Estimating the Probability of Landsliding

R. Fell
B.E., M.Eng.Sc., FIEAust., CPEng
Professor, School of Civil Engineering, UNSW, Australia
B.F. Walker
B.E., M.Sc., DIC., MIEAust., CPEng
Director, Jeffery and Katauskas Pty Ltd, Australia
P.J. Finlay
B.E., GradIEAust.
Research Student, School of Civil Engineering, UNSW, Australia

Summary If one is to use risk assessment methods for landsliding, it is necessary to estimate the probability of landsliding. This can be done on historic evidence, but in most cases sufficient data to do this is not available, and more subjective observational techniques are needed. This paper presents a method which uses a flowchart approach to assist users in quantifying probability of sliding. It is largely based on geomorphological inputs, is subjective and approximate, but is a useful starting point. An example is given of application of the method.

1. INTRODUCTION

Slope instability is widespread in urban and rural areas of Australia, New Zealand and other countries, and often impacts on houses and other development. This has been recognised by Local Government authorities and others, and has led to a requirement by many local government authorities for a "stability assessment" to be carried out by experienced geotechnical practitioners prior to allowing building development. In Australia this has largely been done using the method outlined in Walker et al (1985) as a basis. This method is largely based on the observational approach which is appropriate in most cases.

As discussed in Fell (1992a) the Walker et al (1985) method has several deficiencies including:

- the terms are poorly defined
- there is no consideration of the potential for loss of life
- there is no quantification of risk
- the method was developed for use in the Sydney Basin, which consists of sedimentary rocks, but has been adopted, largely without amendment in other geological environments, where it may not be valid.

In recognition of this, the Australian Geomechanics Society set up a sub committee to review and establish new guidelines. The first two authors are members of this committee (B.F. Walker is the Chairperson) which has progressed a long way towards developing new guidelines. It seems likely at this stage that the committee will recommend a more quantified approach based on risk assessment approaches.

In any case, some practitioners in Australia, Canada, Hong Kong and elsewhere are using risk assessment methods. Papers by Varnes (1984), Whitman (1984), Einstein (1988), Morgan et al (1992), Fell (1994) and Morgenstern (1995) give overviews on the subject.

There is no accepted standard approach or definitions for risk assessment, although the principles are consistent. For this paper the definitions given in Fell (1994) are adopted. These are:

Specific Risk (R_S) is probability (P) x vulnerability (V) for a given element, ie. $R_S = P \times V$.

Probability (P) is the probability that a particular landslide occurs within a given time, usually a year.

Vulnerability (V) is the degree of loss to a given element or set of elements within the area affected by the landslide(s). It is expressed on a scale of 0 (no damage) to 1 (total loss).

For loss of life, vulnerability is the probability that a particular life (the element at risk) will be lost given that the landslide occurs.

Elements at Risk (E) means the population, properties, and economic activities, including public services etc in the area potentially affected by the landslides.

To estimate risk, it is necessary to estimate the probability of landsliding. This can be done in several ways:

- use of historic data for the particular landslide under consideration. This may be available from landowners, councils, and consultants and is the most accurate way of assigning probability, particularly if related to causative effects, such as rainfall, construction activities etc
- use of historic data for a population of slopes in the vicinity of the area being studied, subject to consideration of topography, geology, construction activity etc. An example of such an approach for cuts is given in Fell, Finlay and

Mostyn (1996). This method first obtains the average probability for the population of slopes, and then determines relative probabilities for individual slopes based on analysis of the factors affecting probability

Often the historic data is related to rainfall, allowing the statistics of rainfall to quantify the probability. Examples are given in Siddle et al (1985), Lumb (1975), Premchitt et al (1994) and Fell et al (1988). Again, these methods allow estimation of the average probability of sliding for the population of slopes

- relating piezometric levels to rainfall and factors of safety. The method outlined in Fell et al (1991) is an example of this approach. Other examples are given in Haneberg (1991) and Okunishi and Okumura (1987). The methods are attractive in principle for larger, single slides for which detailed investigation and monitoring is available. However, they are of limited accuracy because of the heterogenity of landslides and the complex infiltration and drainage characteristics of landslides, and often need several years of records to calibrate
- use of geomorphological information for the site, and a judgemental approach to assigning probability. This may be calibrated by historic data.

This paper describes a geomorphological approach which was developed primarily by the first two authors as part of the AGS committee work, and gives an example of application of such an approach which was done by the first and third authors in suburban Melbourne.

