OO4

BAY OF PLENTY REGIONAL COUNCIL

Submission Number
Office use only

RECEIVED
03 NOV 2014
BOP Regional Council

Submissions close at 4:00 pm on Thursday, 13 November 2014.

Submission on publicly notified Proposal for Policy Statement Change

Clause 6 of Schedule 1, Resource Management Act 1991

TO: The Bay of Plenty Regional Council
PO Box 364
Whakatāne 3158

Fax: 0800 884 882

or email: livingwithrisk@boprc.govt.nz

Name of submitter [*Full name*]: Neville Innes HARRIS

This is a submission on Proposed Change 2 (Natural Hazards) to the Bay of Plenty Regional Policy Statement:

1 I ~~could~~ / could not* gain an advantage in trade competition through this submission.
[*Delete as required.*]

(a) I am / ~~am not~~ directly affected by an effect of the subject matter of the submission that adversely affects the environment; and

(b) My submission ~~does~~ / does not relate to trade competition or the effects of trade competition.

2 The details of my submission are in the attached table.

3 I wish / ~~do not wish~~ to be heard in support of my submission.
[*Delete as required*]

4 If others make a similar submission, I will consider presenting a joint case with them at a hearing.
[*Delete if you would not consider presenting a joint case.*]

N. I Harris — Date: 03/11/2014

Signature of submitter
(Or person authorised to sign on behalf of person making submission.)
[A signature is not required if you make your submission by electronic means.]

Address for service of submitter: 7 Pioneer Place, Matata RD4 Whakatane 3194

Telephone: 07-322-2380 Daytime: Same After hours: Same

Email: N/A Fax: Same

Contact person [*Name and designation, if applicable*]: Neville HARRIS

Note to person making submission: Include 5 sets of refference.

If you are a person who could gain an advantage in trade competition through the submission, your right to make a submission may be limited by clause 6(4) of Part 1 of Schedule 1 of the Resource Management Act 1991.

Total 26 Pages

A1927512

SUBMISSION POINTS:

The specific provisions of Proposed Change 2 (Natural Hazards) to the Bay of Plenty Regional Policy Statement that my submission relates to are:		My submission is: [*include*: • *whether you support or oppose the specific provisions or wish to have them amended; and* • *reasons for your views*]		I seek the following decision from the local authority:
Page No.	***Reference (e.g. Objective, Policy, or Method number)***	***Support/Oppose/ Seek amendment***	***Reasons***	**[*Give precise details*]**
1	2.8 Natural Hazards	Amend.	All refferences to debris flow to become debris flow / ~~f~~ flood	Debris floods can be as damaging as a debris flow - see ref 1. Page 1,2+13
—	Building in Hazard Area.	Add.	Debris flows more freqent than L75yrs / Death risk greater than acceptable	Prevent building on proven debris flow Fans - ref 2 P6+9

Submission on Proposed Change 2 [Natural Hazards] to the BOP Regional Policy Statement.

1/ Debris floods damage property far greater than a normal flood. Ref 1 pages 1,2 & 13. If debris flood is not named it is possible insurance companies will use this to prevent paying out.

2/ The Building Codes recommend dwellings not be subject to structural damage more frequently than once in every 475 years. Matata's return period for debris flows is about 35 years, Ref 1 page 38. Now days the return period for the size of this 18 May 2005 debris flow is put at 200 to 500 years, all within the 475 year period. The Ohinekeo stream [next west of the Awatarariki stream] debris flowed only 7 years earlier than the 2005 event, damaging SH2 and Murphy's Motor Camp. Was a similar size to the 2005 event.

3/ Ref 3. Numerical modelling of debris flows and mitigation structure at Matata, NZ puts the 28 May 2005 debris flow at approx 250 000m3. Page 3005.

4/ Ref 4. Assessing debris flows using LIDAR differencing: 18 May 2005 Matata event NZ. Puts volume of debris flow at 350 000m3 + or - 50 000m3 to 390 ooom3 + or - 1000 000m3. To these figures need to be added the water volume of all the lagoons infilled by the debris flow.

5/ Ref 5. Shows an area Whakatane District Council has declared Intolerable risk to life. By this they have destroyed the value of peoples major asset. This area includes property that WDC got subdivided out of NZ Railways land in the 1970's, Pioneer Place. The last major debris flow in this area was 16 May 1950.

6/ It is our opinion that the work done by Tonkin & Taylor Ltd in relation to the size of the Matata 2005 event is well short of what really happened.

N. J. Harris

Neville Harris.

