In such situations a much simpler 'infinite slope' model is often considered appropriate, especially when the strength parameters or slip surface are not well defined.

Having decided on the most appropriate geotechnical model and determined values of the geometrical and geotechnical parameters for a slope, a value of the factor of safety F may be determined. Thus the performance function, F, is single-valued and does not reflect the variability or uncertainty associated with the geotechnical parameters or with the geotechnical model itself. However, sensitivity analyses may be carried out to evaluate how the value of F changes with the variation in the values of individual parameters. Sensitivity analyses have been used in the case studies discussed in Chapter 9.

The conventional deterministic approach can be regarded as an individual and rather crude evaluation of the probability of landsliding. The greater the value of the calculated factor of safety, the lower the probability of overall failure or landsliding.

2.6.2 The rationale for a probabilistic approach

Soil deposits and bedrock materials are rarely homogenous and isotropic and it is appropriate to consider the variability of geotechnical parameters. Uncertainties are also associated with the laboratory or field tests used to estimate these parameters. These 'systematic uncertainties' can be as significant as those associated with natural variability. Moreover, there are uncertainties associated with geotechnical and geological models and methods of analysis.

Apart from spatial variability of geotechnical parameters and other uncertainties mentioned above, some parameters change with time. In particular, changes in pore water pressure with time are important and cannot always be predicted accurately.

The disturbing forces may also be subject to uncertainty and this aspect is most important when the behaviour of slopes during earthquakes is to be analysed. However, such analyses are outside the scope of this thesis.

Considering the uncertainties associated with the assessment of geotechnical parameters and geotechnical and geological models, one can appreciate the limitations of the deterministic approach. A unique factor of safety is, at best, a crude indicator of performance. Slopes with calculated factors of safety greater than 1 often fail. Conversely, it is also possible to grossly underestimate the performance of a slope and one may incorrectly predict failure or inadequate performance. Therefore, geotechnical researchers have devoted considerable effort to the development of probabilistic approaches.

The main outcome of a probabilistic analysis is p_f , the probability of failure. However, the role of a probabilistic approach is not merely to replace the factor of safety by the probability of failure, p_f.. The most important reason for developing or adopting a probabilistic approach is that the systematic analysis of uncertainty or variability can be addressed by such an approach. Another important reason is an acknowledgment of the fact that performance can not be characterised by a binary yes/no format and that there is always a probability of failure, however small.

Probability estimation facilitates the assessment of hazard and risk. Indeed the expected cost function associated with a failure event includes probability as a parameter. Thus one needs to supplement a deterministic analysis by a probabilistic one. Alternatively, subjective judgements have to be made about probabilities of failure. Indeed it may be necessary to rely on experience and engineering judgement to evaluate probabilities in some situations.

There are other important reasons for using probabilistic approaches which are again outside the scope of this thesis. Most importantly, the probabilistic framework enables new perspective's of performance. For example, the deterministic modelling of failure progression within a slope or geotechnical structure is not feasible. On the other hand, the probabilistic framework enables the development of models of progressive failure (Chowdhury and Grivas, 1983, and Chowdhury et al, 1987).

More directly relevant to slope performance and especially hazard and risk assessment of landslides are the concepts concerned with conditional events, conditional probability and total probability. Slope performance in terms of F or p_f. is often conditional on specific events. For example, slope performance may depend on triggering events such as rainfall. Therefore, the probability of occurrence of such an event (eg. a rainfall event of particular frequency and duration) is important in arriving at estimates of failure probability, hazard and risk in a given situation.

Updating of hazard or risk can also be facilitated within a probabilistic framework. Bayesian approaches have this potential and the application of such an approach to slope stability has been demonstrated by several researchers, eg. Chowdhury and Zhang (1993).

2.6.3 Calculation Methods for Probability of Failure

The basis of a probabilistic framework for analysis is the recognition that the calculated, or estimated, factor of safety reflects imperfect knowledge about site conditions such as slope geometry, shear strength parameters and pore water pressures. The factor of safety, F, is therefore, a random variable. Thus the factor of safety will be characterised by a probability distribution. Generally, this distribution is not known and it is necessary to assume its form, eg, normal or Gaussian, log-normal, beta, etc. Having chosen the form, the parameters of the distribution are then estimated from the data. Alternatively, Monte Carlo simulation is used to generate a probability distribution.

The random variable F depends on a number of parameters such as cohesion, angle of internal friction, unit weight and the pore water pressure. Any of these may also be regarded as a random variable, each with a characteristic probability distribution.

