

# Developing and using landslide size frequency models

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**ABSTRACT:** Predicting the size and frequency of landslides is essential in landslide risk assessment. Records of past landslides are invariably incomplete and often provide little guidance on infrequent events. Presenting size frequency models graphically has the advantage of showing how observations, interpretations and judgements are interrelated, allows patterns to be recognized and understood, and models for different situations to be easily compared. Slope retreat rates were used to calibrate landslide size frequency models for individual slope units on an oversteepened escarpment above a road threatened by landslides in Australia. Evidence based models should be developed early and should be based on how slopes form and fail over a range of time scales. The size of deposits, historical records and measured movements can be used to help assess landslide process rates. Regional models can help in the judgement of how a particular slope may behave.

## 1 INTRODUCTION

### 1.1 *Limitations of the historical record*

Predicting the size and frequency of landslides is essential in landslide risk assessment. Records of past landslides can provide some information on what has happened, but are invariably incomplete and often provide little or no guidance on less frequent events that may occur. In landslide risk assessment, one of the most important questions to ask is what might happen in the future and often judgements have to be made about the likelihood of infrequent events with serious consequences with little, or no help from historical records.

### 1.2 *Using slope models*

Slope models can be used to support judgements about what might happen which go beyond the limitations of the historical record. Lee & Jones (2004) and Baynes & Lee (1998) discuss and give examples of the essential role of slope models in assessing the probability of landslides. Although slope models provide simplified views of reality, they enable prediction and they can be tested and updated with local and regional knowledge and relevant knowledge from elsewhere.

The slope models need to answer questions like:

- How did the slope form?
- How fast is it eroding?
- What proportion of the erosion is by landslides?
- What is the size frequency distribution of the landslides?

### 1.3 *Scope of this paper*

We have found landslide size frequency models useful in practice. This paper shows how models can be presented graphically, gives an example of their recent application and discusses the knowledge and evidence on which models are based.

## 2 PRESENTING JUDGEMENTS ABOUT THE SIZE AND FREQUENCY OF LANDSLIDES

Observations and judgements about the size and frequency of landslides can be presented in words, tables or diagrams. Presenting size frequency models graphically has the advantage of showing how observations, interpretations and judgements are interrelated, allows patterns to be recognized and understood, and models for different situations to be easily compared. Figure 1 is an example of the graphical presentation of a landslide size frequency model.

