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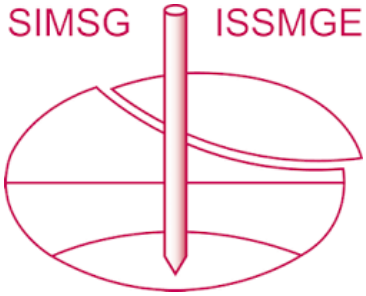

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Will it happen? - Quantitative judgements of landslide likelihood

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Summary: Application of risk management principles to slope management has led to increasing attempts at quantifying landslide likelihood. In doing so, judgements are made about whether or not particular events will happen. The judged probability is a measure of the degree of belief that a person has that the event will occur, rather than an answer that can be found by analysis. It is essential to present and discuss the evidence on which each judgement is based. Six likelihood terms are presented which cover broad ranges about which realistic judgements can be made. Examples of how these terms can be used in practice are given. The need to be open about uncertainty and realistic about what is really known is discussed.

WHY QUANTIFY LANDSLIDE LIKELIHOOD

Judging how often and how much an existing landslide will move is difficult. Judging the likelihood of a new landslide occurring is even harder. Until recently, it has been common practice to describe the likelihood of a landside occurring using relative terms such as possible, unlikely, etc. Increasing application of risk management principles to engineering in general, and slope management in particular, has led to increasing awareness of the limitations of using purely relative, unquantified terms. Quantification is discussed and encouraged in recent papers on landslide risk management (eg Australian Geomechanics Society, 2000 and Ho et al, 2000). Without some attempt at quantification, however limited, it is difficult to compare risks from different sources and make informed decisions on priorities and where to spend limited resources.

The purpose of this paper is to discuss some of the issues associated with quantifying landslide likelihood, and the benefits and limitations of quantification. Six likelihood terms which we have found useful in practice are presented. In this paper the term likelihood is used to refer to judgements of probability.

JUDGEMENT, EVIDENCE AND EXPERTISE

Judgements not answers

The assessed probability of a particular event (or series of events) is not a property inherent to the event(s). The particular event (e.g. first time earth slide on a suburban block) or series of events (e.g. rock fall, rolling down slope, across road, into building, demolishing wall etc.) will either happen or not happen in the time frame of interest. There is no right answer (unique probability) that can be found by analysis. We make judgements about the probability because we do not know whether or not the event will happen.

The judged or subjective probability of an event has been described as:

- *"the degree of belief that a person has that it will occur given all the relevant information known to that person"* (Morgan and Henrion, 1990);
- *"what the evidence permits one to believe it to be"* (Hartford, 1998); and
- *"degree of credibility or confidence dictated by the evidence...evidence based probability"* (Kaplan, 1997).

Kaplan (1997) and Vick (2002) explain the central role of evidence and logical inference to subjective probability and engineering judgement. Although the assessed probability of an event is a subjective judgement, it should, like a bookmaker's odds, be based on evidence.

Assembling, understanding and interpreting the evidence

The evidence on which judgements of landslide likelihood are based has to be assembled, understood and interpreted. This process involves developing a slope model that reflects a sound knowledge of how the slope was formed, how it behaved in the past and how it might behave in the future. The ability to build up such a model comes from knowledge of the slope and its surrounds, knowledge of similar slopes in similar environments, and a range of skills and knowledge bases that result from training and experience.

Geological knowledge, skills and experience are essential to the development of slope models. Seddon, (1996) and Baynes, (1999) describe some of the distinctive characteristics of geological practice including:

- linking knowledge from superficially unrelated data sources;
- using multiple working hypotheses;
- an awareness of a range of timescales;
- recognising the importance of extensive field experience; and
- using drawings (including plans and sections) and photographs to communicate.

Stapledon (1995), Baynes and Lee (1998) and Hutchinson (2001) provide specific guidance on the development of slope models and techniques to support landslide likelihood judgements. Stapledon (1995) describes the central role of geological modelling in landslide investigations, lists typical questions that need to be asked and explains how to go about answering them. Baynes and Lee (1998) explain how geomorphological principles and techniques can support quantified judgements of landslide likelihood, and Hutchinson (2001) provides excellent practical examples of what geomorphology can contribute to the understanding of slopes on engineering projects.

Particular skills and knowledge bases relevant to developing slope models include understanding of:

- slope failure mechanisms (e.g. Leroueil, 2001);
- landslide travel distances and speeds (e.g. Hunter and Fell, 2002);
- the relation between landslides and the intensity and duration of rainfall (e.g. Flentje and Chowdhury, 2002);
- landslide hydrogeology (e.g. Macfarlane and Pattle, 1991 and Leroueil, 2001); and
- landslide process rates (e.g. Baynes and Lee, 1998 and Moon et al, 1996).

