DOI: 10.4408/IJEGE.2006-01.S-24

DOES THE BIG QUESTION HAVE AN ANSWER? - POTENTIAL LANDSLIDE SIZE

M.J. McSaveney(*) & T.R. Davies(**)

(*) Institute of Geological and Nuclear Sciences, PO Box 30 368, Lower Hutt, New Zealand
(**) Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand

INTRODUCTION

WHAT BIG QUESTION?

The impact of a landslide on society is determined by many factors but principally its location, speed, and size. Location is with reference to people and their infrastructure, and it is not a fundamental landslide property. In contrast, speed and size convey information relating to a landslides impact on its surroundings. They would be useful information to know in advance of a landslide's occurrence. By "size" of a landslide, we mean any of the quantities of mass, volume, and area (in any projection) that indicate how big it is, or might be, either before or after failure. So the big question is "How big will a landslide be?" Can one determine landslide size in advance of its occurrence?

HOW LONG IS A PIECE OF STRING?

When a question is not specific enough to be answered, it may well receive in reply a well known rhetorical question "How long is a piece of string?" When it is asked, a technically correct answer such as 1026 m is not expected. Nevertheless, much can be said about string lengths: none are negative, many are short, and few are long. A log-normally distributed universe of string lengths is a useful model in string budgeting: it reveals that string expendature can go horribly wrong. When we buy a 10-m roll of string, we do not expect it to be exactly 10 m long, but we might demand that one 9.5 m long be replaced. We do not expect one 15 m long either, but are unlikely to return the extra 5 m. The manufacturer will have anticipated a Gaussian string-length distribution and ensured that the mean value is just sufficiently longer than 10 m that demands for replacement are minimal. An efficient manufacturer will have statistical data on past string sales and will only make enough of a given quality to satisfy an anticipated demand (considering prices of competators' string, and market trends). "How long is a piece of string?" need not be rhetorical – it has a variety of answers. So too with landslide sizes.

When we ask "How big will a landslide be?" we seek a quantitatively useful answer or answers. The question can take many forms: Where along New Zealand's Hutt River valley can such landslides as shown in Figure 1 occur? Which ones might block the river? Along Hutt River's lower reaches, much of the former flood plain is urbanised behind large raised banks. There is no provision in the the flood protection for diverted water to re-enter the main channel. Estimates of landslide volumes are needed to reassess the flood-mitigation design.

In 1991, the summit and northern flank of New Zealand's highest peak fell in a huge rock avalanche. What determined the size of this, or any other historical landslide? Why was it not larger (or smaller)? Mt Cook has had previous rock avalanches and the shape of this and other peaks derives from episodic, large-scale gravitational release of rock masses. What is the statistical size distribution of such landslides? Are the rock avalanches end-members of a rockfall probability-density distribution, or are rockfalls and rock avalanches fundamentally different? Mount Cook is episodically shaken in great earthquakes, but has not been shaken by one in historic time. What is the likely release volume at Mount Cook in the next great earthquake? This event has a probability of 10 percent in the next 20 years!

In March 1929, a M_L6.9 earthquake triggered the release of 50

Figure 1 - In February 2004, following several days of heavy rain, a landslide of some 300000 m^3 fell from deeply weathered bedrock along the scarp of New Zealand's Wellington fault. It briefly blocked flooded Hutt River and diverted it through a golf course, creating a major water hazard and isolating 6 holes. Many other places where such a landslide could divert the river are more highly urbanized. Photograph by Graham Hancox

x 10^6 m^3 from Falling Mountain, on the main divide of New Zealand's Southern Alps. What determined this release volume, and not some other volume? If the earthquake had been larger, could a larger volume have fallen? Why is the size of the Falling Mountain rock avalanche such an anomaly in the region's rockfalls and landslides of March 1929?

We will not answer any of these big questions here; what we wish to address is which big questions are likely to have answers, and which may as well be rhetorical.

