

Report on:

Mauao Slopes: May 2006

Rockfall & Landslide Risk Review



Client: Tauranga District Council

July 2006

Avalon Report No: 0627 A

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EXECUTIVE SUMMARY

Avalon specialises in geotechnical consultancy on rock and soil slopes and has undertaken investigation and Quantitative Risk Assessment (QRA) to assist TDC in assessing whether the rockfall risks on Mauao are acceptable. Over the last three years our understanding of the processes involved has improved greatly although some parameters in the QRA remain judgmental.

Since 2003 Mauao has experienced a series of rockfall and slips triggered by; fire, minor earthquake, intense rainfall, ongoing erosion and human activities. These events necessitated remedial actions to the tracks and slopes.

Large naturally falling boulders on one occasion came very close to the campground and members of the public have been seen accidentally dislodging rock which has fallen onto tracks below.

Reports were produced in response to each event. In early 2006 a peer review was carried out by Terrane Ltd which discussed the subjective issues, largely concurring with Avalon's findings. TDC subsequently requested Avalon carry out this review, summarising events to date and re-working the QRA, in association with Terrane.

Rockfall Risk

The statistical likelihood of rockfall affecting various publicly frequented areas and causing fatalities has been estimated. Probable triggers of rockfall, their respective frequencies and visitor patterns were taken into account when calculating the risks.

One of the main destabilising influences is erosion, exacerbated by the slow speed at which vegetation has re-established following the 2003 fires. The soils on the steep upper slopes are rockfall debris in wind blown sand. Grass is extremely beneficial in binding the surface and without it wind and rain soon scours sand away revealing new loose rock on the surface and eventually triggering rockfalls.

Rock scaling reduces the hazard but the benefits are being continually offset by scour on the steep upper slopes, many of which are now littered with loose rock.

Quantitative risk analysis is a relatively recent development and is not an exact science. QRA should be used only as a tool to assist in decision making. Few organisations publish risk criteria and acceptable values are not universally agreed (although the general principles are).

The QRA indicates that the current rockfall risk on the North Western Oruahine track (under the rock climbing areas) may be ten to one hundred times greater than on the other upper tracks and is likely to be above acceptable limits for all but the briefest of visitors.

The risk on the other tracks may be tolerable for the average visitor but should continue to be managed and kept as low as reasonably practicable.

The rockfall risk to a typical person camping on the slope boundary row of campsites in the campground may begin to become questionable with a stay time of more than a month or so, although even then it is calculated as well over ten times smaller than the risk taken by the person who walks the Oruahine Track for once a week.

Mauao's high visitor numbers lead to significant total exposure and a calculated rockfall fatality return period in the order of ten years given the current frequency of rockfalls.

Rockfall Risk Mitigation

Some contributing factors to the current level of rockfall risk can be mitigated relatively easily.

TDC's planting and weed control programme should give priority to getting grass established on the loose colluvium and must take care to prevent any drift when weed spraying.

One of the most significant triggers of rockfall is thought to be persons crossing the very loose steep slopes off-track, including TDC's contractors. Preventing off track public access (rock climbers exiting the top of the routes) to the slope above the North West Oruahine track will significantly help mitigate the local risk. There also appears likely to be a justifiable in installing a number of discrete, unobtrusive catch fences in rockfall concentration locations.

The hazard to the Campground may be most cost effectively mitigated by close attention to monitoring and controlled scaling at the rockfall source areas although design options and cost benefits of a catch fence continue to be worth further consideration.

Regular rock scaling programmes are an effective management option that are well proven overseas to minimise exactly this type of hazard and is recommended as an ongoing annual operation.

Avalon is continuing to carry out monitoring inspections at six monthly intervals.

Landslip

Landslip hazard was briefly considered some years ago and was evaluated as a low risk. The May 2005 flood event included one large slip on Mauao's lower South West slopes which prompted Avalon to re-examine the potential for slips.

Mauao's lower slopes form an almost continuous series of slip scars, some of which would have released very large debris flows into what is now the campground.

The May 2005 flood was (approximately) a 1 in 100 year event. A very preliminary assessment shows that if a similar slip occurs with this frequency then slips may represent a greater threat to the campground than rockfall.

Further investigation is required if we are to better understand the landslide process, hazard and risk. Investigation should aim to determine the soil material properties, hydrology, rockhead profile and above all the age of the scarp features.

It is recommended that no absolutely no earthworks or drainage works be carried out in or above the campground without serious consideration of the potential consequences.

Safe access

It is extremely difficult to walk any distance on the steep upper slopes without dislodging rock. All persons accessing these areas pose a serious hazard and this is as applicable to TDC staff and contractors as it is to the public.

During Avalon's operations the public have ignored signs and even dodged security guards. Track closures must be effective during any operations on the slopes.

Using ropes for access and fall arrest is the only practical means of complying with OSH guidelines and the HSE Act whilst working on the steep slopes. However, ropes increase the hazard as whilst running over the loose ground they can trigger rockfall.

More hazardous accidental rockfall is likely from trainee and inexperienced rope access operatives. Using only experienced industrial rope access contractors will minimise the hazard.

Recommendations

- For the North West Oruahine Track, the highest risk area, measures should include access restriction, rock scaling and consideration of fences.
- The hazard to the Campground is likely to be most cost effectively mitigated by monitoring and controlled scaling at the rockfall source areas (if necessary) although catch fences continue to be an option.
- TDC's planting and weed control programme should give priority to establishing grass to help stabilise the loose steep upper slopes.
- Public off track access to the steep upper slopes should be prohibited, particularly the rock climbers top exits.
- Effective track closures must be in place before any TDC staff or contractors access the steep upper slopes off track. Any persons entering these areas must be suitably experienced, competent, trained, equipped, insured etc.
- Monitoring and inspection should continue six monthly.
- Annual rock scaling is recommended.
- No earthworks or drainage works should take place in the campground without careful consideration of slope stability.
- Investigation should aim to determine the age of Mauao's lower landslip features.

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1 INTRODUCTION

1.1 Background

Avalon specialises in Geotechnical Engineering services in difficult and high access environments. s 7(2)(a) Privacy has specialised in slope stability for over 16 years.

In 1999 a Mauao Stability Assessment report was produced for Tauranga District Council (TDC) by Dr Laurie Richards, Rock Engineering Consultant. Dr Richards recommended Avalon for ongoing consultancy work.

Detailed investigation of Mauao's slope hazards was prompted following widespread fire damage in January 2003.

Over the last three years Avalon's investigations have included rockfall and slip hazard and risk assessments in response to fires, earthquakes, floods and human activities. All these events, investigations and responses were documented and reported to TDC. This has allowed Avalon to build up an understanding of the processes and risks on Mauao.

1.2 Peer review

In February 2006 a peer review of Avalon's reports to date was presented to TDC by s 7(2)(a) Privacy Engineering Geologist with Terrane Ltd.

On 3 April 2006 a meeting was held between TDC, Avalon and Terrane, to review the work to date.

Remaining differences of opinion were agreed to be largely matters of engineering judgment, rather than definitive differences based on fact.

Possible approaches to future risk management were discussed, including; investigation, monitoring, access management and physical works.

s 7(2)(f)(ii) with TDC requested Avalon produce a report which would review events to date, rework the numerical risk assessment and resolve some (relatively minor) points of difference between the peer review and Avalon reports.

As the information to date had been spread through a number of reports, some of which are rather technical, it was realised it could be difficult for the Mauao Steering Group to interpret.

This report reviews the previous Mauao slope risk investigation works and attempts to present the state of our knowledge at this time, in a more accessible format than used previously.

1.3 Previous correspondence

The most significant events and correspondence have been:

<i>Date</i>	<i>Item</i>
March 99 31/3/99	Dr Laurie Richards. Sitework for stability report. Dr Laurie Richards. <i>Mauao Stability Assessment</i> . Report to TDC.
January 03	Extensive fires affect 10% of Mauao's slopes.
19/2/03 20/2/03	Dr Laurie Richards. Site visit to review rock slopes following the fire. Dr Laurie Richards. <i>Mauao Rockfall Review</i> . Letter to TDC.
March 03 21/3/03 12/7/03	Avalon. Rock scaling and hazard investigation. Avalon. <i>Mauao Slope Remedial Works Interim Report</i> . Report to TDC. Avalon. <i>Mauao Rock Slopes & Rockfall Hazards</i> . Report to TDC.
October 03 26/10/03 7/11/03 14/11/03	Avalon. Routine monitoring visit finds spalling and instability on Camp Bluff. Avalon. <i>Mauao Camp Bluff Investigation</i> . Report to TDC. Avalon. <i>Mauao Camp Bluff Drill & Blast Proposal</i> . Letter to TDC. Avalon. Blast scaling to eliminate extreme hazards on Camp Bluff.
13/1/04 15/1/04 16/1/04	TDC Mauao Ranger finds movement of 3t boulder on NW slopes. Avalon site visit and scale the boulder plus routine monitoring inspection. Avalon. <i>Zone 4 Boulder Scaling Works</i> . Letter report to TDC.
2/2/04 26/6/04	Avalon. <i>Mauao Rockfall Risk Assessment & Management</i> . Proposal to TDC. Avalon. <i>Mauao Rockfall Risk Assessment & Management</i> . Report to TDC.
18-22/7/04 22/7/04 26/7/04	Mauao experiences minor earthquake swarm triggering many rockfalls & slips. Avalon. Damage inspection following quake. Avalon. <i>Earthquake Damage & Revised Risk Assessment</i> . Report to TDC.
23/11/04	Avalon routine monitoring visit.
9/3/05 10/3/05	Avalon routine monitoring visit. Avalon. <i>Mauao Slopes; Routine monitoring report</i> . Report to TDC.
18/5/05 June 05 24/6/05	Mauao receives 350mm of rainfall in 24hrs and experiences multiple slips and rockfalls. Avalon. Damage inspection and hand scaling following floods. Avalon. <i>Proposal for stabilisation on 4wd track hairpin</i> . Letter to TDC.
22/6/05 22&23/6/05 27/6/05	2-3m diameter boulder naturally fails and rolls 25m to rest at camp fence. Avalon. Inspection & movement of boulder into stable position. Avalon. Inspection of lower slope areas above campground (Zone 6).
28/7/05	Avalon. <i>Mauao Slopes; Zone 6 Hazard & Risk Assessment</i> . Report to TDC.
2/8/05	Avalon. <i>May 05 Flood Damage & Slope Remedial works</i> . Report to TDC.
29/8/05-2/9/05 30/8/05-1/9/05 5/9/05	Avalon. Installation of minor erosion control on 4WD hairpin. Avalon. Zone 6 Boulder scaling. Avalon. <i>Zone 6 scaling report</i> . Letter report to TDC.
31/9/05	Rockfall on mid slopes above campground kills two sheep.
14/12/05	Avalon routine monitoring visit. Mauao Ranger reports rockfall onto W Oruahine track caused by climbers.
22/2/06	Terrane. <i>Mauao Rockfall Hazard – Peer review Report</i> . Report to TDC.
1/3/06 3/3/06	Mauao Ranger reports hazardous rock on upper E slopes. Avalon. Site inspection finds severe scour has developed unstable Boulder approx 1t. Also sees climbers causing rockfall. <i>Email report to TDC</i> .
22/3/06	Avalon. Scaling to remove 1/3/06 boulder. Monitoring of W slopes.
3/4/06	Meeting at TDC to discuss peer review.

2 DISCUSSION OF THE PEER REVIEW

All questions raised by Terrane's peer review are commented on below. These points were discussed at the review meeting. Extracts from Terrane's document are in blue italics and Avalon's replies are given below:

3.0 ROCKFALL RISK ASSESSMENT

The quantitative risk assessment (QRA) given in the Avalon reports appear to be generally reasonable. We would note the following:

- *The QRA includes a number of assumptions. It is important to appreciate that several of the factors used in the analysis are subjective. The two factors which appear to have the greater subjectivity are (1) exposure distances and (2) the vulnerability to fatality;*

Rockfall frequency may be equally subjective, if not more so. Exposure distances have been identified by analysis of actual rocks falling during scaling operations. The remaining uncertainty is likely to be within $\pm 50\%$. Vulnerability can only be between 0 and 1 the assumptions made are unlikely to vary by more than, again $\pm 50\%$. Some elements of rockfall frequency, particularly the human triggered component, could be inaccurate by an order of magnitude.

- *Vulnerability (the probability of death if directly in the path of a boulder) for persons within the campground was assessed as being 0.5. This could be slightly low given that it relates to the 12 hours per day that a site was occupied;*

This is judgmental. It was discussed in the peer review meeting and in this report has been increased from 0.5 to 0.7. *

* Other refinements in this review report in regard to vulnerability include allocating realistic values with different track sections and in assuming the persons 'target' dimension when on a track is 0.5m rather than the 1.0m used previously (this immediately halves the calculated risks).

- *For the Waikorere and Oruahine tracks, the total length of each track appears correct, however there does not appear to be allowance for concentration of boulders within gullies/rock clefts. While the frequency of rock falls would increase for these sections, the reduction in risk over the majority of the track segment would be likely to reduce the calculated probability of a fatality;*

The increased risk (frequent rockfalls but low exposure time) for the person in the gully affected section of the track would be balanced by the decreased risk for the (fewer rockfalls but longer exposure time) remainder of the track. If a fatality occurs it is more likely to occur below a gully and the fact that gullies might offer an opportunity for relatively small and non-obtrusive yet effective risk mitigating catch fences has been mentioned previously.