The range of skills and knowledge bases used when assessing landslide likelihood can be very wide. For example, Moon (1997) describes an initial assessment of the likelihood of a landslide carried out by a risk workshop group in which *"the group had to use knowledge, insight and understanding, of at least the following:*

- *slope development processes;*
- *periglacial processes;*
- *fluvioglacial terraces;*
- *long and short term climatic change;*
- *long and short term changes in flora and fauna;*
- *tectonic processes (including folding, uplift rates and seismicity);*
- *dating methods (e.g. thermoluminescence);*
- *effects of European settlement and changes in land management practices;*
- *soil formation processes and soil association;*
- *landslide response to inundation ..."*

The expertise of the assessor and presenting the evidence

With so much judgement involved in assessing landslide likelihood, the experience and expertise (skills, knowledge, insight and understanding) of the assessor are critically important to the quality of the judgement. Kaplan (1997) emphasises that *"we should never ask an expert for his opinion. What we want from an expert is, his experience, his information, his evidence"* and warns about *"opinions, personalities, moods, politics, positions, special interests, or wishful thinking"* getting in the way of the evidence.

Opinions on landslide likelihood without presentation and discussion of evidence are of limited value. Such opinions cannot be evaluated against other people's experience and knowledge or reviewed in the light of new evidence. Interpretations and opinions change (and should be continually reviewed) but primary evidence (such as careful field observations) increases in value with time.

LANDSLIDE LIKELIHOOD RANGES AND TERMS

Hartford (1998) discusses protocols for eliciting expert judgements including "word mapping" schemes that explore the links between qualitative and quantitative terms for probability. Morgan and Henrion (1990) point out that the interpretation of words is *"very context dependent"* and that it *"seems wiser to seek clear specifications of the events and quantities used in models ... to avoid linguistic imprecision as a source of uncertainty."* In developing likelihood terms, our approach has been to explicitly define the probability ranges to be judged, to avoid unnecessary confusion about the meaning of words (such as unlikely).

Likelihood terms, which we have found useful in practice, are given in Table 1.

Table 1. Likelihood ranges and terms

Judged indicative annual probability	**Implied indicative landslide recurrence interval**	**Term**	**Example - Implied likelihood of landslide in a 50 year design life** [1]
Greater than 0.2	Less than 5 years	Extremely	Almost 100%
0.2 to 0.02	5 to 50 years	Very Likely	64% to almost 100%
0.02 to 0.002	50 to 500 years	Likely	10% to 64%
0.002 to 0.0002	500 to 5,000 years	Possible	1% to 10%
Less than 0.0002	More than 5,000 years	Unlikely	Less than 1%
Very much less than 0.0002	Very much more than 5,000 years	Very Unlikely	Very much less than 1%

[1] The implied likelihood (P_L) of a landslide in the design life (e.g. 50 years) is calculated from the equation: $P_L = 1 - (1 - p)^L$ where p is the judged indicative annual probability and L is the design life.

The likelihood terms are directly related to "indicative annual probability", as opposed to "indicative landslide recurrence interval". This is because the latter can carry a connotation that judgements are being made about long periods of time based on long periods of evidence (Heidebrecht et al, 1983). However, because likelihood evidence relates to years not abstract numbers (e.g. year of last slope movement, return period of landslide inducing rainstorms), many practitioners find it easier to think in terms of "landslide recurrence intervals", and then convert the judgements to annual probabilities. In practice, it is also useful to present the "implied likelihood of a landslide in the design life" for the project, as shown in the example in the last column of Table 1.

The judged probability ranges adopted are compatible with the typical design life of structures and the ranges used when assessing other hazards (e.g. earthquakes). Order-of-magnitude ranges about which realistic judgements can be made are used (i.e. the ranges do not imply unrealistic understanding). We have deliberately not quantified the boundary between Unlikely and Very Unlikely because it is usually unrealistic to do so. However, on some projects, we have found it practical to make the subdivision qualitatively based on relative variations in likelihood within the Unlikely range. This subdivision of likelihood, in combination with consequence assessments, is useful in providing a finer subdivision of risk in risk assessments.

When assessing landslide likelihood, care needs to be taken to recognise and explain situations where landslide likelihood changes with time. For example, a landslide near a coastal cliff may be Unlikely now but may become Very Likely in the future because of coastal erosion.

In our experience it is not necessary to use the likelihood ranges for every project. For example, the terms are not useful to describe very frequent events (e.g. many per year). Also, on projects where only one or two judgements of likelihood are required, direct explanations of likelihood such as *"on average large rock slides are likely to occur every 10 to 20 years"* avoid the need to define and discuss likelihood terms.