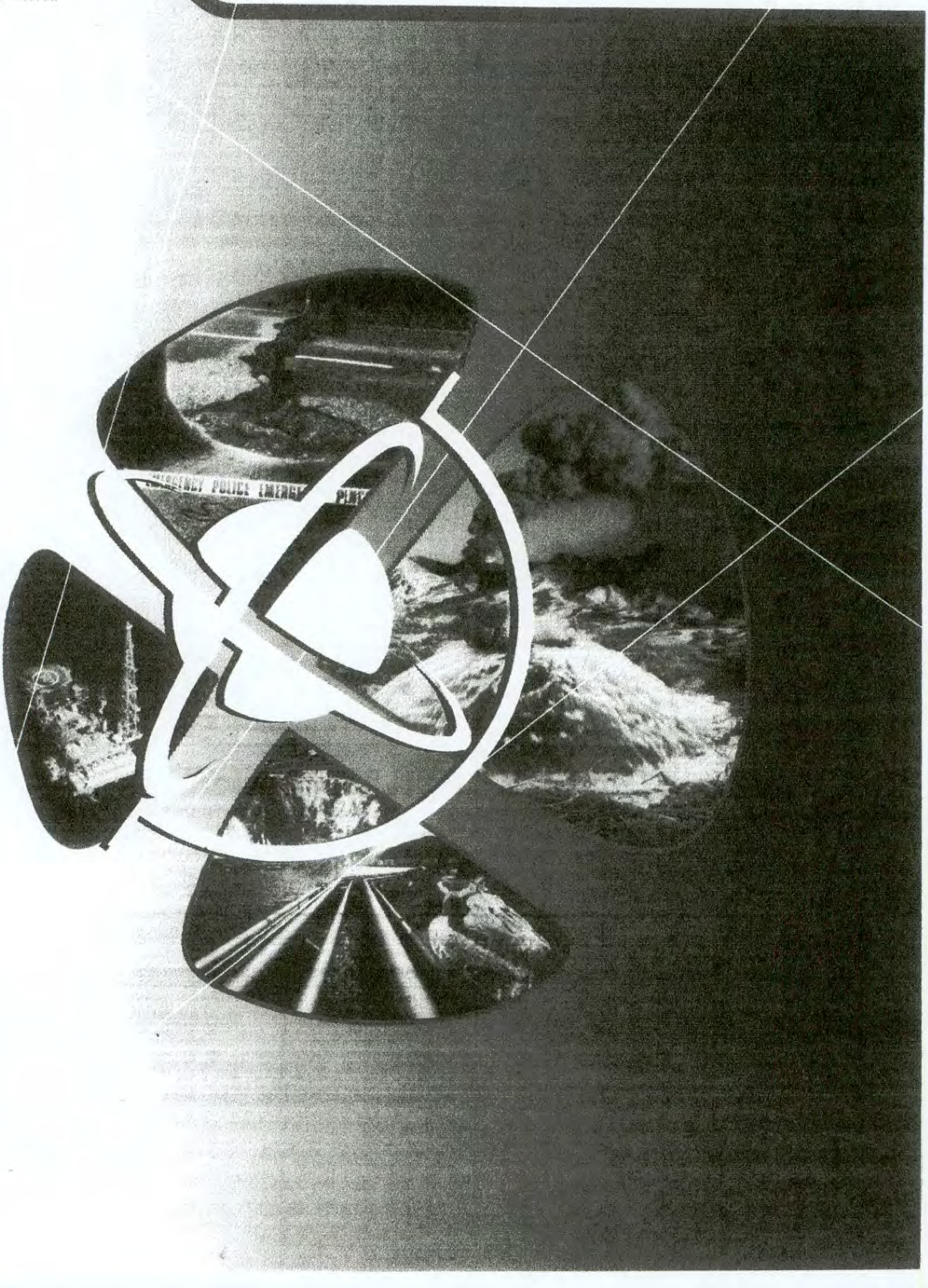
Institute of
GEOLOGICAL
& NUCLEAR
SCIENCES
Limited

Confidential

The 18 May 2005 debris flow disaster at Matata: Causes and mitigation suggestions

by M. J. McSaveney, R. D. Beetham
& G. S. Leonard

Client Report
2005/71
June 2005



EXECUTIVE SUMMARY

On 18 May 2005, a band of intense rain passed over the catchments behind Matata. It triggered many landslips, and several large debris flows, which, with their associated flooding, destroyed 27 homes and damaged a further 87 properties in Matata. SH2 and the railway were closed for many days. The rainfall appears to be not more than a 500-year recurrence event (about 10% probability in 50 years), and it is convenient to treat the associated debris flows as having a similar recurrence interval. There is evidence that equally as large, and larger debris flows have occurred many times since 7000 years ago. Historical records indicate that probably four smaller debris-flows have occurred since 1860.

Witness descriptions and physical evidence indicate that debris flows caused the damage to Matata in the vicinity of Awatarariki and Waitepuru Streams. Debris flows are classified by experts as a type of landslide. They are dense fluid mixtures of all manner of rock, soil, organic debris and water which move rapidly, and are capable of carrying immense boulders. Boulders up to 7 metres across were moved by Awatarariki Stream's debris flow. Evidence in the stream headwaters indicates that the primary causative events that inevitably led to the debris-flow damage at Matata were landslips of the type termed *debris avalanches,* triggered by exceptionally heavy rain. The debris flows directly damaged some homes and property. Other homes and property were damaged by debris floods that extended beyond the debris flows. A debris flow is usually accompanied by a debris flood, which is regarded by experts as an integral part of the total debris-flow event.

We also determined from physical evidence that:

- A debris flood damaged property in the vicinity of Waimea Stream. We could not determine whether this debris flood had an associated debris flow. A debris flood is less damaging than a debris flow, and can occur in the absence of a debris flow.
- A debris flood damaged homes and property in the vicinity of Awakaponga Stream. It was a direct consequence of a debris flow that caused no direct damage.
- In the vicinity of Ohinekoao Stream, a debris flow reached to SH2. Its associated debris flood damaged the railway and property beyond.
- The landslides directly from the hillsides above Matata, and beside SH2 to the west, were debris avalanches. These are similar to debris flows, but lack a confining channel. Similar landslides falling into catchments south of Matata initiated the debris flows.
- Landslides that fell ***after*** the first debris flows had passed are the only evidence for debris dams in the streams. The highly erosive debris flows cleaned out the valley bottoms, and destabilised slopes along the channel, causing secondary landslides.

The boulders carried by the debris flows came mostly from boulders that were buried in the stream beds and banks. They got there by falling from the bluffs above the stream at various times in the past. Most of the harder boulders are derived from strongly welded ignimbrite of the Matahina formation. The boulders eroded from the channels already are being replaced by collapse of the steep slopes, a continuing process. The supplies of boulders in the channels were depleted, but not exhausted on 18 May. Further debris flows are possible whenever there is rain with high enough intensity to trigger landslides on the steep slopes.

The earthquake swarm that has been shaking Matata for many months did not contribute to the disaster. Landslips that occurred in the far stronger 1987 Edgecumbe earthquake were the source of some of the boulders that were carried by the debris flows. Others fell in landslips on 18 May, but many were already in the bed and banks of the channel from earlier events, and were picked up by the immensely erosive debris flows.