- *The threshold of considering only boulders at least 1m³ size appears reasonable;*
- *Based on the boulder run-out paths resulting from the blasting of 2004, the 50 m distance for penetration into the campground could be considered to be somewhat on the high side, but probably not worth specifically changing;*

The initial report [and this report] assumed only the first row of camp sites along the boundary to be at risk. Run-out distance was used when looking specifically at the large Zone 6 boulders, many of which have now been scaled (20m put 50 sites at risk). This methodology was not explained in detail previously.

- *The acceptability by society of a multiple fatality event is lower than for a single fatality event. The very large boulder that moved in June 2005 would have been sufficient to put at risk more than one person occupying a tent site;*

Slips which could result in debris flows into the camp, although also rare events, have the potential to cause multiple fatalities.

- *The QRA analysis correctly includes rockfalls generated by humans. The scaling of obviously loose boulders would have significantly reduced the proportion of risk originating from deliberate (vandal) action;*

Very significant rockfall risk remains associated with human activities, the majority of which are probably accidental rather than due to vandals. On the steep slopes it is almost impossible not to trigger rockfall if off track.

Scaling did reduce the quantity of loose and marginally stable surface rock, however, where grass has not become re-established, ongoing scour since the fires has now re-created a situation similar to immediately following the fire, with loose surface rock littering the ground.

- *Assessment of the recurrence frequency of events is not an exact science and some factors may be subject to revision in the future. A good example of this is the recent revision of rainfall storm intensities within Tauranga City, where recent revision of rainfall events in Tauranga (including five years of rainfall data and including the May 2005 storm event) resulted in rainfall of 280 mm within a 48 hour period previously categorised as a 100 year return period event is now considered to be a 35 year event.*

The Avalon report for Zone 6 concluded that the overall level of risk appeared to be marginal (page 24). It is not clear whether this included or excluded the risk posed by the approximately seven highest-risk boulders which were subsequently stabilised.

The seven boulders were included and the risk is now reduced. The calculation within this report takes this into account.

A sensitivity QRA analysis varying the factors mentioned above and other parameters confirmed that a range of outcomes/levels of risk can be conceived. However, given the inherent uncertainties within the QRA, this would be unlikely to shed any more clarity on the issue.

Overall, the conclusion given in the Avalon reports that the level of rockfall risk at Mauao is towards the upper end of what would generally be considered acceptable in terms of landslide risk, appears to be slightly on the high side, but it is definitely within the range that requires Council to carefully assess and then manage the risk on an ongoing basis.

The previous reports estimated the incremental risk on the Western Oruahine as 2E-7, largely being due to human induced rockfall (assumed at 20 rocks per year). More recent observations suggest one person traversing 100m of slope would be likely to trigger at least one rock.

In this [review] report we have refined the model and, assuming 100 rocks triggered annually by human above the Zone 4 Oruahine track, calculated the incremental risk at 1.5E-6; an order of magnitude greater. This may still be an underestimate; we do not have reliable data on how many persons go where off track.

4.0 POINTS OF DISCUSSION

4.1 Management of Future Rockfall Risk

Natural weathering processes will continue to generate potential rockfall events.

The scaling work undertaken to date is a reasonable management tool.

It is important to appreciate that periodic inspections and scaling work will reduce but not eliminate the risk of future rockfall events.

A key question is what level of risk of injury or fatality is considered to be acceptable. We concur with the Avalon conclusion that the level of risk of a fatality due a rockfall is within normally accepted levels (annual exceedance probability less than 10⁻⁶ and preferably less than 10⁻⁷).

New data leads us to estimate the highest risk at 1E-6 for a single walk. This may no longer be an acceptable level.

The work undertaken by the management team over the last 8 years or so has significantly reduced the level of rockfall risk (regular inspections, rock scaling, rodent control, restrictions on access to unstable areas, etc).

The improvements due to previous scaling are being lost due to ongoing scour. Access might not have been sufficiently restricted to the more marginally stable areas off track, particularly as far as rock climbers are concerned.

If the current level of risk is judged to be unacceptably high, then (1) the risk of dangerous rockfalls must be reduced and/or (2) protection measures must be put in place to reduce the risk to people.

Techniques such as rock netting and bolting could be used to reduce the magnitude of the hazard, but would be very unlikely to be acceptable.

There is a significant difference in the vulnerability and exposure time of people walking along tracks and those within the camp ground. Accordingly, if a material reduction in the overall rockfall risk was deemed to be necessary, then the logical approach would be to concentrate on the eastern slopes.

Avalon would recommend that the simplest mitigation be effected for the highest risk area; the Zone 4 Oruahine track and would be achieved via; regular scaling, access restriction, rock climber education, grass growth and possibly small catch fences (in no particular order).

The rockfall risk to campers is significant, now at 2E-7 for a 1 week stay (previously 4E-7) and might be the second priority to address.

Given requirements such as visual effects, the best approach would be to install rockfall fencing along the upslope fence line of the campground.

Given the iconic status of Mauao it would be essential that any protection system be discrete and have no irreversible impact.

While not cheap, construction of the protection fence can be staged, with the highest risk corridors installed first.

We would expect this approach would give a significant reduction in the level of the rockfall risk.

4.2 Rock Scaling Programme

The latest Avalon report (for Zone 6) recommends that rock scaling be undertaken on an annual basis as part of the risk management programme. The scaling work undertaken up until now has certainly removed many of the highest risk situations. However:

- the work undertaken to date has included a "historical catch-up";

Unfortunately much of that work has now been offset by new rock appearing due to accelerated scour post-fire, particularly where grass has not re-established.

- removal of rocks can lead to increased soil erosion and loosening of adjacent rocks;

Yes, if poorly controlled. This is why experienced personnel must be working under the direction by an Engineering Geologist and removing only surface rock, preferably picking it over by hand.

- the rate of weathering the Mauao rhyolite is slower than (say) greywacke; and

Yes, the rhyolite outcrop was reasonably well scaled previously and as ongoing weathering will be relatively slow we would not anticipate development of many new rockfall hazards on the outcrops.

The main problem now however is not the rock outcrop; it is the weathering of the colluvium; wind and rain scour of the sand and silt component revealing new surface rocks and boulders.

- *no matter how extensive, rock scaling can only reduce – but not eliminate – the risk of sudden rockfalls.*

Scaling will never remove all hazards but an approach to these types of natural hazards is that annual scaling returns a continual reduction in the levels of risk and as far as we are aware it is common practise internationally.

Accordingly, we have reservations about the benefit of an annual rock scaling programme for Mauao. It is perhaps a question of phraseology rather than intent. The periodic inspections by TCC staff and Avalon should be continued. It is important that as much continuity is achieved as possible.

Hopefully the above comments better explain and address these reservations.

4.3 Soil Slide/Flow Failures (“Mass Slips”)

There are several very large, vacated landslip scarps within the lower parts of the colluvial fan around the mountain. They are referred to as “mass slips” in the Zone 6 report by Avalon, which also raises the question as to whether these features represent an additional slope stability hazard to that posed by rockfall.

To our knowledge there is little or no substantive data on these features. Judging by their size and location we would interpret that they are pre-historic features (c.f. Avalon’s description as historic slips) and probably related to sea level fluctuations – that is, thousands to tens-of-thousands of years old.

Historic (technically incorrect) was used as these features appear too sharply defined to be thousands to tens of thousands of years old.

Regarding eustatic sea level changes; our review of the easily available research appears to suggest sea level has not been significantly higher on Mauao (within 1m) for the last 6,000 years.

Overall the risk posed by this type of failure appears to be low to very low and somewhat less than indicated by the Avalon report. Notwithstanding this, it is appropriate for them to be considered further. The engineering geological assessment should include geomorphic mapping, assessment of topsoil/subsoil development within the landslip scarps, stability analysis, and radiometric dating if suitable samples were obtained.

We have observed the active formation of these features; the May 2005 rainfall event generated one 8,000m³ slip (along with many smaller) which resulted in fresh scarps appearing like those in question. If this (35 to 150yr return period) event generated one large slip then is this representative? If so then we might expect at least, say, 10 such slips in 1,000 years. If they are evenly spread over the colluvial apron the camp ground might receive two of these. This is the line of logic which leads us to believe the possibility should probably be further investigated.

The preliminary calculation within this report suggests the incremental risk to an individual on a one week stay may be in the region of 1E-6.

5.0 SUMMARY OF KEY RECOMMENDATIONS

- (a) Continue the current programme of periodic visual inspections, by both parks staff and geotechnical consultants (Avalon).*
- (b) Confirm the level of risk deemed to be acceptable within the campground sector.*
- (c) Assess the viability of a rockfall fence on the upslope side of the campground. A staged approach would reduce costs.*

(d) Review the regime for periodic rock scaling – better to be on an “as required” basis than consistently annually?

(e) “Mass slips”: undertake an engineering geological investigation to better assess the age of these relic soil slide/flow failures. This should include consideration of post-event development of the topsoil/subsoil profile, radio-metric dating (if possible), etc.

(f) Confirm the methodology, cost etc, for rapid installation of a telemetered monitoring network, should this become necessary at short notice in the future.

(g) Eradication of pests who burrow under/behind the boulders has distinct benefits to the mitigation of the rockfall risk. Although unlikely to occur, any decrease to the current (intensive) programme should be considered in the rockfall risk assessment.

- (a) Is being done.
- (b) To be considered by TDC; this report should assist.
- (c) To be considered by TDC; this report should assist.
- (d) To be considered by TDC; Avalon recommends regular scaling.
- (e) To be considered by TDC; this report should assist.
- (f) To be considered by TDC (reaction time may be too slow).
- (g) Programme should be continued.

3 INTRODUCTION TO QUANTITATIVE RISK ASSESSMENT

The process used is based on that outlined by the Australasian Geomechanics Society in NZ Geomechanics News, Dec 2000* and is consistent with AS/NZS 4360:1999 "Risk Management".

The risk management process comprises three components:

- Risk Analysis
- Risk Evaluation
- Risk Treatment

The process involves answering the following questions:

- What might happen?
- What damage or injury may result?
- How likely is it?
- What can be done about it?

Risk is by definition a measure of the probability and severity of the consequences of a hazard. This report is concerned with the likelihood that rockfall will kill a member of the public on Mauao.

Although quantitative risk assessment (QRA) gives a numerical value to the risk, many of the inputs into the process require subjective judgment. Strictly speaking the assessment is only semi-quantitative, although professional engineering judgment and experience are valid and accepted when developing this type of model.

The QRA is a systematic approach intended to assist in understanding the problem and determining whether the current risk levels are acceptable or tolerable and also to identifying the relative risk in different areas on Mauao, allowing prioritisation of management.

Tolerable and acceptable risk levels are not absolute boundaries and society shows a wide range of tolerance to risk; risk criteria are only a mathematical expression of societal opinion. Risks can change with time due to natural processes or human intervention.

Information gained regarding rockfall behaviour during the rock scaling exercises has been invaluable in this report but rockfall frequency essentially remains based on engineering judgement.

The risk assessment method used in this report is a refinement on that used previously. Revisiting an analysis of this type can often lead to significant change due to increased data.

* Australasian Geomechanics Society, Sub-Committee on Landslide Risk Management. "Landslide Risk Management Concepts and Guidelines". NZ Geomechanics News. 60, December 2000.

4 SITE DESCRIPTION

4.1 Geology & geomorphology

Mauao is a volcanic dome 232m high and approximately 1,400m N-S x 800m E-W. The upper bluffs and rock outcrops are near vertical and typically formed of a strong rhyolite rock with some flow banding structure and very widely spaced, open, vertical and horizontal perpendicular joint sets. More weathered rock material can locally be slightly weaker.

The colluvium (soil) on the upper slopes is typically; very loose silty sand containing rock fragments from gravel to boulder size. Upper colluvial slopes often lie at or above the maximum angle of repose for this generally non-cohesive material. In gullies it can be very steep due to the wedging effect.

The mid and lower slopes form a colluvial apron composed of poorly graded angular rocks and boulders (eroded and fallen from the outcrops above), set in a loose matrix of wind blown (beach) sand and tephra (volcanic ash) in varying proportions.

The lower slopes are littered with numerous surface boulders embedded in the colluvium to varying degrees. These represent thousands of years of rockfall.

Occasional fine volcanic ash layers have weathered to clays within the lower colluvium and can present less water permeable layers. The colluvium shows some local stratification but in many places has probably been disturbed by slips.

The base of the lower slopes is in the east, south and west, defined by a continuous series of slip scarps, typically between 10m and 60m above mean sea level.

Small depressions representing water sinkholes can be seen in a number of locations on the lower colluvial slopes.

The northern slopes are typically steeper than the southern slopes, probably reflecting the erosion of colluvium due to greater exposure to ocean storms.

In engineering geological terms, the typical RHYOLITE rock description is:

Reddish pink, slightly weathered, flow banded, locally brecciated, typically extremely strong (locally moderately strong where vesicular and slightly weathered), RHYOLITE.

Vertical & sub-horizontally jointed, joints are typically very widely spaced (3 to 5m), persistent >10m and extremely wide open (often 10mm to 1m). Joints behind the outer block set are often infilled with sandy colluvium. [MT MAUNGANUI (MINDEN) RHYOLITE] locally shows spherulitic textures and vesicular areas.

The COLLUVIUM (debris) slopes range from extensive planar slopes to uneven 'gully and bluff' areas. The material is typically;

Brown, unbedded, silty SAND and GRAVEL with some boulders. Loosely packed and heterogeneous, clast supported in some areas, matrix supported in others. [COLLUVIUM]. Angular, typically tabular clasts of RHYOLITE (rockfall debris) in a matrix of wind blown silty SAND.

4.2 Water

4.2.1 Rainfall and groundwater

High groundwater levels following intense rainfall events are the most frequent triggers of rockfall and landslides in New Zealand.

The sandy colluvium generally has high permeability although volcanic ash within the colluvium has locally weathered to clay minerals, creating some (relatively) impermeable layers.