2. THE PROPOSED METHOD FOR ESTIMATING PROBABILITY

The proposed method for estimating probability is shown in Figure 1. It is based on history of instability (if that is available), geomorphological evidence, geological and groundwater conditions, data from test pits/boreholes (if available), and the influence of existing or proposed development. It is applicable to landslides in soil and soil/weathered rock.

The flowchart has been developed based on the authors' experience in a wide range of geological environments. It is approximate and judgemental, and should not be followed slavishly, or used by persons with no understanding of slope instability processes and geomorphology.

The flow chart has several components which will now be discussed to give some of the background and qualifications:

A. History and/or direct evidence of landsliding

The history of landsliding of an area under study may be obtained from landowners, local councils, consultants and neighbours to the site. It may also be evident on old air or terrestrial photographs.

There may also be direct evidence of and times for landsliding from the landowner, or photographs. Examples are fences out of line (and) cracks or displacements in roads, and buildings, and in larger slides which have been instrumented, inclinometer and survey data.

It is best to relate these to rainfall to quantify the probability, but it is often difficult to properly determine whether landsliding is controlled by short or long period rainfall. Larger slides are often affected by one or more months of antecedent rainfall as well as shorter intense rain.

B. Geomorphological evidence of landsliding

It is not the purpose of this paper to describe geomorphological mapping, or the detail of features which can be identified which relate to landsliding. Reference should be made to Walker et al (1987).

Strong evidence of landsliding, relating to high probability (or recent occurrences of lower probability slides) can be exhibited by features such as:

- sharp changes in slope (freshly exposed soil scarps at the extreme)
- hummocky ground, particularly where adjacent slopes are more uniform
- reverse slopes, ponding of water, areas of reeds
- presence of colluvial soils, shear surfaces
- extensive areas of tilted or bent trees.

More subtle evidence of such features, eg. rounded changes of slope, gently hummocky ground, may be clear indication of landsliding, but because the features are smoothed out by time, they are likely to be older, and would be expected to have a lower probability.

Geomorphological mapping is best done systematically and presented in plan as shown in Figure 2. It is important to "think big" enough when doing such assessments. There is no point only looking at a single house block if it is part of a much larger landslide.

The flowchart (Figure 1) includes reference to whether the slope has been reshaped, eg. by farming, subdivision development, bulldozing, with the default don't know and yes cases assigned higher probabilities. This has been included based on the authors' experience on several sites, eg. a farm in a basalt area in Lilydale Shire, Melbourne, where slide scarps were smoothed over in less than a month by the owner/farmer by plough, and the Chelston St Landslide, Speers Point, NSW, where photographic evidence shows several 1m scarps in 1950, which were smoothed out by the owners sufficiently that two consultant groups failed to identify the area as a landslide in the 1970s and 80s.

C. No geomorphological evidence of landsliding

This part of the flowchart deals with sites where there is no identified geomorphological evidence of landsliding. Generally one would expect lower probability of sliding, since much or most landsliding is due to reactivation of old sliding. However, if slopes are steep enough (coupled with adverse groundwater) sliding may occur, but probably of relatively small magnitude. The slopes shown are the natural ground slope, not that from cuts and fills, and the probability relates to instability in the slope, not a cut or fill.

The soil depths, slopes and probabilities of sliding shown in the flowchart are very dependent on local geological and climatic conditions and should be treated with caution. It would be best to develop local criteria based on recorded data or experience. The figures shown are intended for use in the clayey soils derived from sedimentary rocks, such as in the Sydney Basin. It should also be noted that on a slope affected by overall sliding (which should show geomorphological features of sliding) the flatter parts of the slope may well have a higher probability of sliding in the case of particular geological sequences.

D. Geological and groundwater conditions

There are certain geological and groundwater conditions which are more conducive than others to landsliding. In Australia, the most landslide susceptible geological conditions are areas underlain by:

- tertiary (and others) basalts
- tertiary sediments
- coal measures
- interbedded fine and coarse grained; and fine grained sedimentary rocks
- volcanics.

Details are given in Fell (1992b).