We consider the likelihood terms in Table 1 to be more generally applicable than the likelihood terms included in the example provided in Appendix G of Australian Geomechanics Society (2000). In the Appendix G example, the descriptive terms for landslide likelihood are linked to implied ranges of annual probability in order of magnitude steps ranging down to less than 10^{-6} (1 in more than a million), with a note on their variability from which ranges can be implied. In our experience, there is usually insufficient evidence to differentiate the lower probability terms in the Appendix G example. Also, most practitioners find it easier to work with explicitly defined ranges such as those given in Table 1. To avoid unnecessary confusion, we have used the same descriptive terms for landslide likelihood in Table 1 as those used in the Appendix G example, where the implied ranges of annual probability significantly overlap (Likely, Possible and Unlikely).

LANDSLIDE LIKELIHOOD TERMS IN PRACTICE

The following examples show how the landslide likelihood terms given in Table 1 can be used in practice.

Different likelihoods for different amounts and rates of movement

Table 2 is based on a summary of a risk assessment for a large landslide complex on which there is a variety of different infrastructure. This example illustrates how it can be useful to assess the likelihood separately for different amounts and rates of movement, in different parts of the landslide complex, where such movements are associated with different consequences (and risks).

Part of landslide	What might happen – speed and extent of movements in a landslide event		Likelihood	Consequence [2]	Risk [2]
Headscarp and southern boundary	Slow [1]	Less than 10 mm	Very Likely	Minor	High
		10 mm to 0.1 m	Likely	Moderate	High
		0.1 m to 1 m	Possible	Severe	High
		1 m to 10 m	Unlikely	Severe	Medium
		Greater than 10 m	Very Unlikely	Severe	Low
	Rapid	Greater than 1 m	Very Unlikely	Severe	Low
Eastern toe area	Slow	Less than 10 mm	Very Likely	Insignificant	Low
		10 mm to 0.1 m	Very Likely	Insignificant	Low
		0.1 m to 1 m	Likely	Minor	Medium
		1 m to 10 m	Possible	Moderate	Medium
		Greater than 10 m	Unlikely	Moderate	Low
	Rapid	Greater than 1 m	Unlikely	Moderate	Low

Notes: [1] The boundary between slow and rapid movement was defined as 10 mm per hour for this project.
[2] Definition and discussion of the consequence and risk terms are outside the scope of this paper.

Amount of movement in a single event may be important

In a project involving infrastructure construction where there are existing landslides, the key issue may be what might happen in a single landslide event. In the example given in Table 3, the design life is 25 years but temporary works (for say 1 year) are also considered. This example shows how the relevant judgements and the implied likelihoods of the events for the relevant time frames could be summarised to help in project planning and design.

No	Judged total movements		What might happen in an individual landslide event (over minutes, hours or days)			
	To date	In next 25 years	Amount of movement	Likelihood	Implied likelihood - In 25 years	In 1 year
1	Several metres	A metre or so	At least 0.1 m	Very Likely	40% to almost 100%	2% to 20%
			At least 0.1 to 1 m	Likely	5% to 40%	0.2% to 2%
			At least 1 m	Possible	0.5% to 5%	0.02% to 0.2%
2	Several 10s of metres	Several metres or more	At least 0.1 m	Extremely Likely	Almost 100%	More than 20%
			At least 0.1 to 1 m	Extremely Likely	Almost 100%	More than 20%
			At least 1 m	Very Likely	40% to almost 100%	2% to 20%

Different types of landslides from the same source

Different types of landslide with different likelihoods may occur on the same slope. Powell (2000) gives an example of a risk assessment for a road cutting on a major highway. Four different types of landslide ranging from small debris flows to large rock slides (overall collapse) were considered. The small debris flows were judged Extremely Likely although their likelihood decreased after the first year. The likelihood of overall collapse (referred to as very low by Powell) could have been described as Very Unlikely using the terms given in Table 1.

Landslide likelihood and hazard zoning

The likelihood ranges given in Table 1 can also be used directly in hazard assessment and hazard zoning (where consequences are not differentiated). Hazard assessment and zoning are useful in the following situations:

- at the planning stage before development or as a first step in establishing development controls and management plans for existing development;
- when it is not practical or useful to differentiate the consequences (e.g. when there are many different potential consequences and / or the client is risk adverse); and
- When clients understand the consequences and do not want to pay to be told what they already know.

A DIFFERENT APPROACH FOR CONSEQUENCES

Risk management involves assessment and evaluation of likelihood and consequences. Although definition and discussion of consequences and risk is beyond the scope of this paper, it is important to understand that there are fundamental differences between the assessment of likelihood and the assessment of consequences. The assessment of likelihood is an evidence-based judgement best carried out by an appropriate expert. With consequences, the expert can help by explaining what and who might be affected, and what damage or injury might occur. However, the assessment of the importance (or seriousness) of the consequences is, in the end, a value judgement best made by those most affected (e.g. client, owner, regulator, public). Risk is then a product of evidence based judgements and value judgements.