Debris flows are more dangerous than floods. For two reasons they make the flooding associated with them much worse than it would be without a debris flow: (1) they travel faster than the flow of water in the same channel and pick up all of the floodwater in their path, thus delivering water to the catchment outlet faster than would be possible in a simple flood; (2) deposition of sediment from a debris flow can fill the normal stream channel and allow the draining water to flood into areas not normally accessible by floodwater.

Hyperconcentrated flows of sediment-laden water draining from the debris flows caused debris floods; water so highly charged with sand and silt that it no longer behaved like normal water; it flowed faster and was more dense, and was capable of moving larger boulders than could be moved by a normal flood flow across the lowland fans at Matata.

The landslips that initiated the debris flows were triggered by intense rain, probably in excess of 2 mm/minute which fell during a severe thunderstorm. This intense rainfall fell in a narrow band only a few kilometres wide that passed across the catchments to the south of Matata from near the mouth of Ohinekoao Stream to Awakaponga. Had this band of rain been some 500 m closer to Matata, a different, and much more devastating outcome might have occurred. The existing debris flows could have been larger, and other catchments also could have poured debris flows into Matata. In addition, there may have been more debris avalanches from the slopes immediately behind Matata. Such events have happened many times in the prehistoric past, creating the land on which Matata stands.

Parts of Matata are naturally protected from flooding and debris flows, because the ancient debris flows fans were trimmed by Tarawera River, and the streams draining from the upper catchments now are cut deeply into the toes of the fans, leaving much of the land free from flood risk. The low railway embankment gives some other parts of Matata varying degrees of protection from water and debris floods, by diverting shallow flows. The railway also increases the danger to some areas, because it diverts flows to areas not otherwise at risk.

There are areas around Matata that are unsafe for habitation. Significant areas of present-day Matata have always been at risk from debris flows, debris floods and debris avalanches. These are wider than the currently affected areas. With engineering works, it is possible to reduce the danger to some areas to commonly accepted levels, but there are other areas where such mitigation probably is not feasible. Here, it will be necessary either to accept the risk, or remove dwellings. Of course, areas designated as floodways or debris-flow routes will be uninhabitable, but could be used for recreation.

Accepting the risk need not endanger lives. Weather radar sited in the Bay of Plenty area could provide effective early warning of high-intensity rain storms for the greater Bay of Plenty region and significantly improve existing weather forecasting of severe storms.

A typical debris-flow path can be divided into an initiation zone, a transport and erosion zone, and a deposition zone. Most often, the initiation zone is a slope failure (landslip or slide) in the headwall or side slope of a gully or stream channel. The slope failure may have the character of a shallow debris slide (i.e. sliding rather than flowing), transforming into a debris avalanche (with both sliding and flow). Sometimes, the bed of the channel itself can become unstable during extreme flood discharge, and the debris flow initiates spontaneously in the steep bed of the channel. Generally, the debris-flow initiation zone has a steep slope between 20° to 45° or more. Often the initiating slide is only a few tens of cubic metres in volume, yet it can grow to a major debris flow. Under conditions of extreme rainfall intensities, there may be many shallow slides. Some may coalesce on the hillside to form larger debris avalanches. Also, many smaller debris flows in tributary channels can coalesce to form major debris flows. Such was the case in the catchments south of Matata on 18 May 2005.

Debris flow*s* commonly move in distinct surges or slugs of debris, separated by watery intersurge flows. A debris-flow event may consist of one surge, or many tens of surges. Surging arises for a number of reasons; some surges result from flow instability caused by longitudinal sorting of the debris-flow material. Such surges are characterized by boulder fronts – that are mostly boulders and other large debris (trees). The main body of the surge is a finer mass of liquefied debris, and the tail (or *afterflow*) is a dilute, turbulent flow of sediment-charged water, similar to a debris flood.

The main deposition area of a debris flow commonly occurs on an established fan, usually referred to as a *debris-flow fan*. Deposition occurs because of a combination of slope reduction and a loss of confinement. As a result of the deposition process, debris-flow behaviour varies with distance downstream from the fan apex. On the upper part of the fan, coarse debris forms high discharges and thick deposits. On the lower parts, finer and thinner deposits form, and flow velocities may be reduced. An afterflow of heavily sediment-laden water reaches the margin of the fan and may continue into the stream channel system below, with the character of a debris flood. Many debris-flow deposits on fans are significantly reworked by water flow immediately following a debris-flow event. Because of the often massive deposition at the fan head, the direction of flow of a debris flow on a fan is very unpredictable. Successive pulses of debris flows are readily diverted by the deposits of earlier pulses, and conventional flood protection measures can be overwhelmed.

Another useful term in the context of the debris flows at Matata is *hyperconcentrated flow*[5]. Water floods usually transport mostly fine sediment and in relatively small quantities in proportion to total flow volume, with the suspended sediment having little effect on the flow behaviour. Sediment concentrations are generally less than 4% by volume (10% by weight). At the other end of the spectrum, debris flows may transport more sediment than water, with sediment concentrations often in excess of 60% by volume (80% by weight), and the sediment plays an integral role in the flow behaviour and mechanics. The term *hyperconcentrated flow* is applied to flows intermediate between these end-members. Debris floods as discussed earlier, are large, sediment-rich flow events, which may or may not involve hyperconcentrated flow. Hyperconcentrated flow is a distinct flow process that can occur at low as well as high discharges. A hyperconcentrated flow is a flow of water so highly charged with sand and silt that much of its turbulence is damped out and its flow appears to be smoothed and oily, though it may be moving faster than an equivalent depth of clean water. The normal small-scale surface choppiness and splashes of water are missing on hyperconcentrated flows. A dense, fast-moving hyperconcentrated flow is capable of moving larger boulders along the bed of the flow than is the equivalent normal flow of water. Some witness descriptions of the floodwater at Matata[6] fit hyperconcentrated flow from debris flows, and we saw one small stream west of Matata in hyperconcentrated flow on 23 May when it was far from being in flood (Figure 1.3.7).