Australia is not untypical, and instability is related to these conditions elsewhere. Locally, those who are carrying out landslide risk assessments should be familiar with the detail of geology where landsliding is prevalent. Eg. in the Newcastle-Lake Macquarie area in New South Wales the area underlain by the Fassifern and Great Northern coal seams, and Awaba Tuff in between is the most landslide prone zone within the coal measures. This sort of knowledge, coupled with observations of landsliding in areas adjacent the study area, should be used to judge whether sliding is more or less probable.

Such knowledge can also be used to assess the probability of large and small scale instability. Hence, one could have two assessments, eg. a low probability of large scale landsliding, and a high probability of small scale landsliding.

E. Information from test pits, boreholes, exposures

Data from test pits, boreholes and exposure in road cuts etc is invaluable in increasing the confidence with which an assessment of probability can be made. In particular, such investigation can expose colluvial soils (of landslide origin) which would lead one to an estimate of high probability of sliding, or expose shallow soil over weathered rock, in which case one would estimate low probability.

F. Effect of construction work

Cutting, filling, redirection and interruption of surface and subsurface drainage can reduce or increase the probability of sliding. In many assessments it will be necessary to assess the probability as the site is inspected, and then make an assessment of the effect of construction on the probability. Many sites may be judged high probability of sliding as inspected (particularly for small scale instability, eg. of an unsupported road cut, which could extend to overall instability) but low probability if properly developed. Walker et al (1985) includes sketches of good and bad hillside practice.

G. Reassess when more data is available

The assessment of probability of sliding may be iterative, with reassessment as more data becomes available, eg:

- after assessing in detail the regrading of a site
- when subsurface data becomes available
- when the effects of development are considered.

H. Sanity check

At the end of the assessment, the practitioner should step back and make a sanity check on the answer; and be willing to seek more data to firm up the accuracy of the assessment. Often the outcome will be a range of probabilities, and the range may need to be narrowed by more detailed investigation. Even then, by the nature of the problem, a range with up to an order of magnitude variation or more in probability would not be unusual.

The proposed method is designed to assess the probability of sliding. It does not directly give an estimate or probability of the slide flowing a large distance, eg. as a debris flow. One would assess the probability of a debris flow by first assessing the probability of sliding, and multiplying this by the conditional probability that if a slide occurs, what probability is there it will flow . This was done in the study of debris flow in Montrose, Victoria (Moon et al, 1992) which the first author was involved in.

3. CASE STUDY — KALORAMA, VICTORIA

As part of his studies for his PhD, Finlay (1996), the third author undertook a study of part of Kalorama, which is in the Dandenong Ranges, Melbourne, to assess landslide risk.

This area had mostly been designated as "high risk" in a slope stability zoning study carried out for Lilydale Council by Coffey Partners International (Coffey, 1991).

The area is underlain by acid volcanic rocks with relatively deep soil cover. It was originally developed as orchards in the early 1800s and subdivided for housing in the 1970s.

This study involved preparation of a geomorphological map of the area based on contours, and a walk over survey. This is reproduced in Figure 2, along with geomorphological zone boundaries. This study did not include access to private properties so the boundaries are approximate, and the mapping and outcomes should only be considered as an academic exercise, not one to be used for any planning purposes.

The study also involved a review of the history of sliding in the area, which was described in a book on the history of the area by Lundy-Clarke (1975). This allowed identification of some areas subjected to landsliding in 1850, 1891 and 1934. The earlier sliding may have been influenced by clearing of what is now heavily timbered land for orchards.

Two approaches were taken for the study. The first involved assessment using Figure 1. The second was a site specific approach (a scoring system), which consisted of assigning weighting scores based on history of sliding, the observations of landslide failure surfaces in exposures, the "shape of the land", observations of groundwater and man's activity. Table 1 contains the assessed probability of landsliding in the study area using both approaches. The factors using the first approach (Figure 1) are detailed in Table 1. For the second approach (the scoring system) only the final assessed probabilities of sliding for small and large landslides are reproduced in Table 1.

Comparison of the results of both approaches in Table 1 shows similar results, which is not unexpected, because both are to an extent controlled by the historic values.

The "scoring" system was introduced to assist in assigning relative probabilities between geomorphological zones which were subtly different to each other. This was done by differentiating between:

- areas with scarps and benches, individual scarps, single bench without scarp and uniform slopes, (these grading from the most likely to reflect active sliding in this geological environment)
- superimposed on this relatively large scale morphology are areas of small scale irregularity in the ground surface. These areas were given a greater weighting to indicate higher probability of sliding
- the general shape of the area in plan was differentiated into convex (least likely to slide), uniform, and concave (most likely to slide).

