- **Preliminary design:** to provide sufficient data to enable the concept designs to be selected from possible alternatives based on the risk management requirements.
- **Detailed design:** to enable design of risk control measures to be optimised and to remove sufficient uncertainty such that the design will be satisfactory.
- **Construction:** to confirm the design assumptions and allow modification to the design sufficient to address departures from the assumed geotechnical model.

Not all levels of study will be applicable for every project. For example, for some cases completion of a walk-over investigation may be sufficient to allow detailed design to be completed satisfactorily. For more complex projects, the investigations may be completed in stages (for different levels) to enable the geotechnical model to be progressively refined and uncertainties reduced. The levels of study form a continuum and furthermore the scope will vary from project to project.

The appropriate level for residential LRM should be set out in the regulator's policy and should be at least to a walk-over level but with subsurface investigation as needed to establish the subsurface profile. Preliminary and/or detailed design level investigations may only be warranted once the consent conditions have been set. Such consent conditions may include the requirement to complete the more detailed investigations so that the risk control measures may be properly designed and constructed.

The prescriptive requirements given in the Practice Note are considered to be "best practice" for LRM of individual lots or possibly for subdivision assessments. They would also be applicable for investigation of a particular landslide or area, but should be completed to a more comprehensive level.

Monitoring of ground water levels and responses to rainfall events would be ideal. However, practical limitations (including cost and time) limit how often such monitoring is likely to be completed. Frequently a qualitative assessment is likely to be sufficient. For stabilisation by subsurface drainage some monitoring before and after installation of the drainage measures will be required to enable the effectiveness of such drainage to be assessed.

If a practitioner does not comply with the requirements of a policy, then it should be fully documented in the report as to why not.

C5.3 LANDSLIDE CHARACTERISATION

No further comment.

C5.4 FREQUENCY ANALYSIS

5.4.1 Techniques for Frequency Analysis

i) *Main Techniques*

The Practice Note outlines the main techniques which are routinely adopted. AGS (2000) Appendix C provides further discussion. Lee and Jones (2004) and Picarelli *et al.* (2005) provide more detailed discussion and examples from published papers.

ii) *Limitations for Historical Analysis*

The Working Group notes that, in Australia, gathering of historical knowledge is not usually as easy or fruitful as it should be. Experience shows that local government seldom has a complete listing and records become difficult to retrieve, whilst local papers tend to concentrate on "the human aspect" with little factual documentation, not even of date and time of a landslide event, nor the extent and nature of the landslide. Notwithstanding this, a listing of landslide events (as a basic inventory) is of relevance and aids in assessment of likelihood. Much of the data on the incidence of landslides is held by consultants who work in the area. There would be considerable benefits if local government authorities gathered the data held by all the consultants who work in their area and established an inventory which could be accessed by all.

Within Australia an inherent limitation is likely to be the relatively short time period that development has been exposed to landslides. Historically, original development tended to avoid problem areas based on common sense and possibly trial–and-error. If historical records are limited to say 30 years, then the frequency of single events will be limited to a basic 1 in 30 probability (about 0.03), though this may be modified by the probability of trigger events during that period, and response within a population of similar landslides in similar geology and geomorphology. Table C3 shows the length of historical record required to estimate return periods with selected reliability.

Table C3: The length of historical record required to estimate return period events with 95% and 80% reliability.

Return Period (Years)	Length of record in years required to deliver reliability of return period estimate	
	95% reliable	80% reliable
2.33	40	25
10	90	38
25	105	75
50	110	90
100	115	100

From Lee and Jones (2004) after Benson (1960).

With sufficient data it may be possible to formulate Frequency vs Magnitude curves to summarise the data and gain a better understanding of the overall process and associated frequencies. (For example, refer Moon, Wilson & Flentje 2004, and MacGregor *et al.,* 2007).

iii) Evaluation of Rainfall

Statistical evaluation of rainfall data is relatively easy to perform using computer spreadsheets. These statistics can be related to the incidence of landslides. An example is given in MacGregor *et al.* (2007).