"BUDGETING FOR STRING" – REGIONAL LANDSLIDE HAZARD ASSESSMENT

PROBABILISTIC LANDSLIDE HAZARD ANALYSIS - A NEW ZEALAND EXAMPLE

What is the largest landslide volume that might be expected in the Kyrgyz Republic in an average year? This is the most readily answered type of big question. The particular question can be answered only by using probabilistic landslide hazard analysis of Kyrgyz landslide data. Unless a particular site has a historical record of repeating landslides, such landslide data are likely to be for a region or regions, and will not be site specific.

The New Zealand large landslide *inventory* (www.geonet.org.nz) records locations and areas of all known large landslides but we know very few ages. The New Zealand landslide *catalogue* has fewer data, and less precise locations, but it records time of occurrence. For North Island, the *inventory* contains data on 5773 landslides. Statistical analysis provides excellent information on relative sizes of landslides, but no information on rate of occurrence.

Systematic data collection for the *catalogue* started in August 1996. It records landslides as they occur, compiled by daily monitoring of news media and other sources, and special mapping for events that trigger many landslides. The *catalogue* is "complete" for landslides with footprint areas >10000 m^3. These data provide surprisingly useful data on landslide rate despite the as-yet short (7 yr) record.

New Zealand landslide-area probability-density distributions can be modelled as either inverse-gamma (MALAMUD *et alii*, 2004) or double Pareto (STARK & HOVIUS, 2001) distributions. That for all of North Island is illustrated (Figure 2, top). The large landslide portion of the distribution is fractal, with a fractal dimension of 2.56±0.05 (DELLOW *et alii*, in prep). The *catalogue* data have a statistically similar fractal dimension, and combining the two analyses allows the exceedence probabilities of various landslide areas over time to be estimated (Figure 2, bottom) (DELLOW *et alii*, in prep).

Probabilistic landslide hazard evaluation is achievable with appropriate data. There are no methodological barriers preventing estimation of the size of landslide expected in a given area over a specified interval.

"SELF-INDUCED" NEW ZEALAND ROCK AVALANCHES

BACKGROUND

Many rock avalanches in New Zealand's Southern Alps fall without a recognized triggering event, or prior warning. They appear to be induced by static gravitational stress in the mountain rock mass. One at Mt Cook and two at Mt Fletcher are described by MCSAVENEY (2002), and one at Mt Adams by HANCOX *et alii* (1999). Seismic records indicate that the bulk of the energy from the release at Mt Cook was dissipated within 2 minutes (Figure 3). Witnesses describe the main release as being over within 15 minutes, but the roar from falling rocks continued for an hour and a half, and tremor from falling rocks was recorded for most of the day.