The score components and total scores are given in Table 2. These scores were then calibrated into probabilities by relating to the history of sliding.

4. CONCLUSIONS

The proposed method for assessing probability of landsliding is approximate and will require judgement from persons experienced in landsliding and geomorphology to apply it with confidence. It will be useful in obtaining order of magnitude probabilities for use in risk assessment.

It is essential that local experience with geomorphology, geology and history of sliding be used to adjust and calibrate the flowchart for the particular locale.

The method has been trialled in a workshop situation where about fifteen experienced geotechnical practitioners attended. Of these, about ten had used the method, and checks had been made by the first author on six sites. Reasonable consistency was obtained, and modifications since then, plus the more detailed description given in this paper should ensure reasonable outcomes. Nothing will prevent some errors in these assessment, either through lack of observational ability, or an unwillingness to accept that sliding may have a high probability. In reality, the method should assist in reducing the range of assessments by suggesting a logical approach, and giving guidance on absolute values.

5. ACKNOWLEDGEMENTS

The authors would like to acknowledge the significantcontribution of the other members of the AGS Committee — Alan Moon, John Braybrooke, Warwick Davies, Peter Volk, Andrew Leventhal and Fred Baynes, as well as those others who attended the workshop. The first and third author would also like to acknowledge the financial support of Lilydale Council for carrying out the Kalorama work.

6. REFERENCES

Coffey Partners International (1991). Shire of Lillydale. *Study of the Risk of Debris Flows and Other Landslips.*, Report No. M2120/1-A5.

Einstein, H.H. (1988). Special Lecture. Landslide Risk Evaluation Procedure. *Proc. Fifth Int. Symp. on Landslides*, Lausanne, pp. 1075-1090.

Fell, R., Mostyn, G.R., Maguire, P., O'Keeffe, L. (1988). Assessment of the Probability of Rain Induced Landsliding. *Fifth Australia New Zealand Conference on Geomechanics*, Sydney, 22-23 August, pp. 72-77.

Fell, R., Chapman, T.G., Maguire, P.K. (1991). A Model for Prediction of Piezometric Levels in

Landslides, in *Slope Stability Engineering*, Thomas Telford, pp. 37-42.

Fell, R. (1992a). Some Landslide Risk Zoning Schemes in Use in Eastern Australia and Their Application. *Sixth Australian New Zealand Conference on Geomechanics*, Christchurch, pp. 505-512.

Fell, R. (1992b). Keynote Paper: Landslides in Australia (Ed. D. Bell), *Proc. 6th Int. Symp. on Landslides*, Christchurch, 10-14 February, pp. 2059-2100.

Fell, R. (1994). Landslide Risk Assessment and Acceptable Risk, *Canadian Geotechnical Journal*, Vol No. 31, pp. 261-272.

Fell, R., Finlay, P.J. and Mostyn, G.R. (1996). Framework for Assessing the Probability of Sliding of Cut Slopes, ISL 96. *7th Int. Symp. on Landslides*, Trondheim, Norway, June 17-21 (in press).

Finlay, P.J. (1996). The Risk Assessment of Slopes. *PhD Thesis*, University of New South Wales, Sydney, Australia (in preparation).

Haneberg, W. (1991). Observation and Analysis of Pore Pressure Fluctuations in a Thin Colluvial Landslide Complex Near Cincinnati, Ohio, *Engineering Geology*, 31, pp. 159-184.

Lumb, P. (1975). Slope Failures in Hong Kong, *Quarterly Journal of Engineering Geology*, 8, pp. 31-65.

Lundy-Clarke, J. (1975). *The Mountains of Struggle*, Melbourne, Australia, Lundy-Clarke (self published book).

Moon, A.T., Olds, R.J., Wilson, R.A. and Burman, B.C. (1992). Debris Flow Risk Zoning at Montrose, Victoria. *Proc. Sixth ISL*, Christchurch, February (Ed. D. Bell), Balkema.

Morgan, G.C., Rawlings, G.E. and Sobkowicz, J.C. (1992). Evaluating Total Risk to Communities from Large Debris Flows, *in Geotechnique and Natural Hazards*, BiTech Publishers, pp. 225-236.

Morgernstern, N.R. (1995). Managing Risk in Geotechnical Engineering. *Proc. Xth ISSMFE*, Pan American Regional Conference, October 30-November 4, Guadalajara.