The rhyolite rock material is of very low permeability but the wide open joints on the upper exposures allow free flow of water through the rock mass.

Significant surface streams only develop on the mid and upper slopes during intense rainfall events. Sinkholes can be seen in a number of locations on the lower slopes, eg above the old stone steps gully, indicating that piping (channels) may be eroding underground through the colluvium.

There are at least six springs around the lower slopes of Mauao. A number of these are permanent and at least one is noted on TDC Historic Sites Plans as a large spring and important water source.

The springs were seen to be very significant in the May 2005 storm event when many slips were located immediately above springs. A number of the slips in this event were controlled by slip planes on clay layers within the colluvium. The water supplying the springs appears likely to have followed both clay layers within the colluvium, and the underlying rhyolite topography.

4.2.2 Wave erosion, sea level and tsunami

Wave action and currents during storm surges will erode the base of Mauao, removing material from the toe of the slopes, reducing stability and leaving the slopes more prone to failure (if not actually triggering slips).

Sea level gives a lower limit to the water table and is also a source of erosion via wave action at the toe of the colluvial slopes.

A review of readily available research papers indicates regional sea level changes in the 6,500 years before present (b.p.) to have been:

<i>Years b.p.</i>	<i>Sea level relative to today</i>	
<i>Before 6,500</i>	<i>- 130m</i>	<i>end of last ice-age</i>
<i>6,500 – 5,000</i>	<i>0m</i>	<i>sea level approximately as current</i>
<i>5,000 – 4,500</i>	<i>- 0.4m</i>	<i>minor regression</i>
<i>4,500 – 3,500</i>	<i>+ 0.6m to + 0.9m</i>	<i>minor transgression</i>
<i>3,500 – 2,000</i>	<i>0m</i>	<i>minor regression to current level</i>
<i>2,000 – Present</i>	<i>0m</i>	<i>remains within a few 100mm</i>

Reference; RSNZ Bull 24, 1986, Gibb.

No reference could be found to any localised isostatic sea level changes (those due to local land rising or falling).

The data suggests gradual sea level changes are unlikely to have significantly influenced the current (above water) geomorphology of Mauao, at least in comparison with wave erosion from current sea levels.

Tsunamis cause rapid inundations and currents which may have caused significant erosion of the lower colluvial apron. Even if no slips were directly triggered, the removal of slope toe support would reduce stability and leave the slopes more prone to failure.

A NIWA June 2004 report for EBOP looked at the short historical record (to 1840) and palaeo-tsunami evidence back to 4,000b.p. This reported the following *known* events:

	<i>Historical records</i>			<i>Palaeo Beach deposits</i>	
	<i><0.5m</i>	<i>0.5-1m</i>	<i>1-3m</i>	<i>Under 5m</i>	<i>Over 5m</i>
<i>height</i>					
<i>total events</i>	<i>>6</i>	<i>1</i>	<i>4-5</i>		<i>5 or 6 in 3,000yrs</i>
	<i>Jun 2001</i>	<i>Nov 1922</i>	<i>May 1960</i>		<i>AD 1,302 – 1,435</i>
	<i>Jul 1998</i>		<i>Aug 1883</i>	<i>can not be resolved in</i>	<i>AD 1,200 – 1,300</i>
	<i>Oct 1994</i>		<i>May 1877</i>	<i>geological</i>	<i>AD 1,600 – 1,700</i>
	<i>Jun 1977</i>		<i>Aug 1868</i>	<i>deposits</i>	<i>1,600 - 1,700 b.p.</i>
	<i>Jan 1976</i>		<i>1700?</i>		<i>2,500 - 2,600 b.p.</i>
	<i>Mar 1964</i>				<i>2,900 – 3,000 b.p.</i>

The 500yr (approx) return period for tsunami over 5m is greater than we need consider in terms of risk on Mauao and direct fatalities would be of far more importance than slip issues.

The influence of wave erosion, sea level changes and tsunami on the current day geomorphology is relevant to this investigation in that they influence the lower slope morphology and slips.

4.3 Vegetation

4.3.1 General

Tree roots are generally detrimental to rock stability due to roots penetrating defects in the rock and subsequent growth causing 'root jacking'. The pressures generated by growing roots can move large rock masses as was seen on the Camp Bluff where mature Pohutakawa roots had pushed apart blocks weighing hundreds of tonnes.

Grasses and shrubs are generally beneficial on soil slopes where roots have the opposite effect and help bind the soil together. Vegetation cover also minimises erosional rain and wind scour.

4.3.2 Historical (from Dr L Richards)

Mauao is reported as being "devoid of vegetation" prior to 1925. This appears likely to be true over the majority of Mauao, which was grazed by sheep but some of the mature Pohutakawa are clearly much older.

Pines were "extensively" planted in 1925. The majority of the pines were reportedly felled many years ago and stumps and roots masses are often now severely rotted. Mid slope areas were replanted with bush some time ago and are now regenerating.

4.3.3 Current day

The lower colluvial slopes are sheep grazing pasture with extensive kikuyu grass. The mid and upper colluvial slope areas are generally regenerating bush and scrub with

occasional mature Pohutakawa. The rock outcrops contain occasional living Pohutakawa and old and decaying root systems.

When rockfall has been triggered, collisions with scrub and trees can be beneficial in reducing the energy of rockfall. The bushed areas above the lower slopes can act in this manner, locally trapping a high percentage of at least the smaller rocks. Vegetation can help identify spring locations.

4.3.4 Fires & scour

Fires have occurred often in recent years due to vandalism; notably in 1986, 1997 and January 2003. The 2003 fire burned off large areas of vegetation on the eastern and northern slopes. Approximately 10% of Mauao's slopes lost virtually all vegetation, the roots of which were previously holding together the colluvial slope surfaces.

Due to the very loose sandy nature of the colluvial soils the lack of roots leaves the ground surface extremely prone to erosion and scour by rain and wind.

Scour of sand gradually leaves surface rocks in less stable positions and eventually results in rockfall. A boulder scaled in March 2006 clearly demonstrated this as it was probably completely buried only a year earlier.

4.3.5 TDC vegetation management

Since the 2003 fire a weed eradication and native planting program has been attempting to maximise the native re-growth by selectively spraying herbicide, however, grass appears in some areas less widespread now (2006) than it did in 2004.

The spraying operations, whilst targeting weeds and avoiding the replanted natives may have inadvertently been hindering the re-growth of grasses.

TDC are currently reviewing the spraying operations and developing a new method to allow grass to establish on the steepest loose colluvium.

4.4 Maori historical usage

Maori occupied Mauao until 1819, leaving a number of pa sites and archaeological remains including terraces and middens. The terracing has locally created over steepened soil slopes up to a few metres in height.

Large boulders sitting on top of some terraces initially appear to represent boulder fall since terracing, however, some boulders were deliberately placed for rolling defensively and others may have been too difficult to move.

4.5 Current usage & track system

Mauao is a very popular open space recreational area. Highly frequented walking tracks traverse the slopes. Mauao is also used for sports such as hang gliding and rock climbing. The names and locations of the tracks are shown on the following plan.



Photograph 1. Aerial photograph showing track layout.

The latest data from step counters at track junctions indicates:

- Base track 350,000 visitors per year.
- Upper tracks 75,000 visitors per year.

5 SLOPE HISTORY

The following are relatively brief descriptions. Much greater detail is contained in each of the previous reports.

5.1 Evidence of rockfall prior to records

The lower slopes are littered with boulders fallen from the bluffs above. These have accumulated over many thousands of years, both as individual boulder failures and in multiple episodic events, such as during earthquakes.

The appearance of the vast majority of the boulders is very similar; surface weathered and covered in lichen. Very few show unquestionable indications of having been in place earlier, or later, than their neighbours, suggesting that extensive rockfall must occur relatively slowly compared to weathering and lichen growth (10 years?).

In at least two locations trees can be seen with boulders resting against them. These now mature Pohutakawa would probably not have been capable of holding up boulders, say, 200 years ago, showing at least two boulders fell in that period. Of course many others probably also fell but were not trapped.

Prior to the initial 2003 scaling the stock fences showed damage at a few locations which may or may not be related to rockfall.

5.2 Evidence of slips prior to records

The lowest 20 to 40m (vertical) of the colluvial slopes around the base of Mauao abruptly steepens down to the shoreline.

This change in gradient represents a series of slip scarps, often forming a continuous line.

The colluvial apron above typically lies at 15° to 20° on the lower slopes above the 20 to 40m level. Below the 20 to 40m level the slope often steepens to 25° to 45° down to the shoreline.

The age of these slips is, at this stage of our investigations, has not been determined, however, the crests in some cases do not appear to have weathered a great deal.

In May 2005 one slip of 8,000m³ occurred following an (approx) 50 year return period intense rainfall.

The following Photograph indicates the approximate locations of the slip crests.



Photo' 2. Slip scarp locations (also showing 2003 fire area).

5.3 May 1999; Dr Laurie Richards report

This was a "Report on Mauao Stability Assessment", presented to TDC on 31 May 1999. Dr Richards undertook an overview of the stability of the NE to SE slopes and assessed the risk to the hot pools, camp ground and tracks and made outline recommendations for management strategies.

The campground lessee was interviewed and reported only one known rockfall incident entering the campground; initiated by children, and one small slip; 11/8/98 after intense rainfall a small debris flow (several m³) had just entered the northern area of the camp.

No relevant reports were found in a brief search at Tauranga Library. No evidence was found of recent large scale movement of old landslide features in the colluvial slopes.

TDC staff reported some localised stability problems in the oversteepened cuts above the base track.

Computer simulations indicated a low probability of boulders reaching the campground.

The report calculated that the risks posed by rockfall to the users of Mauao were likely to be acceptable when evaluated to internationally acceptable criteria and it was recommended that the slopes above the campground and hot pools be mapped in detail and that annual walkover surveys be carried out to check that conditions were not changing.

5.4 January 2003; Fires

Fires burned all vegetation, including mature trees, from extensive areas of the northern slopes. Approximately 10 hectares (10%) of Mauao's slopes were affected.

The fires revealed marginally stable areas of rock on the upper slopes and bluffs and the loss of the root binding left the sandy soil prone to erosion by rain and wind.

On 19 February Dr Richards re-visited the site at the request of TDC and recommended Avalon carry out rock scaling and detailed engineering geological hazard investigation. Dr L. Richards. "*Mauao Rockfall Review*". 20/2/02 Letter to TDC. ²

The fire affected areas can be clearly seen in Photo' 2 (previous page), which was taken in January 2003.



Photo' 3. Eastern bluffs post fire.



Photo' 4. Northern bluffs post fire.

5.5 March 2003; Rock scaling and hazard investigation

In response to Dr Richards's recommendation, TDC commissioned Avalon to carry out manual rock scaling and hazard investigation on all slopes affected by the fires.

Numerous marginally stable rocks and boulders were encountered and many of the most severe were scaled; however, it was evident that (in the absence of grass) scour was likely to redevelop the problem relatively quickly.

To give an example of the marginal stability; one boulder estimated to weigh seventeen tonne was easily scaled by crowbar (see Photo's on next page).

The slopes were inspected by Avalon's Engineering Geologist and valuable empirical data was collected on the behaviour of rocks falling down Mauao's slopes.

It became apparent that the larger boulders could, depending on shape and trajectory, reach the lowest slope areas, including the base track and campground.

Stainless steel survey benchmark pins were installed on some of the high bluffs so as to allow accurate future quantification of any movement.

A detailed report was produced which described and Zoned various rockfall hazards; "Mauao Rock Slopes & Rockfall Hazards", 12 July 2003 .

Recommendations included:

- Detailed investigation of the 'camp bluff' and stabilisation options.
- An annual geotechnical inspection and targeted annual rock scaling program.
- Replanting on the fire affected slopes.
- Close the NW Oruahine track and Zig Zag track until vegetation was re-established.
- Minimising public access off track and preventing rock climbers accessing the slopes above the climbing areas.
- Investigating catch fence options in the northern gullies.



Photo' 5. Scaling by hand on the upper slopes.



Photo' 6 a,b,c. Seventeen tonne boulder scaled by crowbar.

5.6 October 2003; Monitoring indicates Camp Bluff movement

TDC requested a six monthly inspection and Avalon's Engineering Geologist carried out a walkover (viewing the slopes from safe areas) and monitored the survey pins.

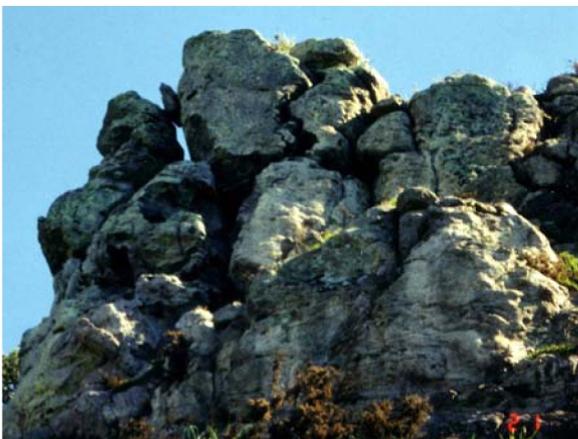
Indications were found of very recent spalling and movement in a large rock mass high on the camp bluff. Avalon. "Mauao Camp Bluff Investigation". 26/10/03 Report to TDC.

Detailed survey showed approximately 100m³ to be in an extremely marginal position; severely undercut and overhanging. Failure appeared relatively imminent and likely to result in a number of very large boulders (up to 50 tonne) with the potential to roll into the campground, directly on the fall line below.

The main destabilising factor appeared to be compression of rotted tree roots.

A peer review by [redacted] Engineering Geologist with Tonkin & Taylor Ltd concurred with Avalon's findings.