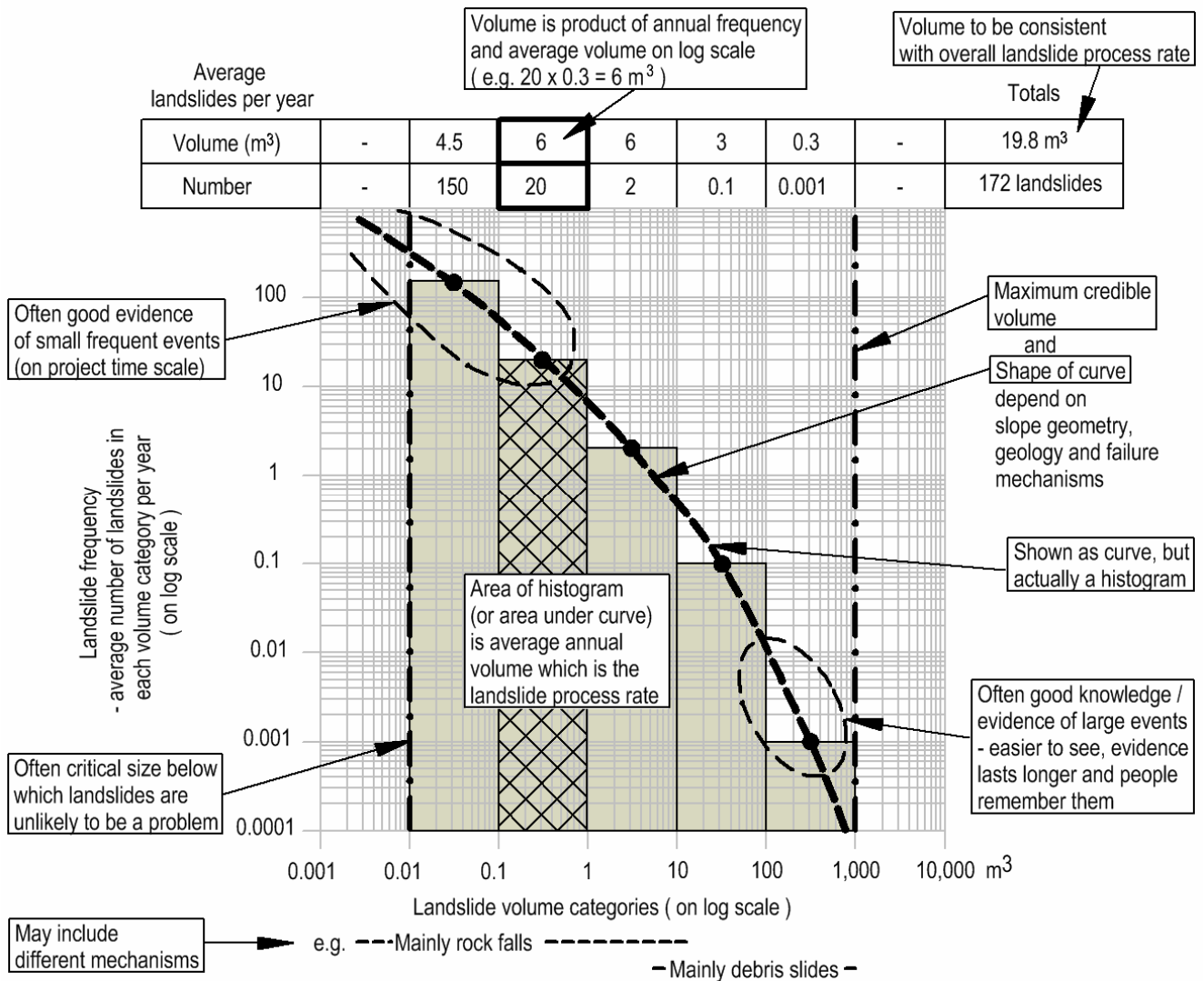


Figure 1 Explanation of the graphical presentation of a landslide size frequency model

## 2.1 Explanation of Figure 1

### 2.1.1 Log-log histogram

The underlying structure of Figure 1 is a histogram on a log-log scale. Showing the underlying log-log structure is useful when developing the graph but does not need to be shown on the final drawing.

The x axis shows landslide volume in order of magnitude categories, although smaller divisions (such as half order of magnitude) can be used if more useful for particular projects.

The y axis shows the landslide frequency which is the average number of landslides per year in each of the landslide volume categories. For example, the highlighted column on Figure 1 indicates that, on average there are judged to be 20 landslides per year with volumes in the range 0.1 m<sup>3</sup> to 1 m<sup>3</sup> (which usually means that there will be less than 20 landslides in most years). Different periods (such as design life) can be used on the y axis if required.

When developing a model it is often useful to show the average annual number of landslides in each volume category above the graph. The aver-

age annual volume of landslides in each volume category can be calculated by multiplying the number of landslides by the average volume on a log scale (e.g. the log average of the 0.1 m<sup>3</sup> to 1 m<sup>3</sup> category is 0.3 m<sup>3</sup>). As shown on Figure 1, the average annual total number and volume of landslides (the area of the histogram) can also be calculated.

Although Figure 1 is a histogram with discrete volume categories, we have also shown the model as a curve (points separated by a dashed line so the actual judged numbers of landslides in each volume category can be clearly seen). Showing the model as a curve rather than columns allows several models to be presented and compared on the same graph. The average volume of landslides per year (or landslide process rate) can then be thought of as the area under the curve (calculated from the histogram as described above).

### 2.1.2 Critical project element and critical landslide size

Before developing a size frequency model for use in risk assessment it is important to understand the potential consequences of landslides and consider

what are the critical project elements or locations at risk. The model can then be developed to focus on the likelihood of landslides of different sizes reaching or affecting critical elements. Critical elements for particular projects may include roads, railways, buildings, footpaths, fences, reservoirs etc.

Defining the critical element or elements for a particular project helps define the critical landslide size (below which landslides are unlikely to be a problem). The potential speed of a landslide may also influence the judgement of critical size. For example, if the critical project element is a road, a large but very slow landslide may present little risk (if minor damage can be periodically repaired) compared to a fast very small landslide (e.g. boulder falling vertically on to traffic).