Okunishi, K. and Okumura, T. (1987). Groundwater Models for Mountain Slopes, in *Slope Stability* (Eds. M.G. Anderson and K.S. Richards), Wiley, pp. 265-285.

Premchitt, J., Brand, E.W. and Chen, P.Y.M. (1994). Rain-Induced Landslides in Hong Kong 1972-1992, *Asia Engineer*, June, pp. 43-51.

Siddle, R.C., Pearce, A.J. and O'Loughlin, C.L. (1985). Hillslope Stability and Landuse, *American Geophysical Union*, Water Resources Monograph.

Varnes, D.J. (1984). Landslide Hazard Zonation, A Review of Principles and Practice, *Natural Hazards*, 3, UNESCO.

Walker, B.F., Blong, R.J., MacGregor, J.P. (1987). Landslide Classification, Geo-morphology and Site Investigation, in Soil Slope Instability and Stabilization (Eds. B.F. Walker and R. Fell), Balkema, pp. 1-52.

Walker, B.F., Dale, M., Fell, R., Jeffery, R., Leventhal, A., McMahon, M., Mostyn, G. and Phillips, A. (1985). Geotechnical risk Associated with Hillside Development, *Australian Geomechanics News*, No. 10, pp. 29-35.

Whitman, R.V. (1984). Evaluating Calculated Risk in Geotechnical Engineering, *JASCE Geotechnical Engineering*, Vol. 110, No. 2, pp. 145-188.

Table 1. Assessment of probability of sliding in the Kalorama study area.

Sub-zone area	Assessment based on Figure 1.													Assessment based on the scoring system[1]	
	Historical Sliding		Geomorphological evidence		Nature of Soil		Geological/Groundwater		Test Pits/Exposure		Degree of Development		Assessed probability range	Landslide Type	
	Y/N	P	Assess	P	Assess	P	Y/N	P	Y/N	P	1–4	P		Small	Large
A	Y	0.02	strong–very strong	0.1–0.02	N/A	–	Y	0.1–0.05	Y	0.1–0.05	3	0.1	0.1–0.05	0.050	0.020
A'	M	0.02	strong	0.1–0.02	N/A	–	Y	0.1–0.05	–	–	3	0.1	0.1–0.05	0.025	0.005
B	N	–	subtle–none	0.05–.01	C	0.05–0.01	Y	0.05–0.01	C	0.02–0.005	1	0.005	0.01–0.005	0.010	0.001
C	N	–	–	<0.005	C	0.005	N	<0.005	C	0.02–0.005	3	0.02–0.01	0.01–0.005	0.010	0.001
C'	N	–	subtle–none	0.2–0.02	C	0.2–0.02	N	0.02–0.005	–	–	3	0.02–0.005	0.02–0.005	0.010	0.001
D	N	–	–	<0.005	?	<0.005	N	<0.005	–	–	1	<0.005	<0.005	0.005	0.001
H'	N	–	subtle	0.1–0.05	N/A	–	Y	0.1–0.05	–	–	2	0.05	0.1–0.05	0.013	0.002
I	N	–	–	0.05–0.01	C	<0.005	Y	0.05–0.02	–	–	4	0.05–0.02	0.05–0.02	0.013	0.002
K	N	–	–	<0.005	C	<0.005	some	0.005	–	–	2	0.005	0.005	0.013	0.002
L	N	–	subtle	0.1–0.05	N/A	–	N	0.1–0.05	–	–	3	0.1	0.1–0.05	0.013	0.002
P	M	0.02	strong	0.1–0.05	N/A	–	N	0.1–0.05	–	–	4	0.1	0.1–0.05	0.033	0.010
Q	M	0.02	subtle	0.1–0.02	N/A	–	N	0.1–0.02	–	–	3	0.1–0.05	0.1–0.05	0.020	0.003
R	N	–	strong	0.1–0.05	N/A	–	N	0.1–0.05	Y	0.1	2	0.1–0.05	0.1–0.05	0.025	0.005
R'	N	–	subtle	0.1–0.02	N/A	–	Y	0.1–0.02	–	–	2	0.1–0.05	0.1–0.05	0.013	0.002
S	N	–	strong	0.1–0.02	N/A	–	moist	0.1–0.02	–	–	3	0.1–0.05	0.1–0.05	0.025	0.005
T	N	–	strong	0.1–0.02	N/A	–	moist	0.1–0.02	–	–	3	0.1–0.05	0.1–0.05	0.025	0.005
T'	N	–	subtle	0.1–0.02	N/A	–	N	0.1–0.02	–	–	3	0.1–0.05	0.1–0.05	0.013	0.002
W	N	–	subtle	0.1–0.02	N/A	–	N	0.1–0.02	–	–	3	0.1–0.05	0.1–0.05	0.020	0.003
W'	N	–	–	<0.005	?	<0.005	N	<0.005	–	–	3	0.005	<0.005	0.013	0.002