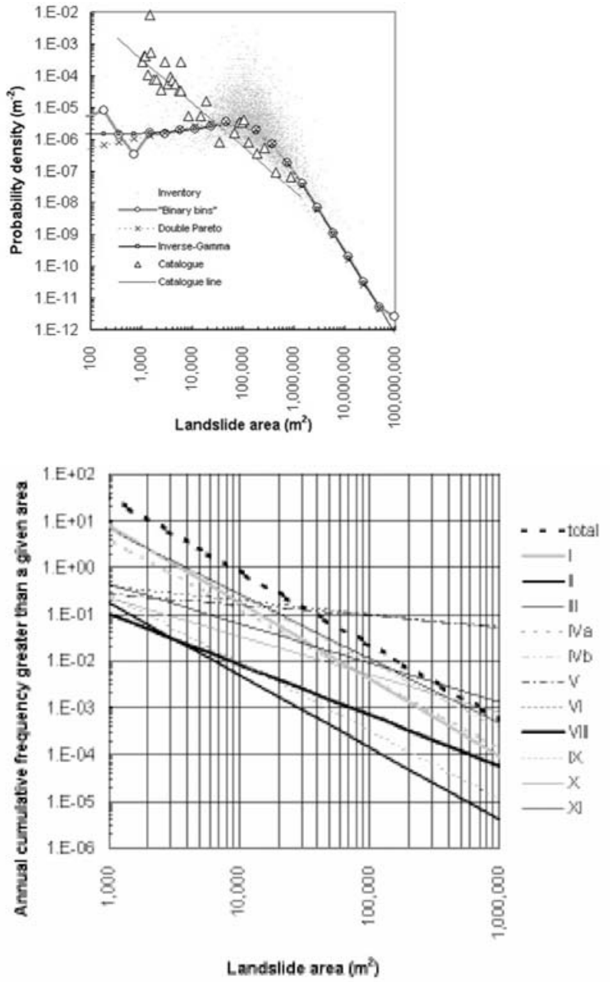

Figure 2 - Top: probability-density distributions of landslide areas for North Island (5773 landslides) in the New Zealand large landslide inventory and landslide catalogue (53 landslides) Such probabilistic landslide analysis for 11 North Island landslide terrains answers the question of what sizes of landslides might be expected in a region over some specified interval (bottom) (from DELLOW et alii, in prep.)

Rockfalls began at Mt Fletcher about the same time, and continued sporadically until the ridge north of Mt Fletcher fell in rock avalanches in May and September 1992. On May 2, witnesses watched several rockfalls during the day, and the whole slope fell that night. Seismic records indicate that the bulk of the energy from the May rock avalanche dissipated within 3 minutes, and similarly in September, but with different phasing and lesser amplitude (Figure 3). There had been numerous large rockfalls from Mt Fletcher over at least the last 50 years, with some involving many thousands of cubic metres of rock, such that the ablation area of Maud Glacier has been kept covered by rock debris. On 6 October 1999, a rock avalanche of some 10-13 x 10^6 m^3 fell from near the summit of Mt Adams and blocked Poerua River (Hancox *et alii*, 1999). Seismically, it was a more abrupt event than the other three examples (Figure 3) indicating a single dominant release as at Mt Cook.

DEVELOPMENT OF RELEASE VOLUMES

McSaveney (2002) reports on slope-stability modelling for Mt Cook. In order to model a deep-enough release surface, he invokes rock-mass inhomogeniety - a stress-release joint system subparallel to the face of the mountain, but dipping slightly more steeply. Because of the low factor of safety calculated for small failures near the base of a buttress, he suggests that the avalanche did not instantaneously release on one surface, but was a rapid cascade of releases that extended up the slope. This analysis is too simplistic. The seismic record comes from the highest rate of energy dissipation in a cataclysmic phase of failure. Preceding this was an unrecorded phase of accelerating creep. Stress redistribution during creep is likely to have progressively developed a single release surface. If creep began at the most highly stressed location, it would have begun near the surface in the lower slopes of a rock buttress, and propagated from there up and into the slope, intersecting numerous stress-release joints. Creep did not lead to any external change that could be recognized as unusual by untrained observers scaling the summit in the early hours of the previous day, or in passing aircraft during the latter parts of the day until sunset. Accelerating creep in the lower slope is likely to have shown as an increasing frequency of rockfalls, but no frequency change was reported. We surmise that the accelerating creep phase was brief, possibly less than a few hours. No unusual rockfall or ice-avalanche activity was noted until people were alerted by the main collapse. Retrogressive failure appears to have been "minor" and due to stress-release cracking in the remaining "intact" rock mass. An "interrupted" slump of ~0.5 x 10^6 m^3 remains on the right upper flank of the release surface. Spalling of rocks from the release surface continued for some weeks, diminishing exponentially from a maximum in the moments after the primary release. Hence, we reason that a cataclysmic release of the rock avalanche took away a 700-metre buttress and the summit in one flowing surge of rapidly collapsing rubble on a single release surface. The principle release volume (~90 percent or more) was in the main event, followed by an exponentially declining series of stress-release rockfalls that diminished in volume and frequency over weeks.