### 2.1.3 Defining and calibrating the size frequency model

Other notes on Figure 1 point out that:

- For any particular slope the maximum credible volume and the shape of the landslide size frequency curve depends on the slope geometry (e.g. height and orientation), slope geology and failure mechanisms.
- Landslide size frequency models may include several failure mechanisms.
- When developing size frequency models there is often good evidence of small frequent events (sometimes on a project timescale) which is helpful in developing and calibrating the model.
- There is also sometimes good knowledge or evidence of some of the larger landslide events which affect the slope of concern (or similar slopes in the area). Depending on the time scale, this is because people remember the larger events and the evidence of larger events is easier to see and lasts longer.
- The average annual volume (or area under the size frequency curve) needs to be consistent with the overall landslide process rate (which can vary with time) as represented by slope retreat rate models or other slope evolution models.

The above aspects of landslide size frequency models are illustrated by the examples given or referred to in the remainder of the paper.

### 2.2 An example of size frequency models

Figure 2 is an example of landslide size frequency models for toppling failures from rock slopes (Moon et al. 1996). In this project, rock falls from a 48 year old, very steep, 30 m high railway cutting in granite at Bethungra in New South Wales, Australia had damaged trains and caused at least one derailment. Most falls resulted from toppling of in-

dividual blocks or columns defined by persistent near vertical joints. As part of the design of slope stabilization works, landslide size frequency models were developed based on a probabilistic toppling failure model calibrated against the history of rock falls.

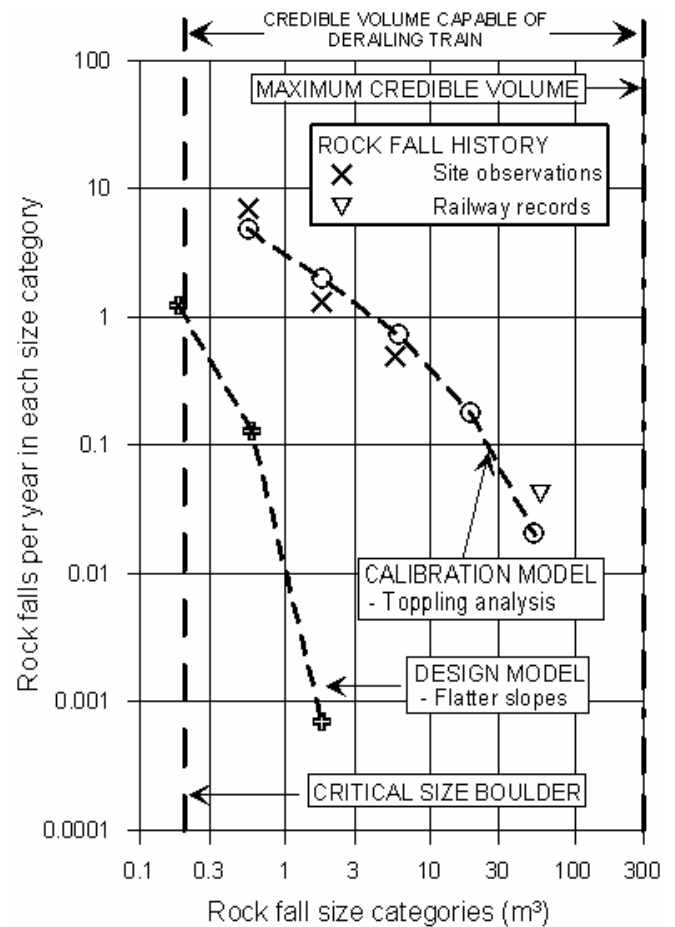


Figure 2. Rock fall size frequency relationship at Bethungra (adapted from Moon et al, 1996).

For this project:

- Half order of magnitude landslide volume categories were used.
- The critical project element was the railway track.
- The critical size landslide was judged to be 0.2 m<sup>3</sup> (anything smaller on the track was unlikely to derail a train traveling at the low speed limit in place at the site).
- The maximum credible landslide volume was judged to be 300 m<sup>3</sup> (based on slope height, potential column widths and stability analysis).
- There was a good record of rock falls (of up to 10 m<sup>3</sup>) for the previous two years and knowledge of two past failures in the 30 m<sup>3</sup> to 100 m<sup>3</sup> range.
- Long term railway inspectors were able to confirm that there had been no decrease in rock falls with time.

- It was possible to assess the average annual landslide volume (landslide process rate) with knowledge of how many wagon loads of rocks had been removed.