1. See section 3 in text for description of the scoring system.

Table 2. Assessment of scores (relative probability of landsliding) in Kalorama study area.

Sub–zone area[1]	Total Score	Components of Score							
		Historical Landslides	Slide Planes	Shape of the Land			Groundwater	Man's Activity	
				Scarps/Benching	Uneven	Shape in plan		Clearing	Earthworks
		Yes=4 Maybe=2 No=0	Present=2 Absent=0	Scarps and benching=3 Scarps=2 Benching=1, Otherwise=0	Yes=2 Maybe=1 No–0	Concave=2 Uniform=1 Convex=0	Springs=2 Moist=1 Dry=0	Cleared=2 Lightly vegetated=1 Vegetated=0	Reshaped significantly=2 Reshaped=1 Untouched=0
A	14	4	0	3	1	2	1	1	2
A'	10	2	0	1	1	2	1	1	2
B	3	0	0	1	0	1	0	0	1
C	3	0	0	0	0	0	0	1	2
C'	4	0	0	1	0	0	0	2	1
D	1	0	0	0	0	0	0	1	0
H'	5	0	0	1	1	1	0	1	1
I	5	0	0	0	0	0	1	2	2
K	5	0	0	0	1	1	1	1	1
L	6 (8)	0 (2)	0	1	1	1	0	2	1
P	12	2	0	3	2	1	0	2	2
Q	7	2	0	1	1	0	0	2	1
R	10	0	2	3	1	2	0	1	1
R'	5	0	0	0	1	2	0	1	1
S	10 (12)	0 (2)	0	3	2	1	1	2	1
T	9	0	0	2	2	1	1	2	1
T'	5	0	0	0	1	1	0	1	2
W	7	0	0	1	2	1	0	2	1
W'	5	0	0	0	0	2	0	2	1