The Mt Fletcher release sequence differed from that at Mt Cook. First, the Mt Fletcher releases were not isolated events. There had been a sporadic sequence of rockfalls and rock avalanches over decades, with two rock avalanche within months that clearly are causally related. Second, the seismic records of the three rock avalanches are different (Figure 3). If Mt Cook was a single-phased release, then the two Mt Fletcher events cannot possibly be single phased. The May and September rock avalanches fell from the same location and traveled the same path; seismogram differences can only be from differing styles of release of the source masses. McSaveney & Downes (2002) read the May seismograms

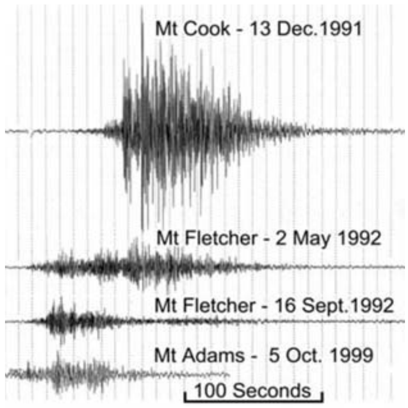

Figure 3 - Top: the east face of Mount Cook collapsed in December 1991 releasing an avalanche of 12 x 10^6 m^3 of rock and ice. Based on seismogram interpretation, the bulk of the rock mass broke from the source in the first 20 seconds of the rapidly escalating collapse, and almost all of the mass was in simultaneous motion. Photograph by Lloyd Homer
Bottom: vertical component seismograms of four large rock avalanches in New Zealand's Southern Alps showing evidence of different phasing of mass release in the various rock avalanches. All from the one station (Berwen) and displayed at equal gain. (details are discussed in McSaveney & Downes, 2002). Photograph by Lloyd Homer

as indicating that the May event escalated “slowly” and had one main but “extended” phase. The September release escalated more rapidly but was not as large as the May event. As the first phase of the September release began to die away, a late release phase, smaller than the earlier phase began, and was prolonged relative to the first phase. Thus, the releases from Mt Fletcher may be retrogressive failures. The whole sequence of rockfalls and rock avalanches can be interpreted as a series of retrogressive failures. The underlying cause of this sequence appears to be rock-mass creep consequent on melting of buttressing ice formerly supporting a structurally weak rock mass forming the right lateral margin of the valley of Maud Glacier (McSaveney, 2002). The structural weakness arises because Mt Fletcher is formed in the hanging wall of the low-angle, reverse Main Divide fault, and its rock mass is very closely jointed. Beginning in late 1991 was a phase of accelerating rock-mass creep when rockfall frequency increased. Stress redistribution in the rock mass of Mt Fletcher is likely to have been over the long term during the thinning of Maud Glacier over a period of more than 100 years. The creep phase has been ongoing for many decades, during which, the rock mass has dilated. A protracted phase of accelerating creep on the lower slopes of the ridge led to an increasing rockfall frequency. There were several large falls in the hours before the rock avalanche in May. Diminishing stress-release spalling of rocks from the failure-surface scar continued for months after both major rock avalanches. The principle mass of the release sequence was split between two main events in a ratio of 2.6:1 (McSaveney & Downes, 2002), with perhaps as little as ten percent in pre- and post-rock-avalanche rockfalls.