The probabilistic toppling failure model, using information on the orientation, continuity and spacing of joints and calibrated against the rock fall history was used to assess the size and frequency of landslides for redesigned slopes with varying amounts of overbreak.

### 2.3 *Other ways of presenting size frequency observations and judgements*

Hungr et al. (1999) point out that magnitude cumulative frequency relationships are used widely in natural hazard assessments (e.g. Gunther-Richter relationship for earthquakes) and present magnitude cumulative frequency relationships on a log-log scale for rock falls and slides along road and rail corridors in British Columbia. Dussauge-Peisser et al. (2002) use a similar approach for rock falls at sites in France and the USA.

We have found the size frequency histogram approach useful because:

- The log-log histogram directly shows the actual number of landslides (point on graph and, if useful, number at the top of the graph) in each size category. This makes the model completely transparent and easier to develop and manipulate in workshops (particularly with non specialists).
- When developing a model, and/or trying to elicit information from non-specialists who have seen landslides, judging whether a landslide is in a particular size category is easier than trying to estimate its actual size.
- Landslides of different sizes usually have different consequences and need to be treated differently. Keeping the size categories separate helps to better understand (and show graphically) the relationship between size of landslide and risk and remediation options (e.g. Wilson et al, in prep.).

The method of presenting observations or models depends partly on what best suits a particular application. For example, Whitehouse & Griffith (1983) present rock avalanche deposit volume against return period (on log-Gumbel paper), Morgan et al. (1992) graphically present a variety of size frequency relationships for debris flows and Baynes (1997) presents a recurrence interval curve for kinetic energies of landslides at critical locations. Graphical presentation of observations and models is invariably useful and some of the aspects of presentation discussed for log-log histograms also apply to other methods of presentation.

## 3 LANDSLIDE SIZE FREQUENCY MODELS AT THE LAWRENCE HARGRAVE DRIVE PROJECT

A 1.3 km section of Lawrence Hargrave Drive (LHD) south of Sydney, Australia is at the base of an oversteepened coastal escarpment (Figs 3, 4). Following a long history of landslides the road has been temporarily closed while bridges are built to avoid the higher risk areas and slope stabilization measures are being carried out elsewhere. The hazard and quantitative risk assessments for the project are described by Hendrickx et al. (in prep.) and Wilson et al. (in prep.) respectively.

### 3.1 *Geological and geomorphological history*

The 320 m high coastal escarpment in the project area is made up of a sequence of near horizontal interlayered sandstone and claystone units of Permian and Triassic age. The stronger sandstone units form prominent near vertical cliffs and the intervening claystones and some of the weaker sandstones, overlain by colluvium, form the intervening slopes (Figs 3, 4).

The most prominent regional geomorphological feature is the escarpment at the edge of the 300 m to 500 m high plateau. In the project area the escarpment has been oversteepened by marine erosion. To the south the escarpment is further inland, the Bulgo Sandstone does not form cliffs and there are flatter lower slopes with a well developed coastal plain (Fig. 3).

Much of the marine erosion that has oversteepened the escarpment in the project area probably occurred during sea level highs during the many interglacial periods in the last 2 million years. During the colder glacial periods colluvium is likely to have repeatedly buried some of the cliffs.

### 3.2 *Escarpment retreat rates in the region and landslides in the project area*

The University of Wollongong has a database of landslides in the region (Flentje 1998) and have been monitoring some of the larger debris slides with inclinometers. Slope retreat rate estimates have been made on the basis of knowledge of rock falls from the Hawkesbury Sandstone, debris flows from steeper slopes and monitored debris slides (Hendrickx et al., in prep.). The estimates (which range from about 0.2 m to 2 m per 1000 years) confirm that that regional slope retreat rates are higher where the escarpment is closer to the sea and the regional estimates are consistent with the slope retreat rate estimates for the project area.

Hendrickx et al. (in prep.) discuss landslide mechanisms and the landslide record in the project area.



### 3.3 Slope retreat rate

Knowledge and interpretation of evidence on the geological and geomorphological history of the region and project area (including escarpment retreat rates and the landslide record) were used to develop a slope retreat rate model for the LHD Project. Figure 4 shows average slope retreat rates (in m/1000 years) for the different slope units (labeled 1 to 7) above the road. Figure 4 also shows the total volume of material derived from each slope unit which would be removed from the slopes during the 100 year project life (calculated by multiplying the slope retreat rate by the length and average vertical height of slope unit in the project area). The model implies that there would be about 20,000 m<sup>3</sup> of erosion. Most of the erosion would be by landslides which would cross the road if no preventive measures were in place. Additional material would be lost from below the road.