1. Numbers in brackets indicate possible historical landsliding in the sub-zone.

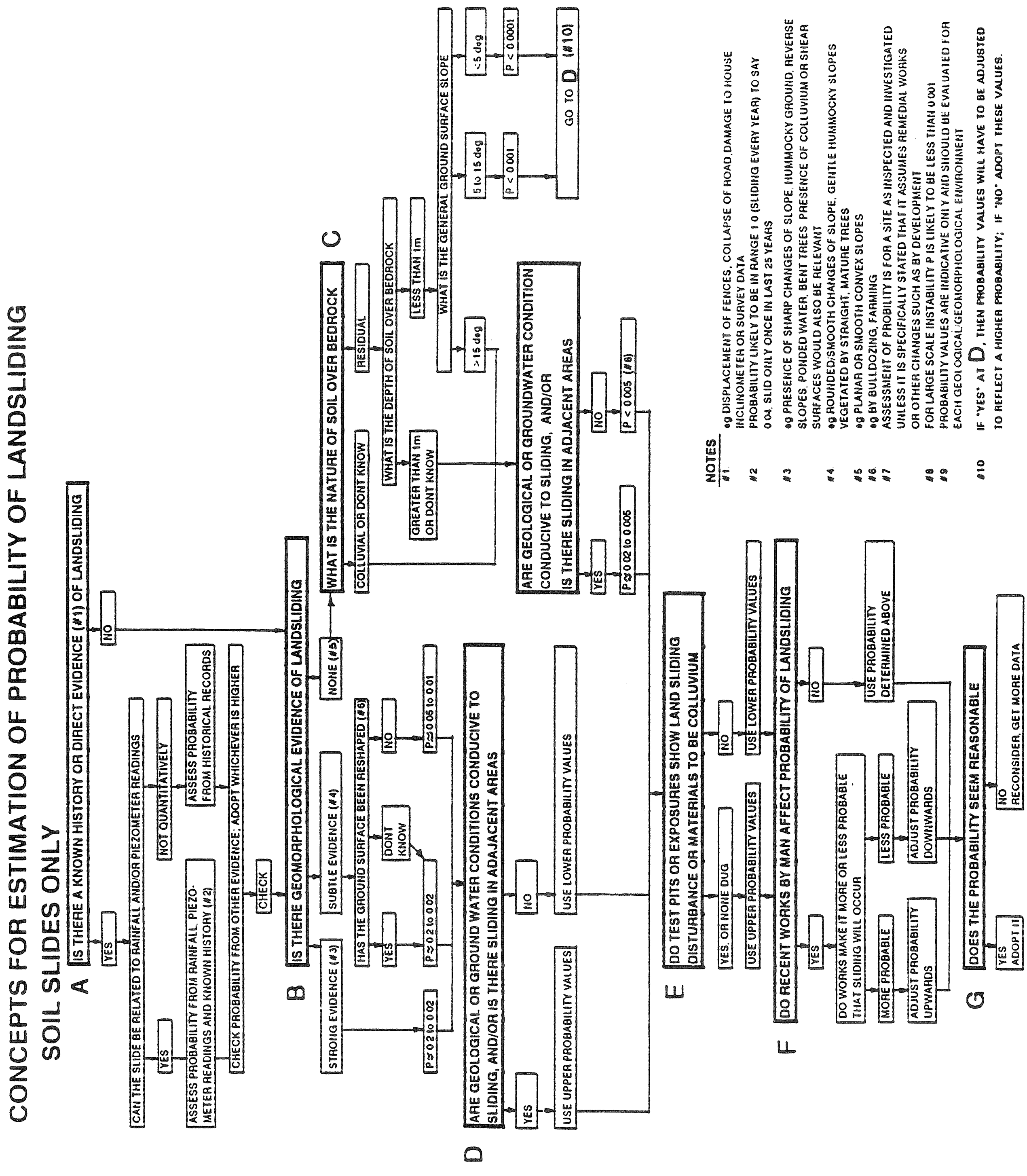
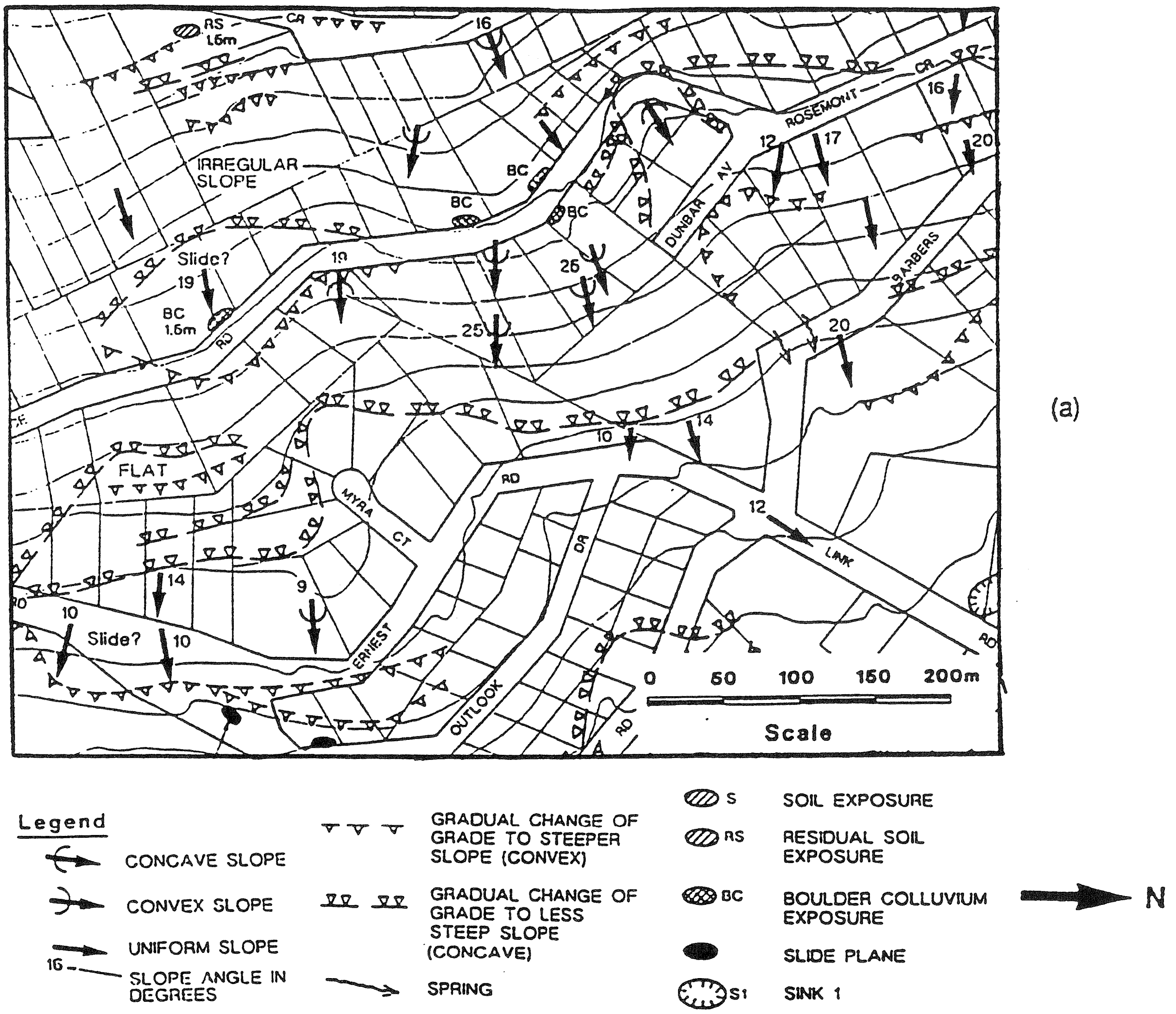