Consideration has to be given to possible trigger thresholds which may relate to rainfall, either in the short term (minutes to hours) or the long term, such as antecedent rainfall over weeks to months. Usually, antecedent rainfall will be relevant where rising groundwater levels are seen as the main trigger, and this is frequently applicable for the larger landslides

In addition, there may be a conditional probability of the landslide event occurring during a given rainfall event, or the conditional probability related to the proportion of similar slopes that might be affected by a rainfall event. Such conditional probabilities may be evaluated by considering the proportion of slopes that have failed in a given rainfall event (based on the landslide inventory in conjunction with the rainfall analysis).

Use of simulation models which predict piezometric responses to rainfall events may assist with calibration and extrapolation to extreme rainfall events. However, these require long periods of records of rainfall and piezometric data, and even when this is available simulation is difficult. Fell *et al.* (1991) gives an example. Table C4 indicates the probability of different return period events occurring over different periods of time. It can be seen that the probability of having a low return period event (for example a 1 in 100 year event) over a relatively short monitoring period such as 5 years is quite low (4%). Thus such models and extrapolation will have obvious limitations but may still be a useful tool for understanding a particular scenario.

Table C4: Percentage probability of the N-Year event occurring in a particular period.

Number of years in period	N = Average return period in years							
	5	10	20	50	100	200	500	1000
1	20	10	5	2	1	0.5	0.2	0.1
5	67	41	23	10	4	2	1	0.5
10	89	65	40	18	10	5	2	1
30	99	95	79	45	26	14	6	3
60	>99.9	98	95	70	31	26	11	6
100	>99.9	99.9	99.4	87	65	39	18	9
300	>99.9	>99.9	>99.9	99.8	95	78	45	26
600	>99.9	>99.9	>99.9	>99.9	99.8	95	70	45
1000	>99.9	>99.9	>99.9	>99.9	>99.9	99.3	87	64

After Lee and Jones (2004).

The effects of 'climate change' may show that use of historical rainfall records has an implied limitation. However, at this stage the effect of climate change cannot be predicted. Some predict longer dry periods, whilst others are predicting higher intensity rainfalls. Since it may be that a changed rainfall pattern may in many cases increase the probability of landsliding, whilst dryer periods may decrease the probability for others, it is considered appropriate at this time not to attempt to adjust the assessed frequency for such changes.

iv) "Degree of Belief" or Subjective Probability

For many cases, the practitioner will have to rely on the "degree–of-belief" method or subjective probability. This will be necessary due to the lack of relevant information such as historical records and/or quantitative analysis of trigger events which would enable an objective assessment of event probabilities. The practitioner will have to make best estimates of frequency/likelihood from limited site data, using experience and broad knowledge of an area or other areas of similar slope form and geology.

Moon and Wilson (2004) provide a useful over-view to developing judgments on landslide likelihood. "*The necessary evidence on which judgments 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."* Many useful references are cited.

Vick (2002) discusses the role of evidence and logical inference to subjective probability and engineering judgment. Although the assessed likelihood will be a subjective judgment, it should, like a bookmakers odds, be based on evidence (Moon and Wilson, 2004).

There are undoubted problems associated with use of "degree–of-belief" methods. The following presents a summary of the discussion in Lee and Jones (2004).

The main potential problems identified by Roberds (1990) are, in summary:

- *Poor quantification of uncertainty*, which may result in significant over estimates of likelihood where the slope forming process is ignored or misunderstood.
- *Poor problem definition*, as a result of the practitioner's experience and background, resulting in emphasis on one area or element of the slope at the expense of another.
- *Motivational bias* which may result in over optimistic or overly conservative assessments depending on the purpose of the assessment.
- *Cognitive bias* where the practitioner's judgment does not match the available facts.