The initial slope retreat model (and size frequency models for each slope unit) was developed early in the project. During the design period, the knowledge gained from new landslides and new historical information enabled the models to be reviewed and improved.

### 3.4 Size frequency models and risk analysis

The size frequency judgements for some of the different slope units are shown as curves on Figure 5.

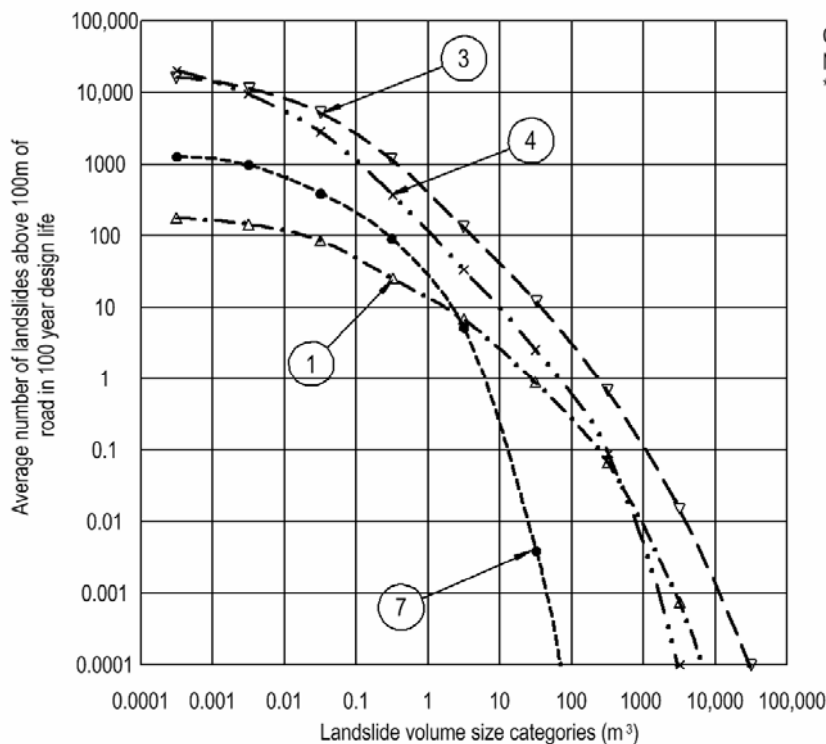
The curves have been normalized to show the size and frequency of landslide debris passing 100 m of road in the design life (100 years). The landslide process rate or yield (area under the curves) is the product of the slope retreat rate, the typical height, the length (100 m) and the judged proportion of erosion that is by landslides (some of the erosion is by other processes such as slope wash following rain and wind action).

In the risk analysis described by Wilson et al. (in prep.) the size frequency distributions shown were adjusted for the actual length, height and rate applicable to the location and slope unit being considered.

The process rate model describes the amount of material removed from the escarpment by landslides but does not imply that all debris from every landslide crosses the road. Some debris is transported by series of landslides and often material will locally accumulate on flatter slopes. In the risk analysis (Wilson et al., in prep), this process was modeled by making judgements about the number and proportion of each landslide reaching the road.

### 3.5 Shape of size frequency curves

The location and shape of the size frequency curves on Figure 5 are related to the landslide process rate, the slope geometry, the geology and failure mechanisms involved. For example:



Curve Number *	Slope unit (see Figure 4)	Adopted in model Typical slope retreat rate *** (m/1000 yr)	Typical height (m)	% erosion by landslide
1	Hawkesbury Cliff	0.3	30	95
(2)	Bulgo Slope	0.3	110	70
3	Bulgo Cliff	3	60	90
4	Stanwell Park Slope	2	40	60
(5)	Typical Scarborough Cliff	1	30	90
(6)	Slabbing Scarborough Cliff **	3	30	95
7	Otford Cliff	1	8	80

\* Curve number in brackets shown in Wilson et al. (in prep.)  
 \*\* Persistent joints parallel to face  
 \*\*\* Adopted rates varied (eg lower where slopes locally flatter)