The statistical parameters of the factor of safety, F, such as the mean $\overline{F}$, and the standard deviation σ_F, can be estimated using well known methods such as (a) the First Order Second Moment method (FOSM) or (b) the Point Estimate Method (PEM) proposed by Rosenblueth (1975). Another alternative is (c) to generate the probability distribution of F from the known or assumed distributions of the basic geotechnical parameters, using the appropriate model or equation for F. The Monte Carlo simulation method is often used to achieve this. Once the probability distribution of F has been generated, its statistical parameters such as F and σ_F, can be derived reliably.

Having assumed or generated a distributions of F, the probability of failure is calculated based on the well known definition:

$$\mathbf{p_f = P[F \leq 1]}$$

Often, it is also useful to calculate the reliability index, β. One of the simplest definitions of the reliability index is as follows:

$$\boldsymbol{\beta} = \mathbf{[\,\overline{F} - 1]/\boldsymbol{\sigma}_F.}$$

This parameter is useful because it combines the expected value or mean of F with an estimate of its dispersion. It is also independent of the shape of the probability distribution which is unknown and has to be assumed or generated from other data.

Returning to calculated probability of failure mentioned earlier, the probability of the triggering event such as rainfall is not included in it. In general, therefore, the temporal probability can not be calculated directly in this way unless an appropriate formulation is adopted. However, if the probability of a significant rainfall event can be calculated, the conditional probability theorem may be used to calculate temporal probability, eg., the annual probability of failure. Detailed consideration of these probabilistic issues is outside the scope of this thesis. However, historical probabilities may be estimated as discussed below.

2.6.4 Historical failure probabilities

This approach involves the use of historical data regarding land instability. It can be explained by examples. Radbruch-Hall et al (1982) prepared a landslide overview map of the United States at 1:7,500,000 scale. Landslide “relative incidence” is shown by three categories (high, medium and low) in colour, depending on the area affected by landsliding as a percentage of the total area of each mapped geological group.

In the Shire of Lilydale, on the slopes of Mount Dandenong in Victoria, Australia, a debris flow occurred in 1891. Its volume was estimated to be 30,000m^3 and it travelled 2km down a slope (Moon et al 1992, and Fell 1992). The area is now an outer suburb of Melbourne and a similar debris flow today may result in the loss of many lives. On the basis of this one event and similar deposits locally, consideration of important contributing factors, geomorphological and geological mapping, and considerable experience amongst the practitioners, a relative risk ranking system was proposed and adopted for a specified area which includes the location of this debris flow. The temporal probability of debris sliding in the various zones ranged from 10^{-1} to less than 5×10^{-3}.

The use of historical data is applicable across most scales of investigation, from local area to regional, and even to national, as evidenced by Radbruch-Hall et al (1982). This method of assigning the probability of landsliding has been used during this research project, as discussed in Chapters 7 and 10.

2.6.5 Relationship between rainfall and landslide probabilities

Landsliding is often triggered by heavy or prolonged rainfall. Therefore it is important to determine a relationship between the two phenomena. This method of assessing probabilities of landsliding is most applicable to specific sites of instability, where a monitoring history has been established. However, with suitable data sets, inferences may be made concerning broader areas or regions. Several chapters of this thesis (Chapters 8 and 9) investigate the relationship between various periods and magnitudes of antecedent rainfall and the occurrence of landsliding in the study area. Therefore, no further discussion is included here.

2.6.6 Probabilities based on engineering judgement

This approach involves the use of appropriate local geomorphological and geotechnical data to estimate probabilities of failure or landsliding. The probabilities calculated in this way may be qualitative or relative. However, quantitative estimation may be made to some extent if detailed data sets are available. In a study of the Lake Macquarie City Council area, Fell and Flentje (1991), characterised numerous land units and subjectively assigned very general relative landsliding susceptibility to each land unit.

For areas where information for quantitative assessment is insufficient, more subjective observational techniques using a flow chart approach have been proposed (Fell, Walker and Finlay, 1996). This approach is based on the history of landsliding (yes/no), geomorphological evidence, geological and groundwater conditions, any subsurface investigation data, and the potential influence of existing or proposed development. A simplified version of this flow chart is shown in Figure 2.12. A field test of this method (Finlay 1996) has been summarised above in section 2.5.4.

2.7 FINAL COMMENTS

A Landslide Risk Management procedure has been proposed as shown in Figures 2.1 and 2.3, and discussed in the above sections, with some examples. However, none of the examples discussed above have followed precisely the seven levels of the proposed procedure. It is clear from these examples that one procedure will not be appropriate for all areas, or for all purposes. None the less, a framework can be developed using several or more of these levels. The purpose of each investigation should, to a large degree, determine the procedure to be used. Moreover, the resources available for the project have to be considered in deciding the scope and intensity of the system of hazard identification, risk analysis, assessment and management.