The effects of these potential problems can be reduced or eliminated by techniques such as those of Lee and Jones (2004):

- *"Self assessment* where the rationale behind every judgment has to be well documented as required by the Practice Note. The same operator bias is likely to apply, but the documentation process clarifies the logic and results in a more defensible judgment.
- *Independent review or second opinion* which also should be well documented. This may still suffer from bias.
- *Calibrated assessment* where the practitioner's biases are identified and calibrated, and the assessment adjusted accordingly. The biases may be identified by peer group review or objectively by a set of experiments or questionnaires.
- *Probability encoding*, which involves the training of practitioners to produce reliable assessments of the probability of various events in a formal manner. This involves six stages:
    1. Training the practitioner to properly quantify uncertainty.
    2. Identifying and minimizing the practitioner's bias tendencies.
    3. Defining and documenting the item to be assessed in an unambiguous manner.
    4. Eliciting and documenting the practitioner's rationale for the assessment.
    5. Eliciting, directly or indirectly, the practitioner's quantitative assessment of uncertainty and checking for self-consistency. The practitioner's uncertainty can be established by determining the probability of various states through comparison with reference situations, such as poker hands, or by choosing between two lotteries (e.g. probability wheels or intervals) until indifference is achieved.
    6. Verifying the assessment with the practitioner and repeating the process if necessary."

Group consensus about a judgment is desirable but is achieved at increased cost and may not be economic. There may be significant differences of opinion between different practitioners. Where such differences of opinion are identified then they should be attempted to be resolved preferably in an open forum. The outcomes from this resolution process can be:

- *Convergence* to a common belief or assessment agreed to by all practitioners in the group.
- *Consensus,* where a single assessment can be determined but the assessment may not be the exact view of each individual. The consensus assessment may be a compromise derived from the individual assessments of group members but without the express agreement of the individuals concerned (forced), or the group may expressly agree to it for a particular purpose (agreed).
- *Disagreement.* Where convergence or consensus to a single assessment is not possible from the multiple assessments due to the major differences of opinion.

More detailed discussion of the above is presented in Lee and Jones (2004).

The Working Group considers that the Practice Note outlines "best practice" for self assessment where a "degree–of-belief" method is frequently adopted. However, it is anticipated that documentation of the assessment will include reference to known history and trigger events to help calibrate the judgment and provide defensibility.

The assessment of frequency should adopt the best means available given the nature of the landslides, circumstances of the geotechnical model, nature of triggering events and requirements of the risk assessment. Where few data are available, then estimates erring on the conservative side should be adopted to cover inherent uncertainty. More detailed studies may then be required to provide more reliable risk estimates.

In considering the circumstances of the particular assessment, the practitioner has to use best estimates from the available data when assigning likelihood (and consequences) values, but will inevitably be based on a subjective assessment of the practitioner's "belief" of the assessment. The assessment needs to consider range/uncertainty/sensitivity of the assessed values to establish confidence. The practitioner has to apply judgment, but must provide an explicit trail, or explanation, of logic applied to derive the best estimates adopted.

Stewart *et al.* (2002) discuss the RTA Guide to Slope Risk Analysis which provides a systematic procedure for LRM for roads based on defined ratings to derive an Assessed Risk Level. The companion paper (Baynes *et al.,* 2002) discusses the issues of accuracy and precision in use of the procedure by many practitioners on a large number of slopes. The methodology of the procedure is based on principles outlined above. Training in use of the system is required to help calibrate each practitioner and reduce bias. Audit procedures are used to derive consensus where necessary.

The state-of-the-art paper by Picarelli *et al.,* (2005) also provides a further overview and examples.

v) Event trees

Event trees enable the logical sequence of events to be considered in a structured manner. A suitable structured approach might, for example, consider for each scenario sequences such as likely trigger event, slope response, and consequence. An event tree can be used for complex scenarios.

The method has the advantage of enabling the logic adopted to be clearly shown together with each estimate of conditional probability, thereby providing clear documentation for review and appraisal.

This matter is discussed further in Lee and Jones (2004), and provides some examples where the method has been used. Hsi and Fell (2005) give an example where triggering by rainfall, over-taxing of a culvert and earthquake is modelled. Mostyn and Sullivan (2002) provides examples in relation to failure of fill embankments along a road. Hill *et al.* (2002) provides further discussion of issues associated with the principles of event trees.