Figure 5. Selected size frequency judgements at Lawrence Hargrave Drive

- Curve 1 is the flattest curve because joints and other defects are widely spaced in the Hawkesbury Cliff and there are relatively few small failures.
- Curve 7 is the steepest curve because the Otford Cliff is not very high and large failures will not occur. It is also the tightest curve because joints are generally widely spaced and so there will also be relatively few small failures.
- Curve 3 yields potentially larger failures because the Bulgo Cliff is the highest cliff. It also has the highest overall yield and a relatively large proportion of smaller landslides because it is relatively closely jointed and includes beds of low strength material.
- Curve 4 is a relatively steep curve with a high proportion of smaller landslides because the Stanwell Park Slope generates many small debris slides and debris flows particularly near the top of the Scarborough Cliff.

The orientation of a slope can also have a big effect on the size frequency curve. Wilson et al. (in prep) show the size frequency curves for the typical and slabbing (where there are persistent joints parallel to the face) Scarborough Cliffs. While the overall landslide process rate is higher for the slabbing cliff, the increase in frequency of landslides is much more pronounced for the larger failures (collapse of slabs larger than 1000 m<sup>3</sup> judged to be 15 times more likely than for the typical cliff).

## 4 DEVELOPING AND USING LANDSLIDE SIZE FREQUENCY MODELS

### 4.1 *Slope evolution models*

#### 4.1.1 *Understand the processes*

The key to developing slope models is to understand how slopes are formed. Selby (1993) describes the materials and processes that form slopes, models of slope evolution and provides quantitative information on slope retreat and general erosion rates in a variety of environments. Lee & Jones (2004) describe slope hazard models (including simulation models for cliff recession) and landslide triggers and Hutchinson (2001) also gives examples of quantified slope development models. Dahlhaus & Miner (2000) describe how judgements about cliff retreat rates were used to help assess the frequency of rock falls.

#### 4.1.2 *Models must be evidence based*

Slope models must be based on evidence from the slope or slopes in question and similar slopes in similar environments elsewhere. Moon & Wilson (2004) point out that the evidence has to be assem-

bled, understood and interpreted. They describe the range of skills and knowledge bases required to develop a sound knowledge of how slopes are formed, how they have behaved in the past and how they might behave in the future. Geological and geomorphological skills and knowledge of failure mechanisms are essential and the quality of the model often depends more on the expertise and experience of those preparing the model than the quantity of the evidence available.

#### 4.1.3 *Develop early*

Whatever the scale of the project there is always knowledge available on the regional geological and geomorphological history which can form the starting point for a landslide process rate model. It is best to develop an initial model early and use as many different approaches for development and calibration as possible. The advantage of an early model is that it demonstrates where the uncertainty lies and enables subsequent effort to be concentrated on collecting and interpreting evidence that improves and calibrates the model.

#### 4.1.4 *Time scales involved*

The importance of understanding how slopes are formed applies to both natural and man made slopes. Slope forming and slope failure processes occur over timescales ranging from seconds to many millions of years. A new slope (e.g. a cliff formed by a river in flood or a temporary excavation on a construction site) may fail instantly while other slopes change very little over very long periods. Twidale (1998) points out erosion rates can be very slow and that some slopes in Africa, Australia and elsewhere are many hundreds of millions of years old. Knowledge of the age of the landscape or slope, whether natural or man made, is essential to the calibration of judgements about overall landslide process rates.

### 4.2 *Landslide process rates*

For the LHD Project, landslide process rates were derived from slope retreat rate models calibrated with a lot of evidence. Other examples and approaches to assessing or calibrating overall landslide process rates and the need to understand how they can change with time are discussed below.

#### 4.2.1 *Size of deposits*

Colluvial fans may represent deposits that have formed by a variety of processes in a variety of environments over a long period. If the origin and age of particular components of the fans (e.g. Holocene debris flow deposits) can be identified, they can be used to help calibrate landslide process rates in the catchment.

Whitehouse & Griffith (1983) used knowledge of the size of Holocene debris deposits (dated by various methods) to help develop a size return period relationship for rock avalanches in the Central Southern Alps of New Zealand.

Volumes of material accumulating over a known period at the base of a cliff or cut slope can also help calibrate landslide process rates. At Bethunga, the size frequency model was derived initially from the events shown on Figure 2. Reliable information on the smaller events was only available for two years but the overall process rate (area under the curve) was also found to be consistent with the number of wagon loads of rocks removed from the cutting over a much longer period. This knowledge helped confirm the long term railway inspector's observations that the overall process rate had not changed significantly over the life of the cutting. Hungr et al. (1999) used deposit volumes to help develop size frequency relationships for landslides in British Columbia.