PROSPECTS FOR PREDICTION

In the above failure scenarios, the initial Mt Cook rock-avalanche mass was defined by propagation of a release surface during creep prior to cataclysmic failure. Hence static 3-D stability analysis of the slope with appropriate generalized rock-strength parameters would have given a useful estimate of the release volume. The summit flanks of Mount Cook appear to have a modal release volume of ~3.6 - 36 x 10^6 m^3 under static loading. The location and volume of the next “self-induced” failure is determined by the current topography and generalized *in situ* rock-mass strength and might be found by searching the existing topography for the site causing the highest local stress concentrations in the rock mass. A great earthquake on the nearby Alpine fault could trigger some of these impending “self-induced” failures, but also could trigger a much-more deeply seated failure. In the Mt Fletcher scenario, the rock avalanches are only parts of a lengthy sequence of progressive failure. Static 3-D stability analysis of the slope with appropriate generalized rock-strength parameters can be expected to give only an estimate of the total volume, and not of the individual components. Nevertheless, we infer that the flanks of Mt Fletcher have a gross modal failure volume similar to that at Mt Cook, ~3.6 - 36 x 10^6 m^3 under static loading. To determine the volume of the next failure in the sequence will require specific knowledge of the thickness and extent of the dilated, creeping rock mass of the larger failure. The obvious rockfall hazard of the site precludes any prospect of obtaining *in situ* geotechnical parameters for the mountainside.

EARTHQUAKE-TRIGGERED ROCK AVALANCHES

NEW ZEALAND’S 1929 FALLING MOUNTAIN ROCK AVALANCHE

On 6 March 1929, 50 x 10^6 m^3 of closely jointed rock were released from near the summit of Falling Mountain (Figure 4) (McSaveney *et alii,* 2000). Although it is the first historical rock avalanche from here, it was not the first release from the local valley wall. An adjacent valley was truncated prehistorically at Tarn Col by cataclysmic loss of its headwaters.

At the top of the source area, the main scarp is about 900 m wide. The main scarp and flanking scarps of the release surface bite deeply into the mountainside. The slide was thicker (up to 100 m) in the crown area. There are no visible crown cracks.

CONTROLS ON VOLUME

The remnants of Falling Mountain show evidence of “ridge renting” or Sackung, and it is tempting to ascribe the size of the failure to the spacing of specific defects associated with the ancient Sackung. However, there are many mountain ranges in the vicinity with similar Sackung and no rock avalanches, and Sackung still survive on Falling Mountain. The geometry of surviving defects does not suggest that the landslide release surface was controlled by pre-existing defects; rather the landslide simply exploited favourably located defects. The defect supply was not exhausted. Many small rockfalls occurred from surrounding slopes in the area, but no other

Figure 4 - Falling Mountain on the main divide of New Zealand’s Southern Alps. The distinctive deep release surface indicates an earthquake trigger. The release volume is almost as predictable as the earthquake location and magnitude. A Sackung ridge crosses the right mid-flank of the mountain. Photograph by Lloyd Homer

long-runout landslides occurred in that event. The Falling Mountain rock-avalanche volume is an extreme outlier among landslides triggered by the March 1929 earthquake. The controls appear to have been the precise location and magnitude of the earthquake.

PROSPECTS FOR PREDICTION

There is prospect for a specific estimate of earthquake-triggered landslide volume when earthquake location and magnitude are predictable. Meanwhile, there are other challenges for seismic slope stability.

There is a family of very deep-seated earthquake-induced rock-avalanche scars that differ markedly from the "thin-slab" failures that occur between earthquakes. These deep-seated failures arise because the rock mass under seismic loading behaves as if it were a weak rock under static loading. It is not in fact weak, it arises because the triggering force is large in comparison to the *in situ* rock-mass strength. Important factors in seismic triggering of landslides are topographic amplification of seismic wave energy, including double-amplitude seismic displacements at reflection of seismic waves. These are not only surface phenomena, they also occur at internal rock-mass defects and velocity contrasts.