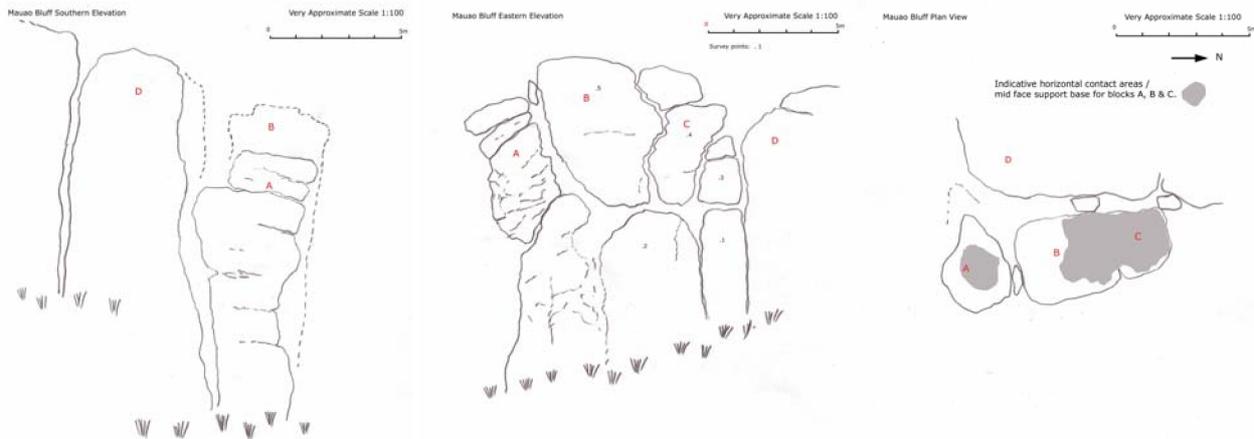
TDC decided that the hazard should be eliminated as soon as possible.



Photo' 7. Camp Bluff from below.



Photo' 8. Spalling at load transfer point.



Drawing 1. Blocks A, B & C were extremely near failure.

5.7 November 2003; Camp Bluff rock scaling

A detailed drilling and blasting plan was devised; Avalon. *Mauao Camp Bluff Drill & Blast Proposal*. 7/11/03 Letter to TDC. The campground was evacuated and Avalon's team was on site on the 10th November.

A close hole spacing and deck loaded pattern used a minimum of explosives whilst breaking the rock mass into boulders as small as practicable.

The shot was successfully fired on 14 November and the rock mass split as intended. A few of the larger boulders entered the campground, where shipping containers had been placed as temporary barriers.

The blasted rockfall was closely monitored and further data was gathered on the behaviour of falling rocks on Mauao. All rocks which entered the lower paddocks were individually assessed and GPS located to allow a statistical analysis.

Avalon commenced work on an analysis and numerical assessment of the remaining rockfall risks on Mauao. This work was presented as "Mauao Rockfall Hazards, Risk Assessment & Management", 26 June 2004.



Photo 9. Post scaling; note the rotted tree roots.

5.8 January 2004; Range finds boulder movement

TDC's Mauao Ranger spotted a boulder on the north western slopes which had very recently moved forward up to 200mm and was in a dangerous position near the top of a very steep gully above the Oruahine and Base Tracks.

Avalon inspected and it was easily scaled by crowbar. The boulder crossed the Oruahine track high in the air and rolled across the Base Track, coming to rest on the shoreline.

Whilst on site a monitoring inspection was carried out on the other slope areas and it was noted and reported that sand scour was becoming quite widespread.



Photo' 10. Boulder scaled in January 2004.

The work was reported in a letter report from Avalon to TDC. 16/1/04, "Zone 4 Boulder Scaling Works".

5.9 July 2004; Minor earthquake swarm damage

Over 4 days Mauao experienced a 10 year return period minor earthquake swarm. Six events were sufficiently strong to be generally perceived by persons. The quakes triggered a number of rockfalls and slips on Mauao.

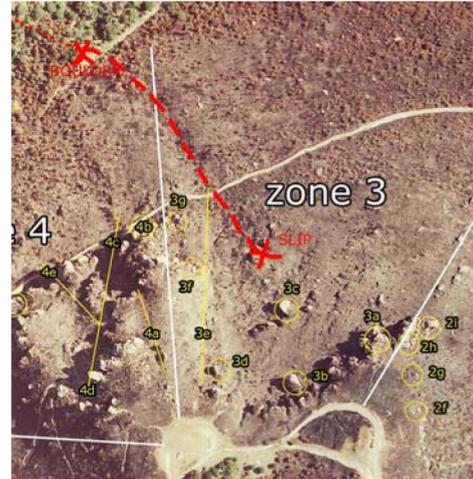
A brief walkover found that the most hazardous rockfall appeared to have originated above the Northern Oruahine track where failure of a number of boulders up to 1.5 tonne had been triggered, along with many smaller rocks. Some apparent movements were noted on the rock faces.

Many shallow surface slips occurred on the colluvial slopes (typically $<0.2\text{m} \times 1\text{m}^2$).

Fifteen slips of 1m^3 to 3m^3 and many more of less than 1m^3 had occurred in the oversteepened cut slopes above the various tracks.

Measurement of the survey benchmarks on the upper bluffs showed movement of up to 10mm but none of these small movements had compromised stability.

It was again noted that significant erosional scour and channelling had locally developed in the colluvium and that rockfall would have occurred over the previous year via this process.



Photo' 11 a & b. Boulder which crossed the Oruahine Track.



Photo' 12. Boulder moved out from rock face.

Photo' 13. Boulder movement above Base Track.

Photo' 14. Typical small slip above Oruahine track.



Photo' 15. Looking down on scour channels above the Waikorere Track.

The earthquake provided valuable data to feed back into the Mauao rockfall risk analysis. This increased the assumed rockfall frequency and the calculated risk.

A detailed report was produced; "*Mauao Slopes Earthquake Damage & Revised Risk Assessment*". Report to TDC 26/7/04.

5.10 November 2004 & March 2005; Monitoring

Monitoring inspections were made on 23 November 2004 and 9 March 2005.

Although the vegetation was generally re-establishing there was local significant scour occurring, particularly in gullies in the colluvial material. This had locally resulted in some very loose and marginally stable areas.

The hazard was reported as highest in the northern areas where rock climbing activity takes place and where there was a high probability that any persons traversing the slopes off track could accidentally dislodge rock.

A rock scaling program and climber education/access control was recommended along with investigation of possibilities for small catch fences at a few critical locations.

It was also noted that rabbits continued to present an erosion problem and would also initiate occasional rockfall.

Reported; 10/3/05 "*Mauao Slopes; Routine monitoring report*". Report to TDC.

5.11 May 2005; Extreme rainfall event; Flood damage

On 18th May 2005 Tauranga received 350mm of rain in 24hrs, a 35 (to 150) year return period event.

Over thirty slips blocked the Base track, 4 slips affected the lower 4WD track, eight slips blocked the upper 4WD track and three slips affected the campground and beach boardwalk.

The largest single mass slip involved an estimated 8,000m³ of material. The next largest was around 250m³.



Photo' 16. 8,000m³ slip on SW slopes.



Photo' 17. 250m³ slip above campground.

Many of the slips were controlled by clay layers within the colluvium and the larger slips tended to occur above springs. The slip material was often completely saturated and appears to have behaved as a fast liquefied debris flow, continuing to travel down relatively low angled gullies.

The slopes and tracks suffered extensive scour as surface streams developed. Gullies were eroded and new channels formed. The amount of loose surface rock had increased very significantly in many areas.



Photo' 18. Boulder fall.



Photo' 19. Scour on Camp Bluff.

The tracks showed rocks and rockfall impact marks. Hundreds of rocks under 150mm appear likely to have crossed the Oruahine track in the North Western areas.

Mauao's lower slope morphology is clearly being actively modified by groundwater triggered landslips and this flood event provided us with more valuable data to feed back into the Mauao rockfall risk analysis. The calculated risk again increased.

The large slip on the SW slopes also re-raised the question of the potential for this type of debris flow to enter the campground. The consequences of such an event could be disastrous.

The slopes have large slip scarps above the campground area. Their age and likely return period is unknown. Further investigation was recommended.

2/8/05 Avalon. *Mauao Slopes; May 05 Flood Damage & Slope Remedial works*. Report to TDC.

5.12 May/June 2005; Flood damage remedial works

Public access to Mauao was closed for approximately six weeks whilst the debris and hazards were cleared and tracks were reformed.

The clearing of the bulk slip debris was achieved by machine. The crests of the larger slips on the lower slopes were reprofiled by hand. All material remained on site and acceptable fill placement areas were established.

Minor stabilisation work incorporating soil nails and erosion control mesh was undertaken on the hairpin corner of the 4WD track.

A manual rock scaling operation cleared loose surface rock from steep areas above the tracks and above areas where TDC's other contractors needed to work.

5.13 June 2005; Boulder rolls to camp boundary

On the 22nd of June the hotpools management heard a large boulder falling through trees immediately up slope of the campground/hotpools.

A well rounded boulder, 2 to 3m in diameter and weighing around 20 tonnes was found at rest behind the campground boundary fence. It failed from 25m up the 30° slope and whilst rolling had dislodged a second, 1.5m diameter boulder.

Prior to failure the main boulder appears to have been shallowly embedded above a rotted out tree stump. Shell middens below, indicated the boulder had probably already moved previously, post Maori occupation.



Photo' 20. Boulder at camp boundary.



Photo' 21. View down from source.

The slopes in this vicinity contain many rotted tree stumps and decayed roots. This, along with the 18 May flood and another spell of further heavy rain preceding the event, appear likely to be contributing factors in the failure.

Had the boulder not collided with trees and the embedded smaller boulder it would probably have entered the campground. This prompted more detailed investigation and hazard/risk analysis of the slopes above the southern campground and hot pools.

5.14 June 2005; Investigation of lower slopes above campground

Due to the steep nature of the slopes and potential for boulders to roll into the campground, the potential for rockfall in this vicinity demanded further consideration. Avalon's Engineering Geologist investigated the slopes, designated as Zone 6 (following July 2003 Hazard Report).

The open lower and mid slopes were relatively easy to investigate but on the upper slopes the vegetation is extremely dense and there is generally little chance of seeing boulders more than a few metres distant.

The slopes were heavily terraced during Maori occupation and this has resulted in over steepened soil slopes up to a few metres in height.

Many of the surface boulders showed fresh signs of animal burrowing.

Twenty three individual boulders were noted as appearing particularly marginal and around half of these appeared likely to be readily scaleable using crowbars.



Photo' 22 & 23. Marginally stable boulders above campground (now scaled).

Reported on 28/7/05; "Zone 6 Hazard & Risk Assessment". Report to TDC.

5.15 August 2005; Boulder scaling above campground

Fifteen boulders, each from 1 to 20 tonnes were scaled. The majority entered the paddocks above the campground at high speeds but none entered the campground. One boulder almost reached the campground boundary and was stopped by a tree. Another could have entered the campground had it not collided with a larger, deeply embedded boulder.

The soft ground of the lower terraced paddocks proved beneficial as bouncing and spinning boulders dug in significantly, losing energy at each bounce.

Although the rockfall risk to camp users was significantly reduced the risks can of course never be totally eliminated, however, the potential for boulder fall from this area now is no greater than elsewhere on Mauao. The work was reported 5/9/05; "Zone 6 scaling report". Letter report to TDC.

5.16 September 2005; Rockfall above campground kills two lambs

Mauao's Ranger reports a rock above the camp ground that slipped during rain and killed two sheltering lambs.



Photo' 24 & 25; The boulder which killed the lambs.

5.17 December 2005; Monitoring

Mauao Ranger reported rockfall onto W Oruahine track caused by climbers. Avalon found that scour is continuing to expose surface rocks. No significant movement was detected on any of the survey benchmarks.

Vegetation locally appeared in worse condition than a year previously; whilst in most areas the post fire re-vegetation was re-establishing well, where the grass has not taken hold, scour was revealing new surface rocks, which occasionally fall naturally but which also present a severe hazard if persons are walking off the tracks.

The fact that another two recorded rockfalls had occurred since the last monitoring visit continued to reinforce the fact that rockfall poses real risks.

Reported via email 15/12/05.

5.18 March 2006; Scoured boulder scaled

TDC's Mauao Ranger spotted a boulder at the base of the Zone 2 bluffs which had become more visible over a few weeks. Avalon was called in to investigate.

On the day of the site visit two persons were found off track on the steep loose slopes high under the Camp Bluff. They caused a few small rocks to fall before rabbits appeared above them, dislodging small rocks. The climbers were alarmed and triggered more rockfall, which also reached the track!

The boulder in question was found to be in an extremely marginal location. It was disc shaped, approximately 1 tonne and only just held in by the wedging action of a few small rocks. The boulder had previously been embedded in colluvium which had progressively eroded from around it.

This area was thoroughly scaled in March 2003 and received a second, lighter scaling pass in May 2005. At that time it can not have been of concern, showing scour can be rapid.

The boulder was scaled on 22 March. It split and half the came to rest in the bush whilst half came to rest just above the stone steps.

In the Photo' on the next page the pale stain on the bedrock indicates the level of the colluvium before scour (indicated by hand).

Gullies up to 1m wide and 0.5m deep have developed since 2003 and the near vertical walls of some of these have clearly been sources of rockfall.

Reported via email 3/3/06.



Photo' 26; The scoured boulder before scaling; 22/3/06.

The pale grey stain (pointed at) was surface level one year earlier.