In other projects, accumulations of debris against fences or walls of known age has helped calibrate landslide process rates.

#### 4.2.2 *Historical information*

On the LHD Project (see Section 3 and Hendrickx et al. in prep.), newspaper reports, old photographs and other old records helped calibrate the landslide process rate. In another project in Australia rock falls from a natural cliff threatened an historic railway bridge. The cliff was in the background of a 19<sup>th</sup> century photograph of a train. Comparison with the present day cliff revealed the size, number and location of rock falls in the previous 100 years. Old maps in Britain have been used to help assess slope retreat rates (Holmes 1972, Brunson & Jones 1975) and Lee & Jones (2004) give other examples of the value of historical records.

#### 4.2.3 *Measured movements*

Measured slope movements can be used to help calibrate landslide process rates. At Roxburgh Gorge in New Zealand many large pre-existing landslides were partially flooded by the reservoir formed behind Roxburgh dam which was completed in 1956. Movement monitoring by survey and air photo interpretation helped establish an overall landslide process rate and calibrate a landslide size frequency model. The model was used to help assess the likelihood of a rapid landslide and landslide dam (Moon 1997).

Inclinometer monitoring of debris slides by the University of Wollongong helped establish slope retreat rates for the LHD Project (Section 3.2). Real time monitoring of inclinometers is now in place (Flentje et al., in prep.).

#### 4.2.4 *Demonstrating slow process rates*

Developing landslide process rate models is easier when landslides are frequent and there are plenty of observations and evidence available. Where slope processes are slow, slope models based on a thorough understanding of slope processes, slope evolution and regional knowledge are even more important. In some cases, demonstrating lack of evidence can help put an upper limit on the overall landslide process rate and point to low likelihood of particular events.

At Montrose in Victoria, Australia, historical records of a large landslide prompted concerns about debris flow risk in the area (Moon et al. 1991). Mapping of one colluvial fan in the area led to recognition of a surface debris flow deposit which could be traced back to the precursor landslide. Elsewhere on that fan and on other colluvial fans an older well developed soil profile (dated to be of Pleistocene age) occurred at the surface. The lack of debris flow deposits overlying the old soil profile elsewhere in the region helped demonstrate that large debris flows are an unusual event in the area (i.e. the debris flow process rate is slow).

In another project in a mountainous area, the likelihood of debris flows from slopes above a small town needed to be assessed. A review showed that similar slopes (similar geology, vegetation, climate, aspect, similar or steeper slope) are widespread in the region and a review of 13 sets of aerial photographs covering a period of 50 years revealed no evidence of past debris flows in the region. The area reviewed was about 50 times the area of the slopes of concern. The evidence from the aerial photographs and other evidence (old valley, little colluvium, well developed soil profile and historical information) helped to demonstrate that the debris flow process rate in the region, and above the town, is slow.

#### 4.2.5 *Process rates change with time*

Baynes & Lee (1998) discuss geomorphological principles in landslide risk analysis and point out that the controls on landslide activity are not constant in time and space. Landslide process rate and size frequency models are predictions for defined periods (usually the design life). Process rates change with time and rate changes in the design life must be anticipated and understood.

Cruden (1997) describes a cutting where there was a reduction in the annual average volume of rock falls over time partly because of the effects of remedial measures. Cruden points out that there was insufficient evidence to assess whether rock falls would have reduced anyway as available loose rock failed. Hungr et al. (1999) also report a reduction in rock fall frequency in transportation corridors following remedial measures. At Bethunga (Sections 2.2 & 4.2.1), the average annual vol-

ume of rock falls did not decrease over time. This was probably because time dependent processes such as stress relief, root jacking, and other forms of mechanical weathering caused joints to open.

The LHD Project provides an example where landslide process rates may increase in time (beyond the project design life). The Bulgo Sandstone is a weak rock mass which only forms cliffs because of local oversteepening in the project area caused by marine erosion (Figs 3, 4). In time, as the Bulgo Sandstone cliff fails and begins to flatten, slope retreat rates (and landslide processes) in the higher slope units will increase as the escarpment tends towards the profile in the background of Figure 3 (i.e. no Bulgo cliff). The slope retreat rate of the upper units is likely to increase even if further marine erosion is prevented (e.g. by engineering works). This increase in process rate was not an issue for the project because of the long time scale involved (many hundreds of years) and the risk will be largely avoided below the highest Bulgo Sandstone cliffs with a bridge.