Figure 1.3.7 A small stream west of Matata, beside SH2 photographed in hyperconcentrated flow on 23 May. The flow appears to be thick and oily. Much of the surface roughness usually seen on a clear stream is damped out because of the high density of the flow. Witnesses described and photographed[7] hyperconcentrated flows at Matata on 18 May.

1.4 Debris flows and lahars

Some people have called the debris flows at Matata *lahars*. The term *lahar* is used for debris flows and related hyperconcentrated flows and debris floods that occur in volcanic materials on the flanks of a volcano. Geologists recognise that the hills to the south of Matata form the northern flank of what is known as the Okataina volcanic centre, arguably New Zealand's largest and most explosively active volcano. It has been so active through New Zealand's pre-history that today it is well hidden and difficult to recognise beneath its deposits. Much of the rock material in the debris flows at Matata was erupted from various vents of this volcano over the last few hundred thousand years or so. Very little of it is younger than 1800 years, however, and a part of the rock material in the deposits also is not from the volcano, but from underlying sandstone and siltstone beds. Hence, it is stretching the lahar concept to apply it to the events of 18 May in the catchments behind Matata. Had the same meteorological conditions of 18 May hit similar-sized catchments without the volcanic deposits, debris flows still would have been a likely outcome. For these reasons, we prefer to use the term *debris flow*.

1.5 Relevant terms in New Zealand statutes

To put the above terminology into a New Zealand legal context with respect to Matata, we refer to terms used in the Building Act (2004) and the Resource Management Act (1991). The Building Act (2004) does not use the term *debris flow*, or list the deposition of sediment on land as a hazard (as did the previous Building Act of 1991), although the converse of deposition (erosion) still is listed as a natural hazard. The Resource Management Act uses similar terminology to the Building Act (1991) with one exception noted below.

Erosion is the process of removal of land, usually by the action of running water. In the Matata context, this is scour of stream banks, and excavation of a new channel after a stream break-out (= avulsion - see below).

Avulsion is the switching of a stream or individual channel from one course to another (often called a stream *break-out*); the flow may create a new channel or use a previously abandoned one. In the Matata context, this happened at all of the major streams where deposition of sediment caused streams to switch to new channels. Avulsion was a natural hazard under the old 1991 Building Act but it is not now a natural hazard in itself under the Building Act (2004). Avulsion now legally is replaced by two natural hazards, erosion and inundation, in the 2004 Act.

Alluvion is an obscure term used in the 1991 Building Act, but not in the 2004 Act (alluvion is the Spanish word for debris flow). In the context of the 1991 Act, alluvion probably was intended to be the more common technical term *alluviation*, which is sediment deposition both in the stream channel, or on adjacent land. The term *siltation* is synonymous with both alluviation and sediment deposition even though the sediment need not be silt. The Resource Management Act (1991) does not use alluvion, but uses the term *sedimentation* in an identical context to the 1991 Building Act's alluvion. Neither alluvion nor sedimentation are natural hazards under the Building Act (2004). However, alluvion (sedimentation) can not occur without flooding, which is a subset of inundation, which is a natural hazard under the Act.

Falling debris is another natural hazard in the Building Act (2004), and is any rock, soil, snow or ice, (and associated vegetation moving) moving under the influence of gravity from offsite to cause harm at a site. *Falling debris* is not a technical term in general use, but is readily understood by technical experts to include any form of landslide that comes from upslope to cause damage below. The Building Act's falling debris should be viewed as the principal natural hazard covering the Matata debris flows. Falling debris (from other landslide types) also is the hazard to homes at the toes of the slopes south of the railway. Those homes, however, that were not affected directly by the debris flows, but by the debris floods that drained from them, experienced the Building Act's natural hazard of inundation (see below). The distinction is only important because the mitigation measures may be different.

Subsidence is another of the natural hazards in the Building Act (2004), and occurs with ground-water use in some areas, collapse of land over abandoned coal and gold mines, collapse into limestone caverns and areas of geothermal solution, collapse over buried melting ice, and differential compaction when soils liquefy during earthquakes. It is one of the natural hazards excluded from coverage by the Earthquake Commission. It is not a significant hazard on currently developed areas around Matata, but could be an issue if urban development occurred on the infilled lagoons.

Inundation includes flooding, overland flow, storm surge, tidal effects and ponding. Flooding and overland flow can be either from flooded streams, or directly from heavy rain. Under the Building Act (2004) inundation has to be viewed as the natural hazard that also includes avulsion, sedimentation and some aspects of alluvion (and also could include debris-flow inundation). Inundation historically has been a significant hazard around Matata.

Slippage under the Building Act (2004) means landslips (= landslides), but in the context of the land on the site moving offsite (and thereby becoming *falling debris* for another site).

Sedimentation is the both the process of deposition of sediment on land and the sediment itself that remains. Sedimentation is to be considered as a natural hazard under the Resource Management Act (1991) but it is not a natural hazard under the Building Act (2004). This is a curious omission, because erosion, which is the converse of sedimentation, and technically can be considered to be negative sedimentation (and vice versa) is a natural hazard in both Acts. Both can be dangerous and destructive. Sedimentation includes deposition by debris flows.

There is no legal anomaly created if any particular potentially adverse natural event (= natural hazard) might be considered to be any of a variety of legally defined natural hazards under one or more statutes, provided that any measures to be considered are appropriate for the type of physical phenomenon. That is, it does not matter whether one classifies *debris flows* as inundation, sedimentation, or falling debris, providing that the measures taken to avoid damage from debris flows is appropriate for debris flows. Further, there are other real natural hazards, such as earthquakes and strong wind that are not listed as natural hazards under Section 76 of the Building Act (2004), but which must be considered in the design and construction of buildings.