6 ROCKFALL RISK ASSESSMENT

6.1 Introduction

Applying risk assessment principals to Mauao rockfall, we need to address the following questions:

- Where do rockfalls occur on Mauao?
- When rocks fall, where do they come to rest?
- How likely is it that a person will be in a falling rocks path?
- If the person and rock coincide, how likely is it the person will be killed?
- What will trigger rockfalls?
- How often will rockfalls occur?
- What is the probability of an individual being killed?
- What is the likely frequency of fatalities?
- Is the risk within acceptable limits?
- How regularly might persons be injured or killed by rockfall?
- Is this acceptable to TDC & the public?
- Does the risk need to be reduced?
- How might the risk be managed?

6.2 This review report vs. previous reports

The detail of the method used here contains some refinements compared with that used previously. These take into account the peer review comments, all data collected since Avalon's initial risk assessment and a thorough review of available references.

6.3 Slope zoning system

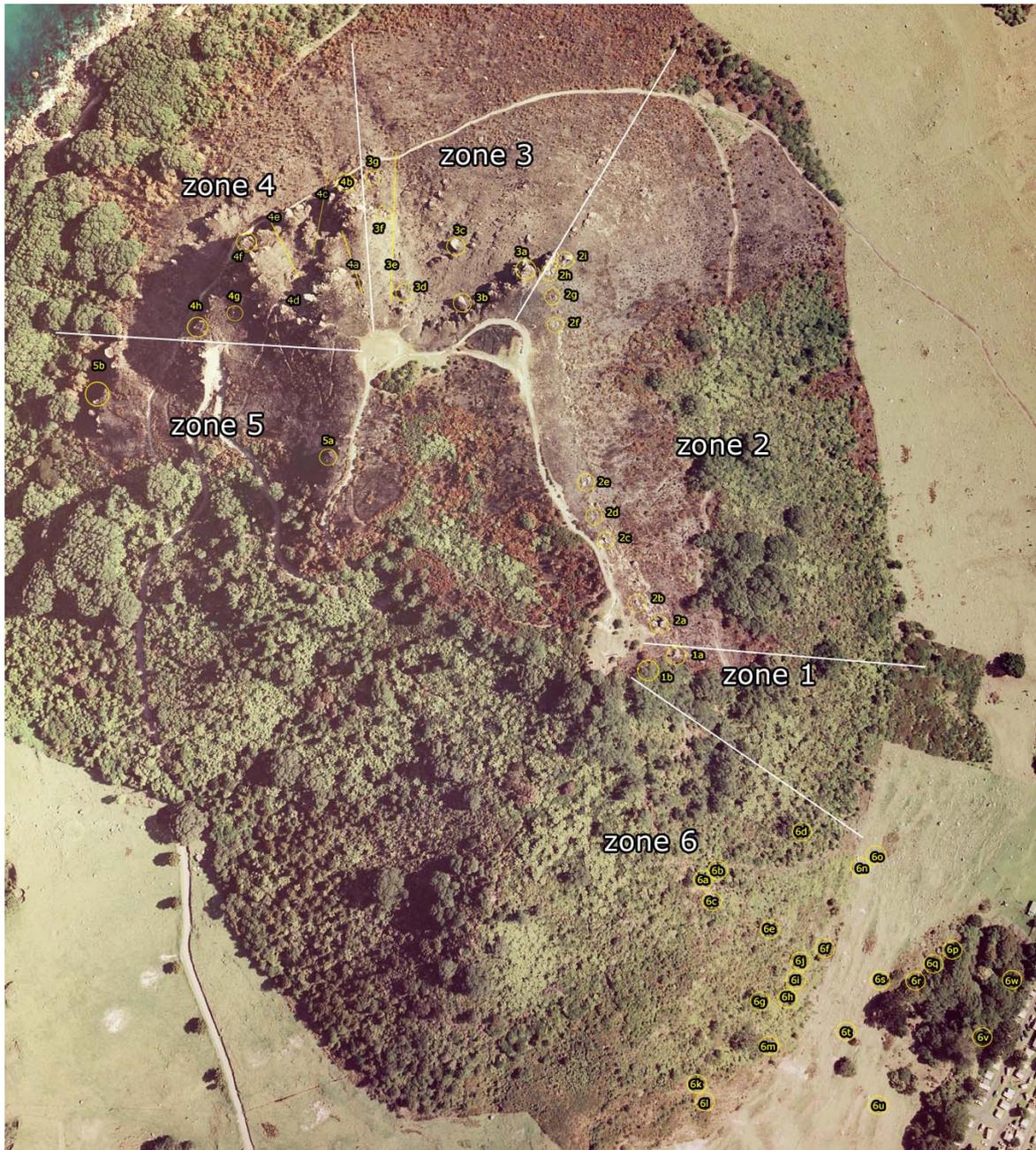
The risk assessment process could be carried through for Mauao as a whole; however, this would not be particularly helpful when looking for management options as rockfalls will be more frequent and consequences more severe in some areas than in others. The public also spend more time in some areas than others and some tracks have higher total visitor numbers than others.

We have broken the slope areas down into six Zones where the rockfalls and hazards are similar in nature. Photograph 27 shows the Zones used along with locations of some specific hazards (some of which have been eliminated).

6.4 Potential rockfall sources

The colluvial slopes and outcrops/bluff ledges are littered with loose rock of various sizes, much of which could relatively easily be triggered to fall.

Previous reports have described the topography and likely rockfall modes in detail, for each slope Zone as well as identifying specifically hazardous boulders or marginally stable areas.



Photo' 27: The slope Zones.

To gain some insight into the quantity of potential rockfall above the various areas on Mauao we made approximations, in round figures, of what may be the equivalent total surface area of step bluffs and over-steep colluvial slope, in each Zone:

Slope Zone	Source Height (m)	Length (m)	Area (m ²)
1	20	25	500
2	20	200	4,000
3	20	100	2,000
4	50	50	2,500
5	50	50	2,500
6	5	100	500
Total			10,000

6.5 Rockfall behaviour

Falling rocks are converting potential energy (height) into kinetic energy (velocity and spin). Rolling, bouncing and colliding down the slopes they lose their kinetic energy and eventually come to rest.

During Avalon's scaling works, excellent empirical data has been collected whilst observing rocks of various shapes and sizes falling down Mauao's slopes.

The 2003 blasted rockfall was assessed in detail; 65 boulders passing below the bushline were GPS surveyed and size and shape was recorded. Smaller rocks were estimated. The data was statistically analysed and reported in "Mauao Rockfall Hazards, Risk Assessment & Management", 26 June 2004.

Where rocks travel is controlled by:

- How high on Mauao they originate.
- Any initial 'push' velocity.
- The steepness and topography of the path they follow.
- The nature of ground/objects they bounce and collide with.
- The mass of the rock.
- The shape of the rock.
- Joints and fractures allowing rocks to split.

An analysis of rock volume vs. resting elevation is shown in the following graph. As would be expected the larger rocks travel furthest.

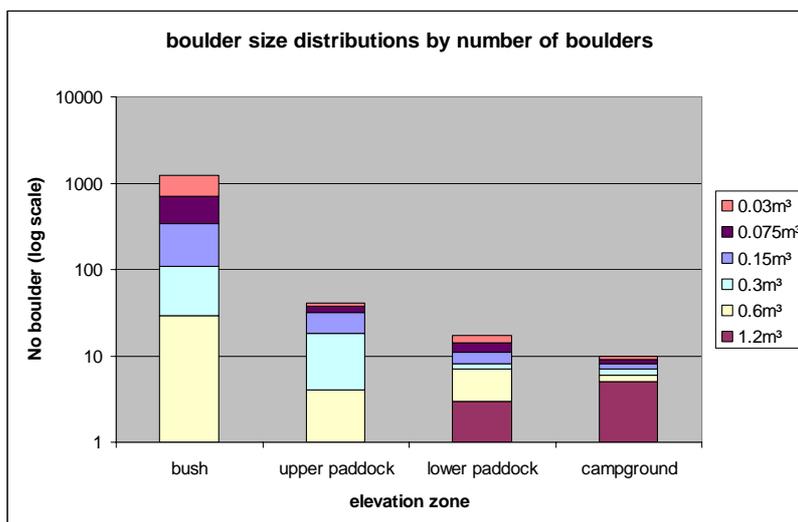


Chart 1; Rock travel distances in Camp Bluff Blast in 2003.

The data was then used to give an approximate probability that a given boulder of a certain size would reach a certain elevation on the slopes:

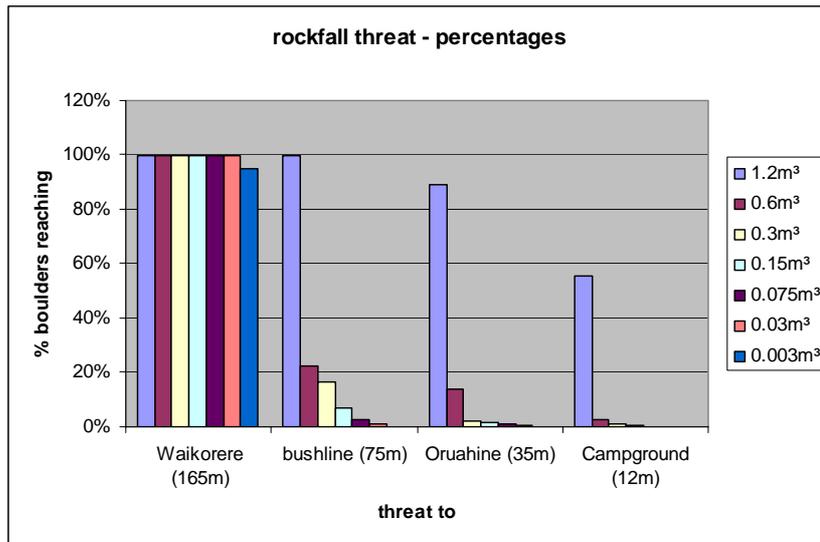


Chart 2; % of boulders of different sizes stopping at various levels.

This was then simplified in the following statements:

Falling boulders around 1m side (1m³ volume).

- 100% cross to the upper slope areas.
- 90 % cross the mid-lope areas.
- 50 % cross to the lower slopes.

Falling rocks of around 0.3m side (0.03m³ volume).

- 100% cross the upper slope areas.
- 10 % cross the mid-slope areas.
- None reach the lower slopes.

Falling rocks of around 0.15m side (0.003m³ volume).

- 95% or more cross the upper slope areas.
- None reach the mid-slope areas.
- None reach the lower slopes.

Of course this data is for blasted rockfall, which was given a significant 'push', or initial energy. The travel distances might be slightly less for natural rockfall.

A shape analysis was also carried out. Disc shapes gain angular momentum, straightening in the vertical plane whilst rolling and can travel long distances whilst maintaining high energies. Mauao also has some very well rounded, spherical boulders which also roll well, although they do not travel quite as far as the discs.

The majority of Mauao's rocks are various tabular, prism and irregular shapes which do not typically travel as far as discs or spheres, however, boulders of 1m³ of any shape were seen to travel to the base.

6.6 Hazard category

We can use the information learned about fall distances to make a subjective, judgmental comparison of the hazard from any rockfall above Mauao's tracks and campground:

<i>Category</i>	<i>Description</i>
1	Directly below steep bluffs (NW Oruahine): <ul style="list-style-type: none"> • 100% of boulders around 1m side. • 100% of rocks around 300mm side. • 90% of rocks around 150mm side.
2	Below upper colluvial slopes (eg E Waikorere): <ul style="list-style-type: none"> • 90% of boulders around 1m side. • 50% of rocks around 300mm side. • 20% of rocks around 150mm side.
3	Mid and more exposed lower tracks (eg NW Base): <ul style="list-style-type: none"> • 75% of boulders around 1m side. • 10% of rocks around 300mm side. • No rocks around 150mm side.
4	Lower tracks (E Base): <ul style="list-style-type: none"> • 30% of boulders around 1m side. • No rocks around 300mm side. • No rocks around 150mm side.
5	Campground: <ul style="list-style-type: none"> • 10% of boulders around 1m side. • No rocks around 300mm side. • No rocks around 150mm side.

Boulders reaching the campground might typically penetrate, say, 10m (1st row of sites at the boundary).

The following table uses these hazard categories to rate the important track sections:

<i>Zone</i>	<i>Track</i>	<i>Category</i>	<i>Track length</i>
1	Waikorere	2	50
1&2	Base	4	600
2	Waikorere	2	400
2	Oruahine	3	450
3	Oruahine	2	250
3	Base	4	400
4	Oruahine	1	150
4	Base	3	250
5	Oruahine	1	200
5	Base	3	200
6	Base	4	500
1&6	Campground bdry	5	400

6.7 Rockfall frequency

6.7.1 Introduction

Rockfall frequency is one of the parameters in the risk assessment process most subject to unknowns and reliant on 'engineering judgment'.

The total quantity of rockfall in each Zone is assumed to be controlled by the size of the source area and the intensity of the triggering event. Triggers will include:

- Rain and wind erosion.
- Vegetation; root decay and growth.
- Earthquake; seismic shaking.
- Animals; mostly rabbits.
- Humans; off track movement.
- Impact from other, already falling rocks.

Prior to Avalon's investigations it was assumed that, given the lack of reported incidents, rockfall was probably quite a rare event. Laurie Richards 1999 assessment assumed a most likely boulder fall frequency of under 0.1 per year (i.e. one every 10 years).

In the last three years we have observed rockfall events triggered by; rapid erosion following the fire, intense rainfall, minor earthquake and persons off track.

6.7.2 Weathering; erosion, scour & vegetation roots

Wind and rain occasionally cause rockfall directly, or by removal of surrounding sandy matrix.

Since the fire, scour has caused increased rockfall. Small rocks will fall far more regularly than boulders but will often go unnoticed.