Initially, any procedure should be simple, with further development based on observation and research work. Field testing or validation of any procedure should be incorporated during its development. Such validations will determine the potential success of approaches for hazard identification, risk analysis, assessment and management.

One of the most basic principles in landslide hazard and risk assessment is that the past and present existence of land instability is often the key to understanding the future

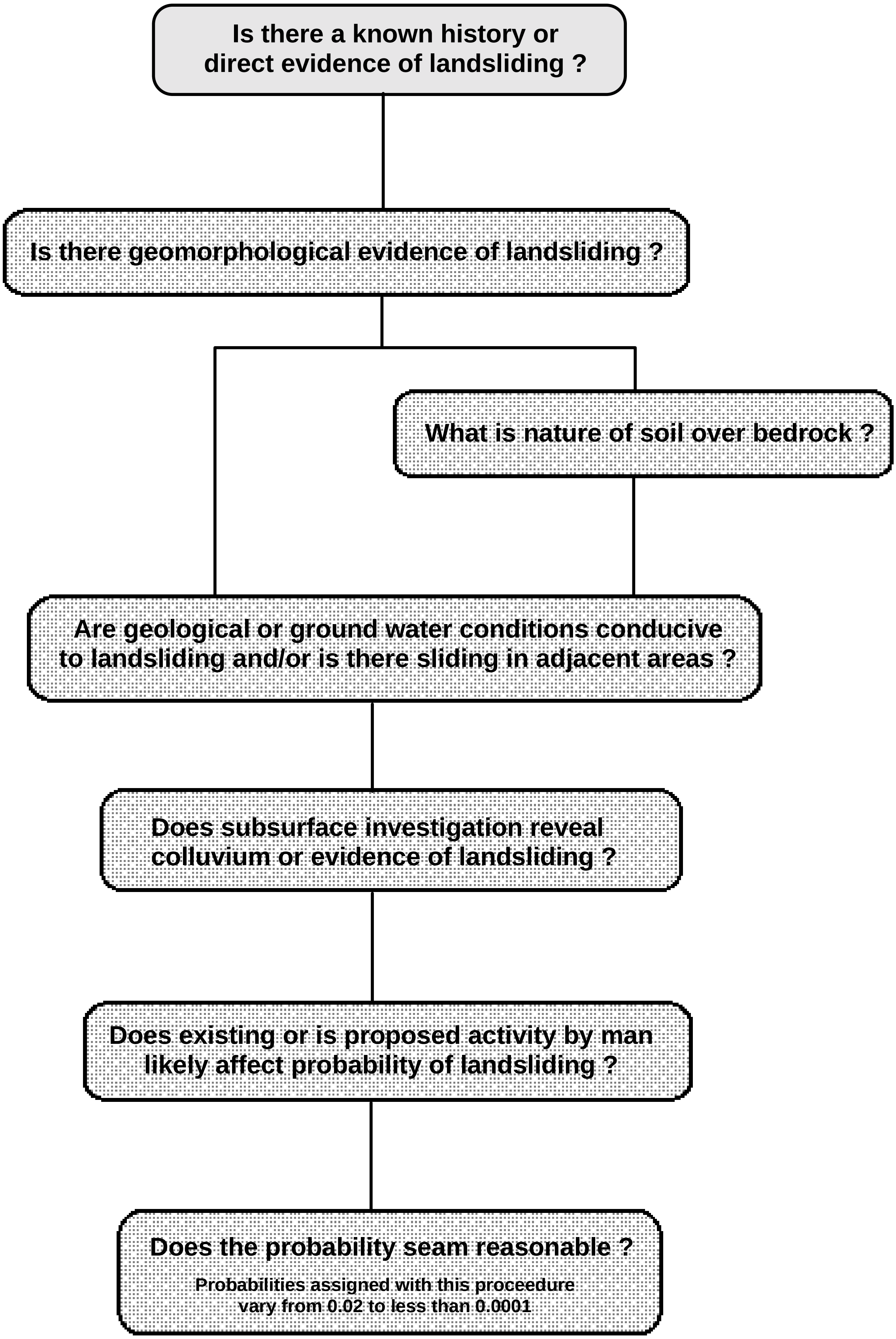


Figure 2.12 Simplified version of Fells flow chart probability procedure.

development of land instability. Hence when assessing land instability in any region, local experience is essential.

Risk assessment, and in particular quantitative risk assessment, is rapidly becoming the preferred tool in hazard and risk management of land instability internationally. Many research workers have emphasised, however, that absolute values of hazard or risk are of less significance compared with relative values. By evaluating risk it is feasible to develop an order of priority for actions to be taken, ranging from avoidance of development within higher hazard areas of land to more extensive and intensive studies.