Debris flows are invariably structurally damaging to buildings they impact on, and not merely an inconvenience as inundation by floodwater often is. Hence, debris flows should be considered in the same context as other structurally damaging hazards such as earthquakes and strong wind. Under the codes associated with the Building Act (2004) it is appropriate to adopt standards of construction of dwellings such that they might have a 90% chance of lasting their expected lifetime, usually taken as 50 years. It follows that the appropriate level of protection from debris flows is that of the debris flow of 10% probability in 50 years (which is usually rounded to an event of 500-year return period), whereas for protection from the inconvenience of non-structurally damaging flood inundation, a lower level of protection may be appropriate (such as the 100-year return period).

2.0 ASSESSMENT OF MAIN CATCHMENTS AND PROCESSES CONTRIBUTING TO DAMAGE

2.1 Geology

The geology and topography of the area around Matata are shown in Figures 2.1.1 and 2.1.2.

2.1.1 Mantling deposits around Matata

The upper-most units mantling the landscape around Matata are young airfall tephras derived from past rhyolitic eruptions from the Okataina Volcanic Centre[8], a explosively active volcano with an eruption record extending back more than 280,000 years. Between them are ancient soils (paleosols) and reworked tephra. Together, the beds of airfall tephras and reworked materials usually amount to a few metres or less in thickness. The airfall layers contain fresh lumps of pumice and the deposits are usually barely-consolidated to soft. The oldest of these relatively fresh tephras is part of the Rotoiti formation erupted from the Okataina centre about 62,000 years ago (C.J.N. Wilson, pers comm., 2005). Ignimbrite is present within the Rotoiti formation along the coastline west of Matata. In the hills around Matata, Rotoiti ignimbrite deposits may be present in isolated pockets. Rotoiti ignimbrite generally contains abundant fresh mineral grains and pumice lapilli, and is loosely consolidated to firm.

Multiple rhyolitic airfall tephra layers, buried soils and other sediments are variably present below the Rotoiti formation across the Bay of Plenty Coast[9]. These range in consolidation from soft to hard and are derived from various Taupo Volcanic Zone (TVZ) eruptions between the 62,000-year-old Rotoiti eruption and the 280,000-year old Matahina eruption[10].

6.0 POSSIBLE WORKS OPTIONS TO MITIGATE RISK AND MINIMISE THE AREA AFFECTED IN FUTURE EVENTS.

All information that we have points to debris flows being relatively rare, but extremely damaging events at Matata. The debris flows of 18 May appear to have been by far the largest of four separate debris-flow events reported to have affected Matata since 1868. That is, the probability of debris flows at Matata is something like once in 35 years or so, but the probability of debris flows as large or larger than those of 18 May may be only once in 500 years or so. Once in 35 years is an unacceptably high probability even for flood inundation, and when the added danger of the debris, with greater damage to property and more danger to life is taken into account, the level of risk is very high, and at a level widely acknowledged to be unacceptable for dwellings.

It is clear that the 18 May debris flows were structurally damaging to all buildings and bridges in their paths. At several locations, the associated debris floods also were structurally damaging. Because of the structural damage, it is appropriate to consider a higher level of protection for debris-flow inundation than would normally be provided for flood inundation. To match other structurally damaging hazards such as earthquakes and strong wind, it is appropriate to choose a high level of protection such that there is a 90% probability of the structure lasting 50 years without being destroyed by a debris flow (an event with 10% probability in 50 years has approximately a 500-year return period). It is fortunate that the 18 May events seem to be of the order of this rare probability (based on the rainfall intensity at Awakaponga), because this provides a sound basis for the design of works to mitigate the debris-flow risk. Whatever measures are taken, they ought to be capable of preventing building damage in events of at least the magnitude experienced on 18 May. In addition, the measures taken should not of themselves make the situation more dangerous in even larger events. That is, we have to acknowledge that it is not possible to provide protection from every conceivable event, and should ensure that the method of protection provided does not cause additional danger when the works are overwhelmed in much larger events. Ideally, the works should still reduce the danger in such overwhelming events.

Four broad options are available to mitigate debris-flow risk. A combination of all four options probably is needed, because the present risk is so high. These options are:

- debris detention (somewhere in the catchments);
- debris deflection (on the fans);
- building regulation (prohibition of building on areas intended to be the paths of future debris flows and debris floods); and
- warning (and evacuation) through early detection of severe storms (regional-scale, high-resolution numerical weather modeling, and regional tracking of storms with weather radar are viable options used elsewhere in New Zealand). This can mitigate the risk to life, but does little to protect property.

21

DEBRIS FLOW EMERGENCY AT MATATA, NEW ZEALAND, 2005
INEVITABLE EVENTS, PREDICTABLE DISASTER

Tim Davies
Natural Hazards Research Centre
Dept of Geological Sciences
University of Canterbury, New Zealand

June 2005

DEBRIS FLOW EMERGENCY AT MATATA, NEW ZEALAND, 2005
INEVITABLE EVENTS, PREDICTABLE DISASTER

Tim Davies
Natural Hazards Research Centre
Dept of Geological Sciences
University of Canterbury, New Zealand

Introduction

The destruction in the community of Matata in the May 2005 Bay of Plenty floods was caused by an erosion event (debris flows) that was inevitable in that particular geomorphic setting, and could have been foreseen had a site survey been undertaken as part of a hazard assessment. Similar events in the past have killed people – for example the Peel Forest flash flood of 1975, the Arthur's Pass debris flow of 1979, the Coromandel event of 2000 and the Rees Valley tragedy of 2002 – and it was extremely fortunate that no lives were lost at Matata; in general, occupants of areas impacted by debris flows are in very serious danger of being killed. Many communities and dwellings are at risk from such events in all parts of New Zealand. Unless adequate provision is made for identification and mitigation of these situations, more such events will destroy dwellings and more people will die.

The science of this disaster

The information in the following sections is drawn from the voluminous scientific literature on alluvial fans (e.g. FEMA, 1989) and debris flow behaviour (e.g. Rickenmann and Chen, 2003; Jakob and Hungr, 2005).