The component of vegetation (root) triggered rockfall, compared to other weathering is impossible to determine.

The May 2005 rainfall event triggered at least ten large boulder falls and hundreds of smaller rocks. One large boulder came to rest at the camp boundary.

TDC's Ranger has reported evidence of ongoing rockfall:

- Impact marks in the track surface below the rock climbing areas.
- One rockfall was reported to the Ranger by the public.
- 2004 identifying a critical boulder requiring scaling.
- 2006 identifying critical boulder requiring scaling.
- Reporting a boulder fall which killed two lambs.

One aspect mitigating risk from rockfall due to weathering is that the majority will occur during inclement weather, when the number of persons on the tracks will be reduced, although of course this is not necessarily the case for the campground.

The quantity and size distributions of rockfall triggered by erosion are largely a matter of engineering judgment; however, our observations over the last three years give us some useful starting points.

Assuming the May 2005 rainfall event was a 50 year return, this triggered, say:

- 20 larger boulders (1m),
- 200 smaller (300mm) boulders
- Unknown, say 2000 (150mm) rocks

Given our observations of at least three other weathering/erosion triggered 1m boulders falling over the last three years, perhaps we could assume, as a convenient starting point, an annual total of, say:

- 1 larger boulders (1m),
- 10 smaller (300mm) boulders
- 100 (150mm) rocks

This may be conservative but this will somewhat offset the fact that, as mentioned, most will fall during stormy weather when visitor numbers will be low. Converting these into frequencies and rounding, gives, say:

	<i>Number of rocks</i>		
	<i>1m</i>	<i>300mm</i>	<i>150mm</i>
<i>Total annual</i>	<i>1</i>	<i>10</i>	<i>100</i>

6.7.3 Earthquakes

The failure of larger boulders, bluff masses and columns of rock will most frequently be initiated by earthquake. The nature of Mauao's topography will cause ground shaking to be amplified at the Mauao upper bluffs.

The quantity and size distributions of rockfall released by earthquakes is also down to engineering judgment and difficult to estimate with certainty; however, the 2004 minor earthquake swarm gives us a useful starting point here.

This 10 year return period, MM (a measure of ground shaking intensity) Intensity VI event initiated failure of at least:

- One larger boulder,
- Six smaller boulders
- An unknown quantity of (150mm) rocks

The following MM return periods are quoted from Smith & Berryman (1992) for Tauranga:

<i>MM Intensity</i>	<i>Return period</i>	<i>Tauranga g</i>	<i>Mauao g</i>
<i>VI</i>	<i>10 years</i>	<i>0.092 to 0.18g</i>	<i>0.3?</i>
<i>VII</i>	<i>42 years</i>	<i>0.18 to 0.34g</i>	<i>0.5?</i>
<i>VIII</i>	<i>180 years</i>	<i>0.34 to 0.65g</i>	<i>1?</i>

The 10% in 50 years acceleration for Mauao's upper slopes is assumed to be 0.7g, see previous reports & refer; *Western BOP Lifelines Study Microzoning for Earthquake Hazards*. August 2003.

0.7g involves violent ground shaking and would have severe consequences throughout Tauranga (i.e. Mauao rockfall would be a relatively low priority).

Perhaps we could estimate:

<i>Return period</i>	<i>Number of rocks</i>		
	<i>1m</i>	<i>300mm</i>	<i>150mm</i>
<i>10 years</i>	<i>1</i>	<i>10</i>	<i>100</i>
<i>100 years</i>	<i>10</i>	<i>100</i>	<i>1000</i>
<i>500 years</i>	<i>50</i>	<i>500</i>	<i>5000</i>

Converting these into annual totals gives:

<i>Return</i>	<i>Annual component</i>		
	<i>1m</i>	<i>300mm</i>	<i>150mm</i>
<i>10 years</i>	<i>0.1</i>	<i>1</i>	<i>10</i>
<i>100 years</i>	<i>0.1</i>	<i>1</i>	<i>10</i>
<i>500 years</i>	<i>0.1</i>	<i>1</i>	<i>10</i>
<i>Total annual</i>	<i>0.3</i>	<i>3</i>	<i>30</i>

6.7.4 Animals (rabbits)

At times there have been large numbers of rabbits on Mauao and their movements and burrowing will have caused rockfall although we could probably safely assume that rabbits will only initiate small size rockfall.

It is understood that control efforts by TDC have been having some success but a recent monitoring visit observed rabbits causing very small rocks to fall.

Perhaps we could add one 150mm rockfall per week, 50 per year to the total, to take account of rabbits:

	<i>1m</i>	<i>300mm</i>	<i>150mm</i>
<i>Total annual</i>	<i>0</i>	<i>0</i>	<i>50</i>

6.7.5 Humans (people off track)

Persons have been observed causing minor rockfall whilst climbing off track. Avalon's experience during the scaling operations was that when crossing the over steep colluvial slopes it is extremely difficult *not* to dislodge loose surface rock. The vegetation management contractors have also reportedly caused minor rockfall.

Human activity on over steep areas of the slopes presents a real risk, particularly during fair weather, when the tracks are also the most populated.

Zones 4 & 5 are of most concern as exiting rock climbers cross over-steep colluvium and climb down the gullies. The Oruahine track lies vertically below and persons will have no warning of rock coming towards them.

Avalon previously recommended no off track access should be available for climbers (or others) to the steep loose slopes.

The situation will hopefully improve as vegetation becomes re-established.

The deliberate throwing of rocks should hopefully be minimised by signage and TDC ranger presence, although it remains a possibility.

In the first instance we will assume that persons only go off track above the North Western Oruahine Track (Zone 4) and the Zone 1 Waikorere Track.

It is probably reasonable to assume persons will only trigger 150mm rocks. How much human rockfall triggered rockfall occurs is very subjective.

In the first instance might arbitrarily assume say 50 per year in Zone four and 25 per year in Zone 1.

	<i>1m</i>	<i>300mm</i>	<i>150mm</i>
<i>Total annual</i>	<i>0</i>	<i>0</i>	<i>75</i>

People off track are probably one of the most frequent triggers of rockfall at the moment and may represent one of the highest risks on Mauao.

6.7.6 Impact from other, already falling rocks.

This is the 'accumulation effect', i.e. one falling rock collides with marginally stable rocks and triggers them also. We will assume that this is already taken into account in the above estimates.

6.7.7 Total rockfall

	<i>Annual component</i>		
<i>Trigger</i>	<i>1m</i>	<i>300mm</i>	<i>150mm</i>
<i>Weathering</i>	<i>1</i>	<i>10</i>	<i>100</i>
<i>Earthquakes</i>	<i>0.3</i>	<i>3</i>	<i>30</i>
<i>Animals</i>	<i>0</i>	<i>0</i>	<i>50</i>
<i>Humans</i>	<i>0</i>	<i>0</i>	<i>75</i>
<i>Total annual</i>	<i>1.3</i>	<i>13</i>	<i>255</i>

The main source areas for rockfall (the bluffs and over-steep colluvium) were estimated earlier in this report as 10,000m².

A 10m high by 10m long section of slope would therefore typically release $(320/10,000 \times 10 \times 10) = 3.3$ rocks per year due to non-human triggers.

6.8 Consequence; visitor numbers & vulnerability

6.8.1 Track visitor numbers

The tracks around Mauao are some of the most intensively used in New Zealand.

In one full year to June 2006 the Base Track stile counter recorded 700,000 steps. We might assume that half of these are full circuits (or equivalent); 350,000 total.

The Oruahine track counter records around 6,000 in winter months and 9,000 in summer; say, 100,000 per year. This traffic will split between the Waikorere and Oruahine. The Waikorere and Oruahine will also collect some traffic from the 4WD track making a total of around 75,000 traverses per year.

6.8.2 Track visitor activities & durations

The following assumptions regarding visitors track activities still seem reasonable:

- 350,000 persons walk the base track
- 75,000 persons on the upper tracks.
- Persons move at an average 2km/hr on all tracks.
- Visitors remain stationary on the base track for ¼ of their walking time.

6.8.3 Track user vulnerability

Assuming a person is in the path of a falling rock, vulnerability is the probability of their being killed, from zero to one.

The colluvial slopes immediately above most of Mauao's tracks will cause rockfall to be noisy and hence persons might often be able to take evasive action. For walkers this might be easy, whilst for persons sitting it will be more difficult.

On the lower colluvial slopes the smaller rocks generally have relatively low speed and will not be particularly lethal. Perhaps a vulnerability of 0.1 might be a good average starting point (i.e. 1 in 10 persons will be killed if directly in the path of the rock).

In Zone 4 and 5 the situation is a little different in that the rocks roll down the colluvial slope then enter freefall over the vertical rock climbing bluffs before striking the track. Some rocks will cross over the people's heads, but the vulnerability is certainly greater than elsewhere as there is unlikely to be any audible warning. 0.4 seems a reasonable starting point.

We have already defined a track/slope hazard category. This is also useful to allocate relative vulnerability, i.e.

<i>Hazard Category</i>	<i>Vulnerability</i>
1	0.4
2	0.3
3	0.2
4	0.1

6.8.4 Campers

The Camp ground has a boundary length exposed to the hazard of around 400m and on this boundary there are approximately 50 sites. We could assume 50% occupancy through the year and 4 persons per site for 12 hours per day total when occupied.

Assuming only the boundary row of sites are at risk (boulders penetrating 10m) then the equivalent number of 'person 12hr days' exposed to the hazard is $0.5 \times 4 \times 50 \times 365 = 36,500$.

Of that 12 hour they might spend 8 sleeping, with vulnerability 0.9 and 4 active, with vulnerability say 0.2, therefore average vulnerability whilst on site would be 0.7.

6.9 Risk estimation method

The method is relatively simple and considers the probability of a typical visitor being in the affected area when a rockfall passes, multiplied by their vulnerability, to calculate the incremental risk to an individual *on a single visit*.

The calculated risk can then be multiplied by the number of visitors per year to determine the annual probability of a fatality, the fatality frequency and the return period for each area of Mauao.

The stages in the calculation are:

- Annual frequency of different sizes of rockfall from the upper slopes, above a given location:
For rocks 1000mm, 300mm and 150mm; $Nr_{(1000)}$, $Nr_{(300)}$, $Nr_{(150)}$
 $Nr_{()} = \text{source area (m}^2\text{)} \times \text{annual frequency}_{()} / \text{m}^2$
- Proportion of rocks crossing the location in question: $Pr_{()}$.

Slope Category	1	2	3	4	5
$Pr_{(1000)}$ =	%	%	%	%	%
$Pr_{(300)}$ =	%	%	%	%	%
$Pr_{(150)}$ =	%	%	%	%	%
- Total number of rocks Nr crossing the location in question:
 $Nr = (Nr_{(1000)} \times Pr_{(1000)}) + (Nr_{(300)} \times Pr_{(300)}) + (Nr_{(150)} \times Pr_{(150)})$
- Time for a single visitor for one crossing of the affected track or one night in the camp.
T (in years)
For tracks this will be; $T = \text{track length} / \text{walking speed} + \text{stopping time}$
For the campground = 12 hours.
- The area inhabited at any one time by a single visitor will be assumed to be 0.5m on tracks and 1m in the camp * so the ratio of space L occupied by one person at any time is:
 $L = 0.5 \text{ or } 1 / \text{track length or camp boundary length.}$
- The rockfall intensity (annual rockfall per m of track) is given by:
 $Nr / \text{track length or camp boundary length.}$
- The probability of coincidence of a rockfall and person in the same space is given by:
 $Pc = Nr \times T \times L$
- The probability of a fatality per visit, the incremental risk, is given by multiplying Pc by the vulnerability: $Pf = Pc \times V$

9. The probability of a fatality per year, the fatality frequency, is Pf multiplied by the number of visitors per year to that area.
10. The return period is the reciprocal fatality frequency.

* This is a refinement in the method; previous calculations assumed 1m for both.

6.10 Risk estimates

A spreadsheet was developed to carry out the calculations and the results are summarised in the following table:

Rockfall source area dimensions

<u>Slope Zone</u>	<u>Height (m)</u>	<u>Length (m)</u>	<u>Area (m2)</u>
1	20	25	500
2	20	200	4,000
3	20	100	2,000
4	50	50	2,500
5	10	50	500
6	10	50	500
TOTAL			10,000

Rockfall hazard category

	<u>% of rocks of various sizes reaching hazard category rating 1 to 5:</u>				
	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>
1m boulders	100%	90%	75%	30%	10%
300mm rocks	100%	50%	10%	0%	0%
150mm rocks	90%	20%	0%	0%	0%
Vulnerability	0.4	0.3	0.2	0.1	0.7

Mauao 'natural' rockfall frequency estimate

<u>Trigger:</u>	<u>Weathering</u>	<u>Seismic</u>	<u>Animal</u>	<u>TOTAL</u>
1m boulders	1	0.3	0	1.3
300mm rocks	10	3	0	13
150mm rocks	100	30	50	180

Rockfall allocated into in the various slope zones

<u>Zone</u>	<u>Natural 1m</u>	<u>Natural 300mm</u>	<u>Natural 150mm</u>	<u>Human 1m</u>	<u>Human 300mm</u>	<u>Human 150mm</u>
1	0.065	0.65	9	0	0	25
2	0.52	5.2	72	0	0	0
3	0.26	2.6	36	0	0	0
4	0.325	3.25	45	0	0	50
5	0.065	0.65	9	0	0	0
6	0.065	0.65	9	0	0	0
TOTAL	1.3	13	180	0	0	75
TOTAL						269.3

Total Rockfall Frequency

1m Freq/m ² source	0.0001
300mm Freq/m ² source	0.0013
150mm Freq/m ² source	0.0255

Visitor No's

Upper Tracks	75,000
Base Track	350,000

Rockfall risk calculation

<u>Zone</u>	<u>Track</u>	<u>Hazard Category</u>	<u>Track Length</u>	<u>Annual Rocks Crossing</u>	<u>Incremental Risk</u>	<u>Fatality Return Period</u>	<u>Fatality Frequency</u>
1	Waikorere	1	50	7.18	6.E-08	217	5.E-03
1&2	Base	4	600	0.18	6.E-10	4,667	2.E-04
2	Waikorere	2	400	17.47	1.E-07	89	1.E-02
2	Oruahine	3	450	0.91	5.E-09	2,567	4.E-04
3	Oruahine	3	250	0.46	3.E-09	5,134	2.E-04
3	Base	4	400	0.08	3.E-10	10,268	1.E-04
4	Oruahine	1	150	89.08	1.E-06	13	8.E-02
4	Base	3	250	0.57	4.E-09	695	1.E-03
5	Oruahine	1	200	8.82	1.E-07	133	8.E-03
5	Base	3	200	0.11	8.E-10	3,521	3.E-04
6	Base	4	500	0.02	7.E-11	42,784	2.E-05
1&6	Campground b (1 week stay)	5	400	0.01	2.E-07	879	1.E-03
TOTAL						10	1.E-01

6.10.1 Discussion; sensitivity analysis

The next step is to consider the sensitivity of the result to the likely margin of error in the assumptions, i.e. whether the values appears reasonable.