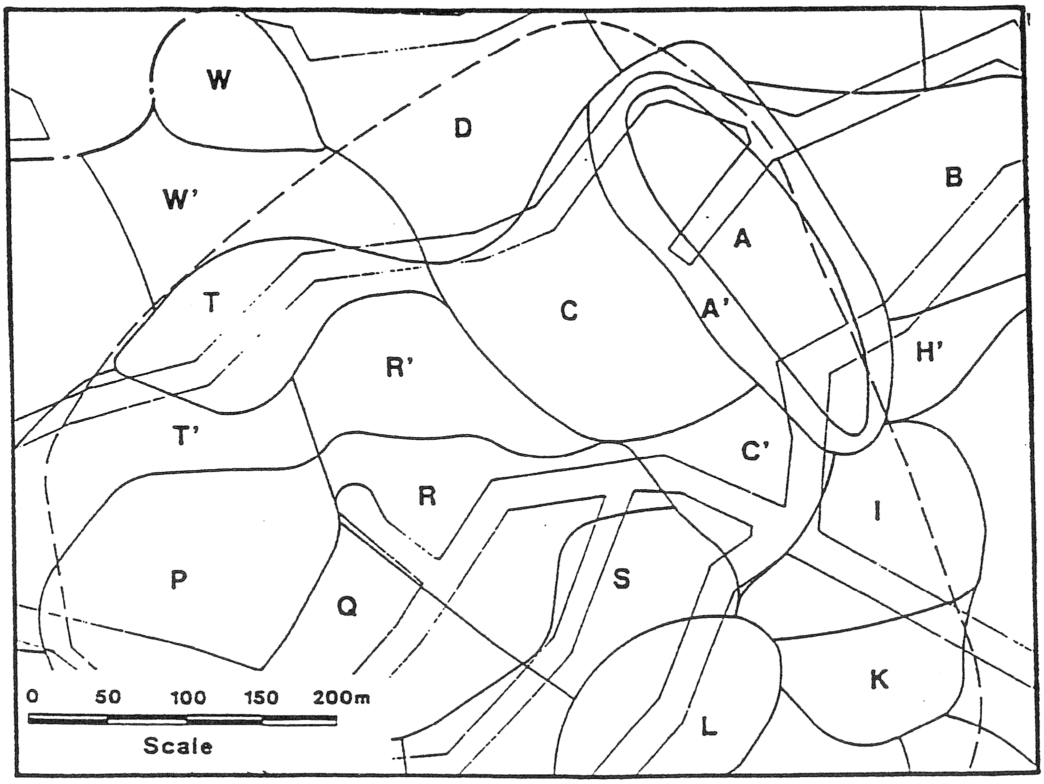


Figure 1. Flowchart for the assessment of the probability of landsliding.



(a)



(b)

Figure 2. Kalorama area — (a) Geomorphology map; (b) Risk zones.