Alluvial fans

Wherever a stream draining a steep, erosion-prone catchment debouches onto flatter land, some of the sediment it carries settles out of the water flow to build up a sloping, fan-shaped deposit called an "alluvial fan" (e.g. Fig. 1). The fan-like shape results from the stream moving to and fro across the surface of the fan, depositing sediment where it flows. This is a fundamentally aggradational landform, growth of which will continue as long as the fan toe is not maintained in a constant position by a river or the sea. If the fan toe is trimmed in this way, the fan is called an "equilibrium fan" and, although the stream can continue to avulse to any position on the fan, it no longer builds up in the long term because local, temporary aggradation of the fan is balanced by local, temporary erosion elsewhere on the fan surface. *Any development on the active surface of an alluvial fan is at risk from flooding and sediment deposition by the stream.*

Many large alluvial fans, however, have incised fan heads; that is, the river flows across the upper part of the fan in a channel well below the fan surface level. In this case it is difficult for the river to flow across the fan head, because massive sediment deposition is needed to elevate it to the level of the fan surface, and the fan head is not normally at risk from flooding.

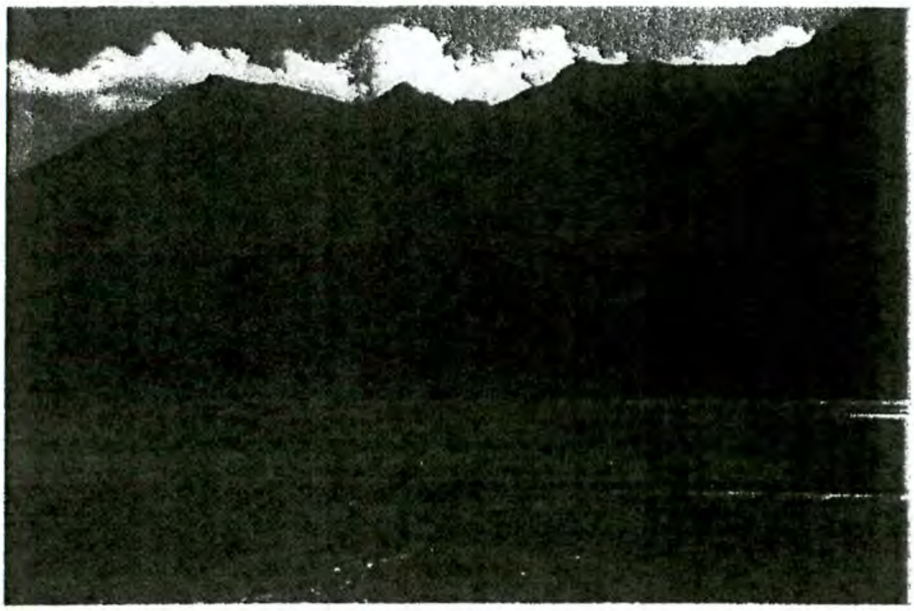


Fig. 1 Alluvial fan in Canada

Small fans also have incised fan heads (e.g. Fig. 2), but the land adjacent to the incised stream is not safe from flooding and sediment deposition. This is because, in small, steep catchments with erodible rock, a quite different erosion process can occasionally occur; this is a "debris flow", and it was this phenomenon that devastated parts of Matata.

Debris flows

A debris flow occurs when sufficient fine sediment enters a steep stream (e.g. from a hillslope failure) that the stream flow becomes a thick, muddy slurry; under these conditions the flow is able to erode and transport rocks and boulders of virtually any size. The flow transforms into the consistency and density of wet concrete, and moves downvalley in a similar fashion. A debris flow can also be generated by a landslide blocking the stream temporarily, and washing away when it is overtopped by the flow. However it is caused, a debris flow differs from normal flood flows in the following ways:

1. it does not flow steadily – the flow forms a series of discrete surges (Fig. 3), that are much deeper and faster than the normal flood flow of water;
2. it does not follow the stream course, especially at bends;
3. it is able to transport virtually all the solid material available to it – e.g. trees, boulders, houses – and often scours its channel to bedrock;
4. it carries the larger solids (boulders, trees) at the front of the flow, forming a battering ram with large destructive ability;
5. it is able to fill an incised fanhead channel very quickly, and subsequent surges can then travel to *any* part of the fan.
6. it occurs very quickly with no reliable precursors

Fig. 2. Debris flow fan north of Westport, with clear evidence of the last debris flow event: note the steep fan slope, the large boulders, the deep, narrow channel, with levees, and the small, steep catchment. A new dwelling is just out of the picture to the right (arrowed).

Therefore *any development on a fan that can experience debris flows is at risk of destruction without any warning.*

Where and when can debris flows occur?

As mentioned already, debris flows occur in steep, erodible catchments. In effect they are confined to fairly small catchments (less than about 1 - 10 km^2), and fans susceptible to debris flows usually have slopes of ~5° (9%) or greater. More detailed predictors are available, but need considerable testing before they can be reliable. It is logical to expect that debris flows can occur *anywhere there is evidence that they have occurred before.* The geomorphic indicators of past debris flows are well-known (e.g. Davies, 1997), including the presence of large boulders on fanheads, as was the case at Matata. However this is not a universally reliable criterion, because the evidence may have been obliterated by subsequent normal stream flows. Absence of evidence is not evidence of absence. It is therefore sensible to expect that debris flows can occur from *any small, steep, erodible catchment affected by intense rain.*

Occurrence of a debris flow requires both intense rainfall and a sufficient volume of available sediment. Since the latter is always possible from a slope failure during an intense storm, then *any intense rainstorm in a sufficiently steep and erodible catchment can initiate a debris flow.* There are predictors that relate debris flow occurrence to rainfall intensity; but since occurrence of the latter is not reliably predictable, neither are debris flows. Once the debris flow has been initiated, it travels very quickly the short distance to the fanhead.