5.4.2 Estimation of Annual Probability (Frequency) ($P_{(H)}$) of Each Landslide

a) Use best estimates for frequency estimates but consider range/ uncertainty/ sensitivity.

AGS (2000) acknowledged that assessment of frequency, or likelihood, is the most difficult part of the risk assessment process.

Assessment is particularly difficult at the medium to low frequency end (say 10^{-4} pa to 10^{-6} pa) because historic data based methods are not applicable. However, such values may still be appropriate by a combination of understanding the slope forming processes and logical elimination of other values. For some cases, such low frequency values may obviously be appropriate to hazards which could only occur over periods of geological time.

Experience has shown there is an inherent danger with Appendix G of AGS (2000), in that some practitioners assessed the likelihood solely based on the Descriptor. The Indicative Likelihood would then be adopted without due consideration. This procedure is incorrect as described below. An estimate of the probability should be made based on the best estimate of performance, trigger probabilities etc. and then the descriptor may be assigned accordingly.

Words such as "likely" can mean many different things to different people and in various contexts. The likelihood descriptors vary enormously in probability value between different publications as shown in the attached Table C5.

The qualitative terminology for Likelihood adopted for the Practice Note Appendix C is essentially the same as Appendix G, AGS (2000). The lowest category of likelihood has been revised to Barely Credible (from Not Credible).

The Descriptors are given to provide a consistent set of terms to assist the non-practitioner to interpret the assessed annual probability. In addition, the Descriptors provide a useful summary term for discussion purposes with due recognition of the inherent limitation of accuracy that is involved.

Table C5: Some published relationships between verbal descriptor and probabilities.

Verbal Descriptor	Conditional Probability				Annual Probability		
	USBR (2003)	Vick (1992)	Bowden *et al.* (2003)	Reagan *et al.* (1989)	AGS (2000) Appendix G	De Ambrosis & Mostyn (2004)	Moon & Wilson (2004)
Virtually certain	0.999	0.99	0.999	0.9	Approx 0.1 *	>=0.1*	>0.2*
Very likely	0.99	0.9		0.85			0.2 to 0.02
Likely	0.9			0.7	Approx 0.01	>=0.01	0.02 to 0..002
Neutral (even chance)	0.5	0.5		0.5			
Unlikely	0.1		0.001	0.15	Approx 0.0001	>=0.0001	<0.0002
Very unlikely	0.01	0.1	0.0001	0.1			<<0.0002
Virtually impossible	0.001	0.01	0.000001	0.02	<0.000001*	<0.000001*	

Note: * Verbal descriptor similar

Consideration has been given to the cumulative probability associated with each Descriptor and the expectation for the probability of occurrence of the lay user for those terms. For example, on first sight the use of the term ALMOST CERTAIN for an annual probability of greater than 0.05 seems inappropriate. However, examination of the Practice Note Figure 2 shows that within a design life of 60 years the cumulative probability of occurrence is about 0.95, and about 0.99 for 100 years. The apparent anomaly is explained by consideration of performance over the design life (as discussed in Section C9.3 below), and it is considered acceptable The indicative probability of occurrence over various design lives is given for each Descriptor in Tables CC1 and CC2 in Appendix CC attached.

Where knowledge based expert judgment or 'degree of belief' method of assessment of frequency is used, the resulting assessment could only be expected to have a precision within about one order of magnitude as discussed by Baynes *et al.* (2002). A consensus assessment by two or more practitioners can improve the precision to a reasonable level.

Although descriptors may have different meanings in other systems or publications, they are well defined in the Practice Note Appendix C. If an alternative system is to be adopted then the alternative should be similarly well defined and include an explanation as to why the preferred scheme was not adopted for the LRM assessment.

b) Estimates of frequency may be derived by partitioning the problem to (Annual probability of trigger event) x (Probability of sliding given the trigger event) over the range of trigger events.