#### 4.3 Regional and site specific studies

Landslide process rate models are particularly applicable to route or regional studies but can also be useful in site specific studies by ensuring that regional evidence/knowledge is brought together and incorporated into the judgements of how a particular slope might behave.

The LHD Project shows how regional knowledge helped develop and calibrate models for particular slopes. While the overall slope rates were identified, it was possible to develop size frequency models for whatever individual part of the escarpment was required.

Tse et al. (1999) also suggest using evidence from areas of similar geological setting when trying to assess the likelihood of infrequent events at particular locations.

While knowledge of the regional performance history is essential, the particular characteristics of the specific slope in question need to be understood. The variety of models shown in Figure 5 for some of the different components of the escarpment at LHD shows how misleading too much mixing of models and observations from different sites could be.

#### 4.4 Interpretation and quality issues

##### 4.4.1 Incomplete observations

Hungr et al. (1999) discuss why data on the size and frequency of landslides is usually incomplete and how such data can be interpreted to reduce errors and Brunsten et al. (1995) discuss how “rules of interpretation” can help in the evaluation of old

records. The interpretation of incomplete data depends on the individual circumstances of the project but it is usually possible to work out what the deficiencies are and take them into account when calibrating size frequency models.

##### 4.4.2 Size observations and judgements

In order to develop size frequency models it is necessary to make judgements about the volume of landslides. When only the plan area is known (or anticipated), the landslide depth can be judged by assessing typical length/depth and width/depth ratios for the geology and geometry and failure mechanism involved and where appropriate using the relationship given by Cruden & Varnes (1996) to calculate volume.

Where a volume has to be estimated from a past event observed by a non-specialist, providing typical dimensions, order of magnitude size categories or comparisons (e.g. the size of a small car) can help assess the size category.

In risk assessment for rock falls it may be the volume of individual blocks at impact which are most relevant. If a jointed rock mass has failed the individual block volume will be smaller than the volume of the intact mass prior to failure and the final mass of debris after bulking. If rocks break on impact and the debris is observed later, the number of rock falls may be overestimated and the largest individual block size at impact may be underestimated. Dents in the road and other evidence can help assess what actually happened (Bunce et al. 1995).

To help understand the risk at the LHD Project, size frequency models were developed for in situ, impact and debris volumes (based on failure mechanisms, defect spacing, fall trajectories and rock strength calibrated against observations). Judgements of individual boulder size at impact helped develop kinetic energy return period relationships for parts of the project where rock shelters and rock fall fences were being considered.

##### 4.4.3 Recognizing patterns and building models

The overall pattern of the inverse relationship between the size and frequency of landslides has been established by many studies (e.g. Dussauge-Peisser et al. 2002, Hungr et al. 1999, Whitehouse & Griffiths 1983). The pattern has also been demonstrated at Bethungra (Moon et al. 1996 and Fig. 2) by probabilistic toppling failure stability analysis based on measured defect characteristics (including orientation, spacing, length). Yokoi et al. (1995) describe how the relative dimensions of landslides are repeated on different scales (self-similar geometry) and establish a similar inverse relationship pattern (for numbers of landslides and lengths and widths) from both observations and fractal models. The well calibrated models devel-

oped for the LHD Project (Fig. 5) demonstrate how the size frequency distribution is related to the geometry, geology and failure mechanisms involved.

The body of knowledge developed (including the patterns established graphically) can provide guidance when models have to be developed for new projects where records and observations are limited.

## 5 CONCLUSIONS

Knowledge of geology, geomorphology and landslide processes can be used to develop landslide process rate and landslide size frequency models. Such models can be developed for both natural and man-made slopes and calibrated against observations. Graphical presentation can be used to show how observations, interpretations and judgements are interrelated and allows different models to be compared.

If the models are based on sound knowledge of slope evolution, slope materials and slope processes they can be used to help make defensible, evidence based judgements of landslide likelihood which go beyond the limitations of the historic record. The approach has worked for a wide range of time scales, landslide sizes and processes.

## 6 ACKNOWLEDGEMENTS

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