Fig. 3 Debris flow surge at Jiangjia Ravine, Yunnan Province, China. The surge is ~ 2m high and is travelling at ~ 7 m/s.

In summary: debris flows can affect any part of a steep alluvial fan below a steep, erodible catchment without warning during any intense rainstorm. In fact, they occur fairly rarely in any specific place, and this is one of the reasons they are so hazardous; most people have not experienced them before, and therefore do not realise they can happen.

Application to disaster prevention

Since debris flows are potentially extremely destructive (Fig. 4), any situation in which human development – particularly dwellings and infrastructure – is exposed to their impact is a fatal disaster waiting to happen. It was very lucky that no lives were lost at Matata.

Modifying the debris flow event

Debris flows are initiated by sudden, very intense events, and are themselves very energetic and destructive. Their occurrence in any given place is rare – perhaps once every few decades or centuries. Thus engineering works to prevent their occurrence, or to modify their behaviour, are extremely costly and difficult to justify on economic grounds; they are also extremely difficult to design because the design loads are very poorly known (Davies, 1997). Structural protection against debris flows is intrinsically unreliable. For the susceptible parts of a community like Matata, sufficiently strong (1-in-475-year standard – see below) protective works, against an event that might not occur for several hundred years, are probably unrealistic. The only specific debris-flow defences in New Zealand reduce the risks to the iconic Hermitage Hotel, Aoraki/Mt Cook, from debris flows on the Glencoe fan.

Risk management

Any development on a debris-flow-susceptible fan is exposed to a risk that is extremely expensive and difficult to manage by conventional engineering works. Since debris flows occur without warning in small, steep catchments, warning-evacuation systems are

Fig.4 Debris flow damage, Matata, Bay of Plenty NZ May 2005

impractical because there will be insufficient time to carry out any evacuation reliably. It is better to be caught in a house by a debris flow than to be caught in the open.

In the majority of debris flow hazard situations the risk is therefore in effect unmanageable.

Risk assessment

What needs to be ascertained, then, is whether the unmanageable risk is acceptable. There exist rules of thumb that describe the level of acceptable risk of various numbers of deaths due to various causes. In a situation like that of Matata, the likely number of deaths during a debris flow event is of the order of 1 - 10, and the acceptable risk is of the order of 1 in $10^4 - 10^5$ per year (MCDEM, 2002). Given that events like that of May 2005 most certainly occur in that particular drainage on average about once every 100 – 1000 years, the risk is actually about 1 in 10^2 to 1 in 10^3 per year. Even though this calculation is extremely rough, it is unlikely to be in error by a factor of 10; thus the risk of deaths due to debris flows *on every occupied debris flow fan in New Zealand* is likely to be at least 10 -100 times greater than that generally considered to be acceptable.

The Building Codes recommend that no dwelling shall be vulnerable to structural damage by earthquake or wind more frequently than once every 475 years (actually a 10% chance in 50 years, which is the same thing). If this rule is applied to also debris flows (which seems logical), it means that any fan that experiences a debris flow more frequently than once in about 475 years on average is unsuitable for residential development (recall that a debris flow can affect *any* part of a small steep fan). The "normal" frequency of debris flows is unknown; but it is impossible to be confident that their frequency on any given fan is less than this, i.e. that the requirements of the Codes are met in dwellings on debris flow fans. Fig. 5 shows what happens to <u>all</u> debris flow fans from time to time.