It is sometimes useful to consider the likely response of a slope to given rainfall events (or other trigger events, such as earthquakes) when assessing frequency. Hence:

Frequency = (Annual probability of trigger event) x (Probability of sliding given the event)

= $P_T \times P_{S:T}$

assessed over the range of trigger events.

The probabilities of sliding are assessed judgementally from historic data and the experience of the practitioner. Table C6 provides an example of employment of partitioning to produce an estimate of annual probability over a range of trigger events.

Table C6: Example of the assessment of the annual probability (frequency) of landsliding employing the annual probability of rainfall and the response of the slope to the rainfall.

Annual probability of the rainfall	Annual probability rainfall is exceeded	Probability/annum rainfall is in this range (P_T)	Estimated conditional probability of landsliding given the rainfall is in this range ($P_{S:T}$)	Annual probability (Frequency) of landsliding
1 in 1	1.0			
		0.9	0.001	0.0009
1 in 10	0.1			
		0.095	0.1	0.0095
1 in 200	0.005			
		0.0049	0.9	0.0044
1 in 10,000	0.0001			
		0.0001	0.99	0.0001
			Total	0.0149

Where there is little historic data on which to assess the conditional probabilities ($P_{S:T}$) it is useful to use inferred relationships known as mapping schemes. These link qualitative and quantitative terms for probability. Table C7 shows a scheme which has been used widely in dams risk assessment in Australia.

Table C7 was developed for use in dams risk assessment, by Barneich *et al.* (1996) from Military Standard (1993), using Baysian theory to assess historical data. This was done by a group of dams and geotechnical experts, and reviewed by Professor A. Cornell. It has been used and validated in other areas such as pavement management systems, environmental risks at mine sites and seismic risk analysis projects. Experience shows the table helps in obtaining consistent estimates of conditional probabilities within event trees.

Table C7: Mapping scheme linking description of likelihood to quantitative probability (Barneich *et al.,* 1996)

Description of Condition or Event	**Order of Magnitude of Probability Assigned**
Occurrence is virtually certain	1
Occurrences of the condition or event are observed in the available database	10^{-1}
The occurrence of the condition or event is not observed, or is observed in one isolated instance, in the available database; several potential failure scenarios can be identified.	10^{-2}
The occurrence of the condition or event is not observed in the available database. It is difficult to think about any plausible failure scenario; however, a single scenario could be identified after considerable effort.	10^{-3}
The condition or event has not been observed, and no plausible scenario could be identified, even after considerable effort.	10^{-4}

c) Complete a review of the assessed frequency in relation to the implied cumulative frequency of the event occurring within the design life and known performance within the area.

Practice Note Appendix C Likelihood table has included the "Implied Indicative Landslide Recurrence Interval". The correspondence to the Approximate Annual Probability is not strictly correct, especially at low probability values. As discussed by Moon and Wilson (2004) the recurrence interval has a connotation about long periods of time based on long periods of evidence. The reality is that data in relation to the annual probability values of about 10^{-4} or less will be limited. "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 judgments to annual probabilities" (Moon and Wilson, 2004).

The inclusion of likelihood terms for annual probability values of less than 10^{-4} is considered to be appropriate to allow for differentiation, particularly where the probability of spatial impact may be quite different for different hazards. This also offers easy differentiation for hazards where the probability of landsliding is barely credible, for example on a plateau area remote from any escarpment or possible regression (except over geological time) and having relatively gentle slopes underlain by competent strata the probability is likely to be less than 10^{-6}pa.

5.4.3 Assessment of Travel Distance and the probability of spatial impact ($P_{(S:H)}$) of the elements at risk

For most risk assessments it will be adequate to estimate travel distance using empirical or simplified methods. Only in very detailed studies of large and important landslides would it be necessary or useful to use methods such as finite element or distinct element analyses to estimate deformations of individual slides, or to use numerical methods to model debris flows or rock avalanches. Hungr *et al.* (2005) provides an overview of methods for estimating travel distance.