As explained in Australian Geomechanics Society (2000) there can be many direct and indirect consequences of a landslide which can be difficult to anticipate, let alone quantify and cost. The situation is analogous to the cost of work place accidents. Such costs are often difficult to quantify, and the hidden costs can range from less than one to more than 20 times the visible direct costs (Dorman, 2000).

The main role of the expert is usually to understand and explain the particular consequences of the landslide(s) that may occur. In our experience, while some clients, owners or regulators attempt to cost some of the direct consequences, many are willing to make judgements on risk acceptability and treatment options based on descriptions of the consequences without attempts at costing. Explicit descriptions of potential consequences are particularly helpful (e.g. rocks up to 0.5 m across may fall onto a parked car) but relative consequence terms (such as minor, major etc.) defined for the particular project can also be useful.

UNCERTAINTY AND BEING REALISTIC

Uncertainty and being aware of our limitations

McMahon (1985), Morgenstern (1995) and Sullivan (1994) discuss different types of uncertainty in geotechnical engineering and the limitations of our ability to understand and predict the behaviour of the ground. In landslide risk assessments, slope model uncertainty and human uncertainty dominate (Moon 1997). Each landslide results from particular combinations of materials, defects, geometry, water and triggering events, and significant geological details often only come to light after a failure. Human uncertainty includes errors and lack of appropriate knowledge, skills and experience. In our judgements of landslide likelihood we must be prepared to openly acknowledge uncertainty to ourselves, our clients, regulators and the public, and be prepared to revise our judgements in the light of new evidence.

Assessments of landslide likelihood are evidence-based judgements dependent on the knowledge and skills of the assessor. Hindsight tells us that we sometimes make poor judgements. Review is necessary and invaluable but agreement between different assessors does not guarantee that the judgement is sound. If a critical failure mechanism has been missed, agreement may only mean that two poor judgements have been made.

Being realistic

Baynes (2001) warns that sometimes the pursuit of quantification *"seems to dull the awareness of practitioners to the imprecision of the very numbers that are being generated."* With so much uncertainty involved in the hazard likelihood assessment process, it is important to be realistic about the adopted judgements.

In practice, judgements about landslide likelihood often have to be made at early stages in a project when there is

limited information available on the slope in question. Uncertainties in the geological model, failure mechanisms and input parameters (e.g. those associated with the variability of materials, defects and pore pressures) limit the role of slope stability analyses. In many cases, arguing whether the factor of safety of an unfailed natural slope is 1.1, 1.3 or 1.5 is likely to be unrealistic because of the uncertainties and the many assumptions that have to be made. In a similar way, arguing which of 10^{-6} (1 in 1.000.000), 10^{-5} (1 in 100,000) or 10^{-4} (1 in 10,000) is a better judgement of landslide likelihood of the same slope is often just as unrealistic.

Simple geometrical relationships (such as relating stability to slope angles) or statistical approaches can also be misleading if applied without adequate knowledge of the geology, geomorphology, site history and failure mechanisms. For example, landslides are commonly more likely on the flatter slopes of an escarpment because the flatter slopes may include past landslides, areas of thicker soil, and/or some other less favourable combination of conditions. Average numbers of events, which may occur in a region over a period, are easier to predict than what might happen at a particular site. While existing landslides may move again, anticipating when and where the first time landslides will occur is much more difficult.

Morgan (1997) discusses slope hazards from a regulatory perspective and refers to the difficulty of quantifying low probability events. Many regulatory authorities understand that it is unrealistic to use purely quantitative criteria in risk management. As discussed in a British government review of risk assessment and risk management (Health and Safety Executive, 1998) it is *"widely acknowledged that managing risks solely on the basis of the probabilistic estimate ... is unlikely to succeed."* Linking regulations too closely to unrealistically precise judgements that you cannot measure or verify is of questionable value.

WHAT DOES UNLIKELY MEAN?

The need for realistic attempts at evidence-based quantified judgements is confirmed by our experience as reviewers of internal and external reports. If an event is described as *"unlikely"* our first questions are *"what do you mean by unlikely"* and *"what is your evidence"*. Without answers to these questions, the description has limited value. Our degree of belief in the answers will depend on the evidence.

Although attempting to make quantified judgements of landslide likelihood is difficult, it is worth the effort. In our experience, the attempt to quantify gets you to ask different questions and usually encourages a more thorough evaluation of the evidence from various sources. In simple terms, the attempt helps you work out:

- what you know;
- what you do not know;
- what you need to know, and;
- what you cannot know.

The result of the attempt is a better understanding of the hazard, consequences and risks, which, as discussed at the beginning of this paper, makes it easier to compare risks and risk treatment options and allows better informed decisions to be made about where to spend limited resources.

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