A ten year return period for fatalities might initially sound high but it could very well represent the real situation since the fire, with persons walking off track on the vegetation free slopes above the rock climbing areas.

By far the largest component of the overall risk comes from the Zone 4 Oruahine track and over half the risk there is posed by human triggered rockfall, which has been arbitrarily estimated at 50 rocks per year.

7 ROCKFALL RISK EVALUATION

7.1 Risk criteria

The aim is to determine whether the estimated risks of fatality (within their accuracy) are acceptable or tolerable. It does not consider issues such as damage to property, public reaction/confidence, environmental issues or litigation consequences.

Tolerable risk criteria are not fixed and society shows a wide range of tolerance to different hazard and risk; risk criteria are a mathematical expression of societal opinion.

Public resources such as Mauao, with very extensive recreational use and under local government management might be expected to meet relatively low risk criteria.

As mentioned previously the accurate quantification of rockfall and landslide risks is dependent on the recognition and understanding of the processes involved and will always be subject to reinterpretation following further investigation.

The calculated risks are in a large proportion based on engineering geological judgment, knowledge and experience and revisiting an analysis of this type can often lead to significant change due to increased data.

There are a number of ways of presenting and comparing risk, one of the most important examples being whether we compare:

- The risk of carrying out an activity one time; "incremental risk".
- The risk whilst involved in the activity (per unit of time).
- The annual risk to the typical person; "individual risk".
- The overall acceptability to society

Previous reports concentrated on incremental risk. This is a measure of the risk to the individual on one walk, one weeks camping, etc.

Even when risks to individuals might appear acceptable, high visitor numbers might lead to unacceptably frequent incidents. Also, the person who carries out an activity every day is exposed to 365 times the risk when evaluated annually.

It is always useful in risk analysis to use more than one approach so for this analysis we will scale the incremental risk up to also consider:

- A person walking the track/camping once per year
- A person walking the tracks once a day/week/camping permanently
- A person static for one hour
- Overall acceptability; societal risk; F-N curves

One of the key aspects is deciding what 'acceptable' and 'tolerable' risks are.

Some general guidance can be taken from the Australasian Geomechanics Society, Sub-Committee on Landslide Risk Management:

There are no established individual or societal risk acceptance criteria for loss of life due to rockfall, in Australasia or internationally. It is however possible to obtain some general principles from other engineering industries:

- a) The incremental risk from a hazard should not be significant compared to the risks to which a person is exposed in everyday life.
- b) The incremental risk should, *wherever reasonably practicable*, be reduced, i.e. the As Low As Reasonably Practicable (ALARP) principle should apply.
- c) If the possible loss of large numbers of lives from an incident is high, the probability that the incident might actually occur should be low. This accounts for society's particular intolerance to incidents that cause many simultaneous casualties and is embodied in societal tolerable risk criteria.
- d) Persons in society will often tolerate higher risks than they regard as acceptable when they are unable to control the risk because of financial or other limitations.
- e) Acceptable risks are generally considered to be an order of magnitude smaller than tolerable risks.

The following table summarises some quoted incremental risk criteria:

Source	Lower bound (acceptable)	Upper limit (tolerable)
HSE (1989a)	10^{-6}	10^{-5}
HSE (1988)	10^{-6} broadly acceptable	10^{-3} divides just tolerable and intolerable. 10^{-4} member of public from large industrial hazard.
NSW Planning (1994)		10^{-6} residential.
HK Gov't (1994)		10^{-5}
BC Hydro (1993)		10^{-4}
ANCOLD (1994)		10^{-5} average. 10^{-4} person most at risk.
NZ Geomechanics News 2000 (new slopes)	10^{-6} average of persons at risk.	10^{-5} persons at most risk.

The figures above are per person per year and intended for risks to which persons are exposed throughout the year.

To get a feeling for the level of risk, these can be compared to the following, (from Higson, 1989, mostly for New South Wales):

Voluntary Risks (average to those taking the risk)	Chance of fatality per person per year
Swimming	5E-5
Owning firearms	3E-5
Transport Risks (average to travellers)	
Motor vehicle	1E-4
Train	3E-5
Aircraft	1E-5
Risk averaged over population	
Road accidents (NZ LTSA)	1E-4
Accidental falls	6E-5
Homicide	2E-5
Flood	3E-7
Lighting	1E-7

7.2 Mauao rockfall risk estimate summary

<u>Zone</u>	<u>Track</u>	<u>Annual Rocks Crossing</u>	<u>Incremental Risk</u>	<u>Fatality Return Period</u>	<u>Fatality Frequency</u>
1	Waikorere	7.18	6.E-08	217	5.E-03
1&2	Base	0.18	6.E-10	4,667	2.E-04
2	Waikorere	17.47	1.E-07	89	1.E-02
2	Oruahine	0.91	5.E-09	2,567	4.E-04
3	Oruahine	0.46	3.E-09	5,134	2.E-04
3	Base	0.08	3.E-10	10,268	1.E-04
4	Oruahine	89.08	1.E-06	13	8.E-02
4	Base	0.57	4.E-09	695	1.E-03
5	Oruahine	8.82	1.E-07	133	8.E-03
5	Base	0.11	8.E-10	3,521	3.E-04
6	Base	0.02	7.E-11	42,784	2.E-05
1&6	Campground boundary (1 week stay)	0.01	2.E-07	879	1.E-03
			TOTAL	10	1.E-01

The breakdown of the tracks/zones has allowed us to identify significant and representative locations. For the sake of simplicity in the remainder of this report we will look at the most hazardous track (Zone 4 Oruahine), a mid risk track section (Zone 2 Waikorere), the highest risk Base Track section (Zone 4 Base Track), a low risk base Track section (Zone 1&2 Base Track) and the campground.

7.3 Comparison with previous 'single visit' risk estimations

The following table compares this reports incremental risk with previous estimates:

	<i>Zone 4 Oruahine</i>	<i>Zone 2 Waikorere</i>	<i>Zone 4 Base</i>	<i>Zone 1&2 Base</i>	<i>Campground</i>
<i>Initial 2004</i>	2E-7	3E-8	3E-9	1E-9	4E-8
<i>Post Quake</i>	2E-7	4E-8	5E-9	2E-9	6E-8
<i>Post Flood</i>					7E-7
<i>This Report</i>	1E-6	6E-8	4E-9	6E-10	2E-7

The risk levels in this report are consistent with those previously discussed and certainly within each others margins of uncertainty.

Variations are due to:

The approach of splitting the tracks into the zones and using the hazard category rating is a refinement on the previous approach.

The frequency of rockfall has been adjusted in the light of new data; particularly important is the frequency of human triggered rockfall which is responsible for the increased risk level on the Zone 4 Oruahine Track.

The visitor numbers are now greater than those used previously.

7.4 Incremental risk evaluation

This evaluation will use the NZ and Australian Geomechanics Societies guideline of 1E-6 being acceptable for the average of persons at risk and 1E-5 being tolerable for the person most at risk. For clarity the values have been colour coded;

<i>Not Tolerable ?</i>	<i>Tolerable ?</i>	<i>Acceptable ?</i>
$\geq 1E-5$	$< 1E-5 \geq 1E-6$	$< 1E-6$

7.4.1 A person walking the track/camping once (per year)

<i>Zone 4 Oruahine</i>	<i>Zone 2 Waikorere</i>	<i>Zone 4 Base</i>	<i>Zone 1&2 Base</i>	<i>Campground Boundary</i>
<i>5 min's walk</i>	<i>12min's walk</i>	<i>10min's walk</i>	<i>22min's walk</i>	<i>84hrs on site</i>
1E-6	6E-8	4E-9	6E-10	2E-7

At 1E-6 in the worst case it appears the single visit per year is at the upper end of acceptable.

7.4.2 A person walking the track every day/week/camping permanently

<i>Zone 4 Oruahine</i>	<i>Zone 2 Waikorere</i>	<i>Zone 4 Base</i>	<i>Zone 1&2 Base</i>	<i>Campground Boundary</i>
4E-4	2E-5	2E-6	2E-7	1E-5

Once a day= 365 times the single visit values for tracks, 52 times for camp:
The risks on the Zone 4 Oruahine Track appear very likely to be unacceptable.

For a person walking the tracks once a week or camping one month we get:

<i>Zone 4 Oruahine</i>	<i>Zone 2 Waikorere</i>	<i>Zone 4 Base</i>	<i>Zone 1&2 Base</i>	<i>Campground Boundary</i>
5E-5	3E-6	2E-7	3E-8	1E-6

The risk to campers appears to possibly be acceptable unless camping on the boundary row for a month or more per year.

7.4.3 A person static for one hour

<i>Zone 4 Oruahine</i>	<i>Zone 2 Waikorere</i>	<i>Zone 4 Base</i>	<i>Zone 1&2 Base</i>	<i>Campground Boundary</i>
1E-5	3E-7	2E-8	2E-9	2E-9

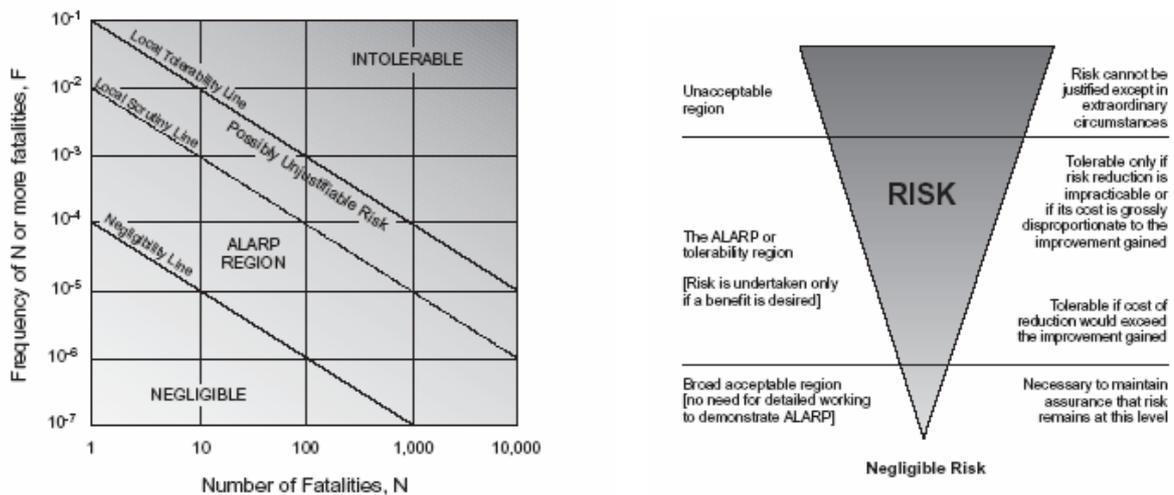
Perhaps this is only relevant as an alternative guide to the relative risk whilst in the area, i.e. standing on the Zone 4 Oruahine a person is 5,000 times more likely to be struck by a rock than when in the campground boundary sites.

7.5 Overall acceptability evaluation

Rather than considering the risk to individuals this looks at societies acceptance of risk; e.g. one plane crash per year killing 200 people is seen as unfortunate but 'acceptable', whereas one crash per week would be likely to be unacceptable.

There are few published guidelines but most apply the "as low as reasonably possible" (ALARP) principle; any means which could give a meaningful reduction should be considered. Cost comes into risk mitigation at this level and one could go on to using concepts such as the 'value of a statistical life'.

ANCOLD is an authority for the dam's industry internationally and offer probably the most quoted guideline, suggesting F-N curves which take into account the number of lives lost:



The zones on the plot are based on a wide range of data for different hazards which result in fatalities.

Of course with Mauao rockfall we are on the left hand side of this plot as we are dealing with single incidents.

The overall fatality frequency we calculated for Mauao was 0.1 (one fatality per 10 years) and plots on the 'Local Tolerability Line', certainly well into the ALARP region.

7.6 Factors likely to alter the rockfall risks

It is worth restating that the calculated values are not fixed but are based on our existing knowledge of the slopes and a number of assumptions and engineering judgments.

The last three years have continued to reveal new information which has refined our picture of rockfall on Mauao. The human triggered rockfall is one of the main uncertainties at present.

As time goes on the risks may also change due to real changes on the slopes, such as ongoing scour, which certainly is continuing to destabilise some slopes.

Changing visitor usage or numbers would of course also alter the risk.