For rotational landslides which remain essentially intact, the method proposed by Khalili *et al.* (1996) or experience with landslides in similar geological, topographic and climatic conditions can be used to estimate the displacement. This method is based on the principle of conservation of energy assuming the factor of safety at failure is unity, adopting the residual strength and the slope geometry to estimate the displacement. The results compare reasonably with case studies. The displacements are greatest for "brittle" failures i.e. where there is a large loss of strength on shearing. The strength loss may be best measured in undrained strength terms, e.g. for soft clays peak and remoulded strengths should be used and for saturated loose (collapsing) granular fills where liquefaction may occur, post liquefaction strengths should be used. For non-circular surfaces, the method may overestimate displacements. Deformation may be modelled for more important projects using finite element, finite difference or distinct element programs.

There is a degree of uncertainty in the methods available for estimating travel distance. Judgment will also have to be applied when consideration of travel direction is relevant in relation to the landslide impacting a particular element at risk. (Such consideration is most likely to be relevant for boulder falls or similar.) For individual allotment assessments, a best estimate or slightly conservative approach may be used, though for more detailed risk assessments, the uncertainty in travel distance and /or travel direction should be modelled as shown in the example presented in Table C8.

Table C8: Example of modelling uncertainty in travel distance and the probability of spatial impact ($P_{(S:H)}$).

Travel Distance Range metres	Estimated Probability the Travel Distance will be in this Range	Probability of spatial impact ($P_{(S:H)}$) assuming the element at risk is 32 metres below the landslide
<20	0.2	0
20 to 30	0.6	0
30 to 40	0.2	0.2
	Total 1.0	Total 0.2

The probability values could be further modified by the conditional probability associated with travel direction, where this is appropriate. For example, if a rockfall is assessed to have a variety of possible trajectories, only some of which will result in spatial impact on the element at risk, then application of the conditional probability for the trajectory would be applied to the travel distance probability.

C6 CONSEQUENCE ANALYSIS

C6.1 ELEMENTS AT RISK

No further comment.

C6.2 TEMPORAL SPATIAL PROBABILITY ($P_{(T:S)}$)

Roberds (2005) gives a detailed account of how to estimate temporal spatial probability where the elements at risk are mobile. AGS (2000, 2002) Appendix E gives details for the case of traffic travelling on a road.

For most assessments involving persons at risk in a building, the practitioner should make an estimate of temporal spatial probability based on the use of the building. This should include assessment of the probability of non-evacuation which may be used as a conditional probability. The landslide velocity and possibility of forewarning of the landslide failure will be relevant considerations.

The assessment may need to be based on a regulator's notional occupancy for a dwelling, not necessarily the client's proposed occupancy. For example, a client may wish to build a holiday house with relatively low occupancy factors (particularly for the time of year most likely to have a landslide event). However, a subsequent owner may be occupying with an average family on a fulltime residential basis. The later occupancy would be more critical and should be adopted for assessment purposes for the development.

C6.3 EVALUATION OF CONSEQUENCE TO PROPERTY

C6.3.1 Estimate the extent of damage likely to property arising from each of the landslides

The assessment of vulnerability and damage to property is subjective, and there is little published information. The Practice Note Appendix F has some data but note that for property this represents the judgements of those doing the study and is not a record of actual vulnerability. There are some general points which should be considered:

- Landslides which move slowly (particularly those with a near planar, horizontal surface of rupture) may cause little damage to structures on the landslide, though those structures which are on the boundaries of the landslide will experience differential displacement.
- For stuctures on the landslide, the rate of movement is less important for damage to the structures, except insofar as it affects the time rate of damage, than it is for loss of life.
- For stuctures below the landslide, the velocity of the landslide has a major effect on the damage and hence vulnerability. Hence structures which are near the toe of a landslide which will travel a long distance are likely to experience a high velocity impact and will suffer extensive damage (high vulnerability), and structures which are near the limit of the travel (or run-out) of the landslide will experience low velocity impact by only part of the landslide mass and will probably suffer "minor" damage (low vulnerability).