A question arises in earthquake-induced landsliding: "If the earthquake were larger, or closer, would the landslide have been larger?" This question cannot be answered empirically: it is impossible to test the same slope to failure under different loading conditions. Among people who claim that the sizes of landslides are determined by pre-existing defects, is a significant subset that claim that if the earthquake had been larger or closer, a larger landslide would have been triggered. How is this possible if pre-existing defects are the control? Do the defects move? An explanation of the role of rock-mass defects comes from failure theory. When materials break, they always break at pre-existing defects, but the breakage is not defect controlled – other, sometimes weaker defects do not break. As stress increases in the rock mass, pre-existing defects that are appropriately aligned to the stress tensor grow while others are inhibited. Failure occurs when sufficient defects coalesce. In this model of failure, a larger or closer earthquake causes a larger landslide from the same site if it activates different and deeper defects. The mechanism of seismic triggering of landslides in brittle rock, however, is not well understood and a number of plausible hypotheses are available. This limits the practicality of numerical modeling to accurately determine the volume of failure. One method of overcoming the inability to investigate the question empirically is through physical modeling. We currently are developing apparatus to investigate this problem.

CONCLUSION

A long-recognized fundamental problem in long-runout landslides is predicting their reach for hazard assessment. Let us consider in a flight of fancy that we have solved the problem of the physics of landslide runout and have an infallible numerical model for predicting the reach of landslides. We can be certain that a key input parameter in this model will be information on the landslide mass or volume. We have to know how big a landslide will be in order to predict its potential runout, or the size of the dam it may form. There are people (probably many people) among us who do not believe that the size of landslides can be determined in advance without a great deal of costly geotechnical investigation. Is it possible that they are mistaken? There is an analogue computer out there that gets the answer right every time. If more effort is put into researching this "big" problem will we obtain useful answers in the intermediate or longer time? One starting point might be to identify failure mechanisms where there might be "simple" solutions, and those where there might not. When we know how big a landslide is going to be, then the calculation of its shape at the end of its runout will have much more meaning.

Edifice shape appears to be much more important than specific, weakest defects in determining the shapes of release surfaces, and so the probability-density distribution of potential failure sizes from a site is intrinsically estimable from topography, general knowledge of the rock-mass characteristics, and the probability-density distributions of potential triggering events. When, however, is quite another question.

ACKNOWLEDGMENTS

This work is funded by the Institute of Geological and Nuclear Sciences and the Earthquake Commission through GeoNet, and by the New Zealand Foundation for Research, Science and Technology through the Public-Good Science Fund.

REFERENCES

DELLOW G., MCSAVENEY M.J., STIRLING M.W., LUKOVIC B., HERON D.W., BERRYMAN K.R., & PENG B. (in preparation, 2004) - *Probabilistic landslide hazard in North Island, New Zealand, from landslide magnitude-frequency distributions.* Institute of Geological & Nuclear Sciences Ltd, Lower Hutt, New Zealand.

HANCOX G.T.; MCSAVENEY M.J.; DAVIES T.R. & HODGSON K.A. (1999) - *Mt Adams rock avalanche of 6 October 1999 and the resulting landslide dam and lake in Poerua River, Westland, New Zealand*. Institute of Geological & Nuclear Sciences Science report 99/19.

MALAMUD B.D., TURCOTTE D.L., GUZZETTI F., & REICHENBACH P. (2004) - *Landslide inventories and their statistical properties*. Earth Surface Processes and Landforms, **29**: 687–711.

MCSAVENEY M. J. (2002) - *Recent rockfalls and rock avalanches in Mount Cook National Park, New Zealand*. In Evans, S.G. & DeGraff, J.V. (eds). Catastrophic landslides: occurrence, mechanisms and mobility. Geological Society of America Reviews in Engineering Geology, **15**: 35-70.

MCSAVENEY M.J. & DOWNES G. (2002) - *Application of landslide seismology to some New Zealand rock avalanches*. In Rybar, J., Stemberk, J. & Wagner, P. (eds) Landslides. Balkema, Lisse, ISBN 90 5809 393 X. p. 649-654

STARK C.P. & HOVIUS N. (2001) - *The characterization of landslide size distributions*. Geophysical Research Letters, **28(6)**: 1091-1094.