8 ROCKFALL TREATMENT OPTIONS

8.1 Discussion

Risk Treatment is the final part of the Risk Management process and provides the methodology for controlling the risk. It is recommended that TDC implement an ongoing Management Plan. Treatment options for Mauao could include:

1. Passive options;

- Accepting the risk; this requires the calculated risk to be within the determined acceptable or tolerable range.
- Avoiding the risk; would in this case mean preventing or discouraging public access.

2. Active options;

- Reducing the likelihood; could possibly in part be achieved in part by; rock scaling, slope reinforcement, vegetation management etc.
- Reducing the consequences; could be achieved by rockfall defences such as a catch fence.
- Monitoring and warning systems; will keep track of and improve the reliability of the hazard and risk assessments and allow adaptation to meet changing circumstances.

8.2 Practical options

8.2.1 Public information

There are areas of Mauao where dangerous steep slopes/cliffs can be accessed very easily, perhaps by persons unaware of the risks.

Signage should inform the public of the rockfall and height hazards and information on hazard and risks could be added to existing notice boards/visitor leaflets etc.

8.2.2 Vegetation management

Since the January 2003 fire TDC has implemented a native replanting and selective weed spraying strategy. Vegetation is now re-establishing well in many places but still has many years to go to reach pre-fire levels.

The rate of scour may be preventing grasses from taking root on some of the loosest sandy colluvium and this may locally have been exacerbated by herbicide spraying. Weed spraying should be very selective.

Until grass is established, relatively rapid scour will continue to reveal new hazards.

8.2.3 Access control

No vegetation control, planting, rock scaling or inspection should take place on the loose/over-steep slopes without serious consideration of track closures below.

Our operations have shown that if track closures are in place, their effectiveness will depend on the type of closure. Signage will be ignored by some people.

Restricting public access on Mauao will be contentious and any measures taken are unlikely to be 100% successful; however, there may be measures which can be taken and which will mitigate the risk.

This assessment suggests the risk on the Zone 4 Oruahine track is an order of magnitude greater than on any of the other tracks. Much of the hazard is triggered by human activity on the steep and loose slopes above and a significant proportion is likely to be triggered by rock climbers.

The steep rock on the climbing routes themselves is reasonably sound, having been regularly climbed for a number of years. The hazard comes above routes for which the normal exit is a 'walk-off' from the top, rather than a 'lower-off' on ropes.

Reducing public access to the areas above the track will reduce the rockfall frequency and risk.

8.2.4 Slope reinforcement

Slope reinforcement would consist of installing physical measures installed to prevent rocks failing and includes works such as; rock dowels and bolts, tensioned rockfall mesh, tensioned wire strops, geotextile etc.

Such works would be likely to be visually and environmentally unacceptable and difficult and expensive to install. It is unlikely that wide area reinforcement will ever be an option on Mauao. Discrete small scale reinforcement could be a future option to mitigate very specific hazards.

8.2.5 Rockfall defences

Rockfall defences stop and trap moving rockfall before it reaches the at risk areas, generally they include catch fences and structures.

The low risk levels over most of Mauao's tracks would probably not justify widespread rockfall defences. There may be two exceptions:

- The Zone 4 Oruahine track may be suitable for small and unobtrusive catch structures above the climbing cliffs.
- Fences at the campground boundary at least merit further investigation.

There are a number of different types of fence options which could be implemented and the cost benefit of these can differ greatly.

Any fences should be carefully designed to retain the likely size and range of energies of rocks at the location.

Environmental and political acceptability will obviously be an issue with any proposed catch fence works but works could be designed so as to be unobtrusive and procedures could ensure installation with minimal environmental disruption.

8.2.6 Regular rock scaling

Annual rock scaling programs are internationally a common and effective means of hazard management on slopes such as Mauao's. An ongoing annual rock scaling program is recommended. This would be a particularly good option whilst scour continues to create new unstable surface rocks.

The scope of annual scaling could include a brief inspection of all slope areas followed by specific areas of concern being targeted for scaling work, with different areas being selected each year.

The most appropriate time would be after winter and before the main tourist season.

Overly enthusiastic rock scaling can of course create more problems than it solves and all rock scaling work should be carried out under the supervision of a competent Engineering Geologist to ensure that only the most marginally stable rock is removed.

8.2.7 Regular monitoring

TDC has established a monitoring programme; Six monthly geotechnical inspections are being carried out and the Mauao Ranger is keeping watch for any evidence of actual or potential rockfall and scour and is reporting as necessary.

The scope of monitoring includes:

- Brief visual inspection of all areas by an appropriately experienced roped access Engineering Geologist (with reference to previous reports). Temporary track closures will be necessary for access to some areas.
- Measurement for movement at established survey markers.
- Special attention to close inspection of areas above Western Oruahine track and Campground.
- Targeted detailed inspection of any other specific areas of concern.
- Installation of additional survey markers if necessary.
- Review and re-estimation of risk levels in the light of any new data.
- Presentation of a written report including recommendations.

A review of TDC's Management Plan would follow with implementation of changes as necessary.

In the event of any major events on Mauao, for example; fires, earthquakes, floods or natural collapse of large rock columns it is recommended that all affected areas be reassessed in detail.

9 LANDSLIDE HAZARD & RISK; PRELIMINARY

9.1 Hazard

Avalon's 28/7/05 report "*Mauao Slopes; Zone 6 Hazard & Risk Assessment*" briefly discussed the possible slip threat to the campground.

Photograph 2 indicated slips scarps in the colluvial slopes around the base of Mauao. Photograph 29, below shows major slip scarps immediately above the campground.



Photo' 29. Slip scarps above campground.

These slip events appear likely to have been over five times larger than the 18th May 2005 slip on the south western slopes (see Photograph 16) and probably released a similarly fast moving, liquefied debris flow.

The present day consequences of such an event could clearly be extremely serious.

We currently have very little knowledge of the potential for, and likely frequency of, these types of events.

In some areas of the campground the toe of the colluvial slope has been excavated to create level camp sites. Such excavations reduce natural slope stability.

Further site investigation has been recommended and could include geophysics such as a resistivity survey in an attempt to determine colluvial thicknesses and location of watercourses and springs.

Other investigation techniques applicable could include installation of piezometers to monitor groundwater and detailed engineering geological logging of exposed sections through the colluvium.

In addition to defining the geology, estimating frequency of slip events will be critical. Identification and dating of ash shower beds or dating of organic material within the colluvium could be of some value in this.

9.2 Frequency

The May 2005 floods appear to have been an event with a return period somewhere between 35 and 150 years (depending on how the data is analysed; the longer period accumulations being most relevant here).

For the sake of simplicity maybe we can assume 100 years. This event triggered one slip of 8,000m³ (We will not consider the smaller events).

The portion of Mauao's colluvial apron with slip scarps is approximately 2,000m in circumference, 400m of which is above the campground.

A simple calculation suggests a rainfall triggered slip of 8,000m³ might occur above the campground every 500 years.

500 year events are generally the maximum return period event that would be considered but, given the potential consequences and uncertainty it is worth taking this analysis further. Also, less intense rainfall, in conjunction with earthquake for example, could have similar effects.

9.3 Consequences

An 8,000m³ slip above the campground would cover; say 100x40m area to 1m deep, if 50% of the material crosses the boundary.

The campground has around 250 sites over 400x75m therefore the slip might cover say 30 campsites.

The vulnerability of persons in a tent/van in the flow path would be quite high; say, 0.5.

If we assume 50% occupancy and four persons for 12 hrs per site then at any time there will be 30 persons in the path of the flow.

9.4 Risk estimation

The incremental risk for a one week stay can be estimated as the product of:

Probability of being on an affected site= 30/250 = 12%

x

Percentage of the day spent on site = 50%

x

One week in 500 years = 1/26,000 = 2.3E-6

x

Vulnerability to death = 70%

Incremental risk = 1.6E-6

This is an order of magnitude greater than the rockfall risk calculated for the campground boundary sites.

9.5 Fatality frequency & risk evaluation

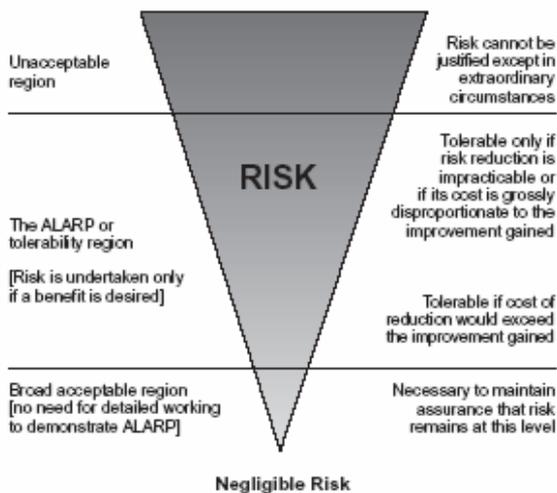
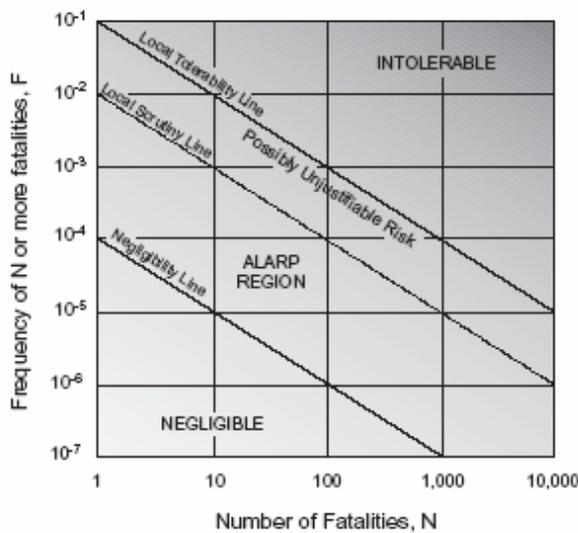
Every 500 years 30 persons will be in the path of the flow and 21 will be killed. This equates to one fatality every 24 years. Therefore fatality frequency = $4E-2$.

For rockfall in the campground we had a return period of 879 years, a frequency of $1E-3$ therefore the risk from a debris flow may be greater than from rockfall.

Society also tends to view multiple fatality incidents differently to single fatalities, generally regarding them as less acceptable.

Of course these values are all currently very provisional and simply show that the risk from landslip may be worthy of further consideration.

The following figure brings repeats the ANCOLD/ALARP concepts on risk tolerability and is derived from UK guidelines.



9.6 Risk treatment

It is not possible to be specific as the risks are as yet too poorly understood. However, to give some examples:

1. Passive options;

- Accepting the risk; this requires the calculated risk to be within the determined acceptable or tolerable range.
- Avoiding the risk; would in this case mean closing areas of the campgrounds.

2. Active options;

- Reducing the likelihood; could theoretically be achieved by slope drainage.
- Reducing the consequences; could be achieved by defences such as walls.
- Warning systems; are unlikely to be applicable.
- Monitoring; is recommended as it will increase our knowledge.

9.7 Recommendations

Further investigation is required if we are to better understand the landslide process, hazard and risk.

Investigation should aim to determine the soil material properties, hydrology, rockhead profile and above all the age of the age of the scarp features.

Appropriate investigation techniques would be likely to include detailed mapping and profile logging, radiometric dating and geophysics.

It is strongly recommended that no absolutely no earthworks or drainage works be carried out in or above the campground without serious consideration of the potential consequences.

10 SAFE ACCESS

As mentioned previously, it is extremely difficult to walk any distance on the steep upper slopes without dislodging rock. All persons accessing these areas pose a serious hazard and this is as applicable to TDC staff or contractors as it is to the public.

During Avalon's operations the public have ignored signs and even dodged security guards on occasion.

It is essential that track closures are effective during any operations on the slopes.

Using ropes for access and fall arrest is the only practical means of complying with OSH guidelines and the HSE Act whilst working on the steep slopes. However, ropes increase the hazard as whilst running over the loose ground as they can trigger rockfall.

More hazardous accidental rockfall is likely from trainee and inexperienced rope access personnel.

Using only experienced industrial rope access contractors will minimise the hazard.



Photograph 30. NW Slopes with highest risk section of Oruahine Track.

11 CONCLUSION & RECOMMENDATIONS

Although the rockfall risks to individuals on single visits may be acceptable, TDC has to consider that the very high visitor numbers lead to significant total exposure.

A calculated fatality return periods in the order of ten years may alone be unacceptable.

For a person walking the upper tracks once a week we the rockfall risk appears marginal on the Waikorere track and likely to be unacceptable on the Western Oruahine Track, under the rock climbing areas.

The rockfall risk to campers appears to possibly be acceptable unless camping on the boundary row for a month or more per year.

Some contributing factors to the current level of rockfall risk can be mitigated relatively easily:

- It is recommended that rockfall mitigation options be considered for the North West Oruahine Track, the highest risk area. Measures should include access restriction, rock scaling and possibly the consideration of fences.
- The hazard to the Campground is likely to be most cost effectively mitigated by monitoring and controlled scaling at the rockfall source areas (if necessary) although catch fences continue to be an option.
- TDC's planting and weed control programme should give priority to establishing grass to help stabilise the loose colluvium.
- Public off track access to the steep upper slopes should be prohibited.
- Effective track closures must be in place before any TDC staff or contractors access the steep upper slopes off track. Any persons entering these areas must be suitably experienced, competent, trained, equipped, insured etc.
- Monitoring and inspection should continue six monthly.
- Annual rock scaling is recommended.

Landslip hazard appears to possibly present a greater threat to the campground than rockfall and requires further consideration.

Any excavation at the toe of a slope reduces stability. It is strongly recommended that no earthworks or drainage works be carried out in or above the campground without serious consideration of the potential consequences.