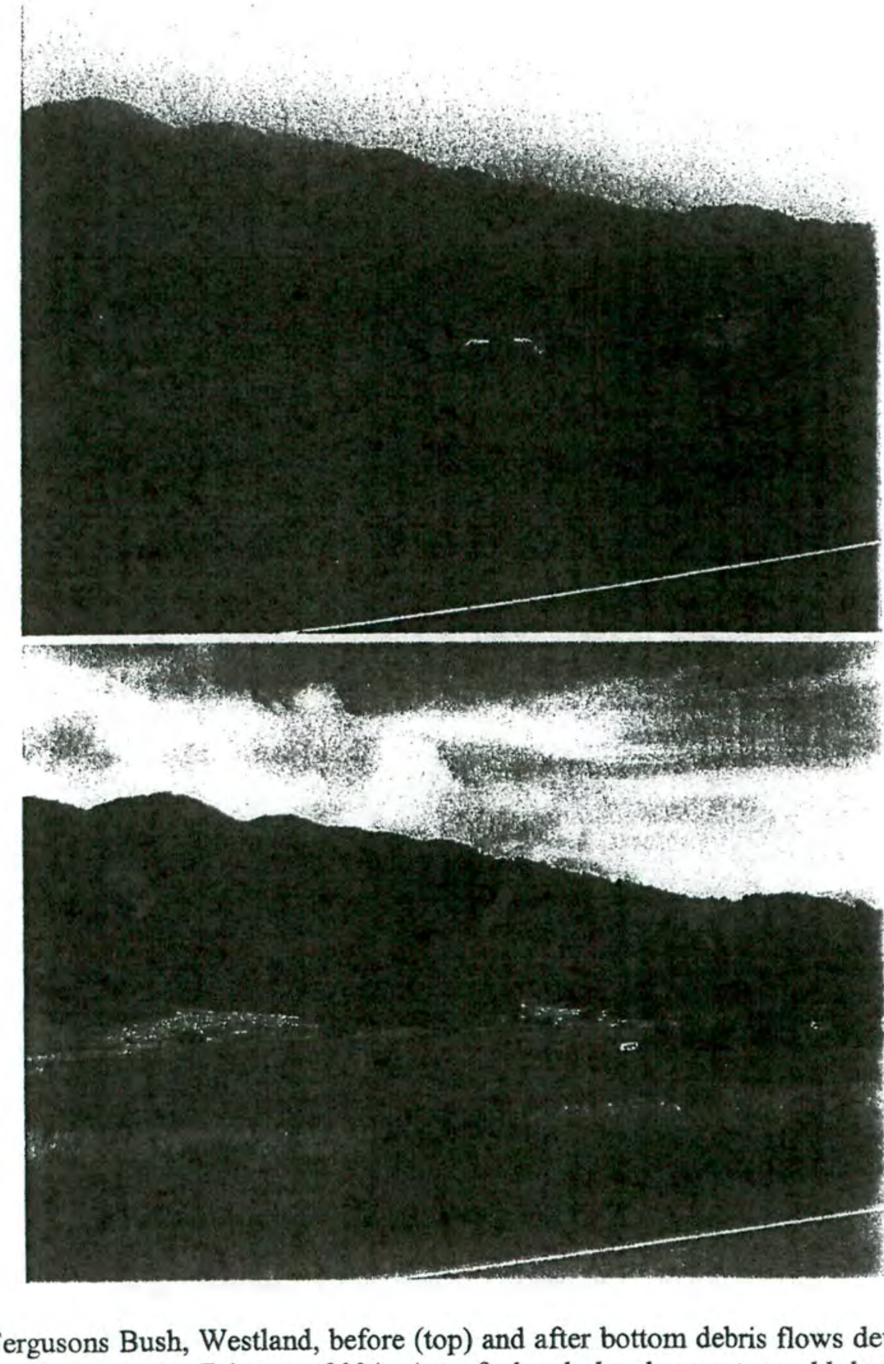


Fig. 5 Fergusons Bush, Westland, before (top) and after bottom debris flows devastated these two fanheads in February 2004. Any fanhead development would have been destroyed.

Extent of exposure
The number of developed debris-flow vulnerable fans in New Zealand is unknown. There are however many examples visible throughout the mountainous and hilly parts of the country; Figs 3, 6 and 7 are unfortunately typical.

Fig.6 Westland. The gully feeding debris to the fan is formed on the Alpine fault.

Fig. 7 South Westland. The gully above the house is formed in moraine.

Further, many new rural developments deliberately choose fanhead sites because they are well-drained, above valley flood levels, have nice views, and often have idyllic little streams from catchments clad in native bush bubbling past large boulders. The problem is thus increasing as rural residential development increases.

Hazard mitigation
The only way to reduce the unacceptable and effectively unmanageable risk to human life posed by development of debris-flow-susceptible fans is to cease to allow their use for dwellings.

Given that

- the science of the natural processes is well-known;
- the risk level calculable, approximately but to a sufficient degree of accuracy;
- the risk level is known to be very much greater than the acceptable risk; and
- the risk effectively (economically) unmanageable;

this conclusion is inescapable.

Land use for dwellings requires a District Council permit, while management of natural hazards is the responsibility of Regional Councils. The existence of buildings on debris-flow fans – as at Matata - indicates that this hazard is not widely known or understood in Councils. Even where there is memory or records of such events in the past – as at Matata – the possibility and consequences of future events can be omitted from consideration.

Hazard assessments are now mandatory under the Civil Defence and Emergency Management Act (2002). This does not however guarantee identification (and hopefully avoidance) of future hazards unless the assessments are carried out in time by appropriately knowledgeable people. Many local authorities at present have neither the required expertise, nor the resources to purchase it; indeed, some of them may not yet know that they need it.

Conclusions

- The Matata disaster was caused by large but perfectly normal debris flows whose sudden occurrence in that location during any sufficiently intense rainstorm was inevitable and predictable.
- Unless concentrated efforts are made to identify similarly vulnerable situations, many similar and worse disasters will occur in the future.
- X The only effective way of managing the risk to residential developments on debris-flow fans is to not permit them.
- Responsibility for assessing such hazards now lies with the CDEM Groups of Regional Councils. Many of these have neither the necessary expertise nor the resources to acquire it. Unless this deficiency is remedied, avoidable deaths will occur in the future.

References

Davies, T.R.H. (1997). Using hydroscience and hydrotechnical engineering to reduce debris flow hazards. In Chen, C.-L. Eds. Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. *Proceedings,* First International Conference on Debris Flow Hazards Mitigation; American Society of Civil Engineers, San Francisco, 787-810.

FEMA, 1989: http://www.fema.org/hazards/floods/lib165.shtm

Jakob, M. and Hungr, O. Eds. (2005). *Debris-Flow Hazards and related Phenomena.* Praxis, U.K., 739p.

Ministry of Civil Defence and Emergency Management (2002). *Waiho River Flooding Risk Assessment.* 44p.

Rickenmann, D. and Chen, C.-L. Eds. (2003). Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment. *Proceedings*, Third International Conference on Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment, Davos, Switzerland, September 10-12, 2003.

31

Geologically Active – Williams et al. (eds)
© 2010 Taylor & Francis Group, London, ISBN 978-0-415-60034-7

Numerical modelling of debris-flows and mitigation structures at Matata, New Zealand

K.J. Hind
Tonkin & Taylor Ltd, Auckland, New Zealand

B.W. McArdell
Swiss Federal Institute WSL, Birmensdorf, Switzerland

ABSTRACT: On 18 May 2005, the small New Zealand town of Matata was impacted by several debris-flows originating from within the Awatarariki and Waitepuru Streams. With dozens of homes either destroyed or damaged, it was probably the most destructive debris-flow event to have occurred in New Zealand in modern times. The consequences of future debris-flow events are to be mitigated by the construction of a flexible "ring net" barrier. Although the flexible barrier would be the largest structure of its type ever constructed, it would still be unable to retain the entire debris volume from the design event. The barrier is therefore to be supplemented with a diversion spillway and fanhead dykes. A critical part of the design process has been achieving an understanding of how future debris-flows would interact with these structures. Numerical modelling has been undertaken using RAMMS (Rapid Mass Movements), a 2D single-phase debris-flow simulation tool. RAMMS was successfully calibrated to the 2005 debris-flow event, enabling the structural elements of the mitigation system to be assessed and optioneered. The major benefit of RAMMS was found to be its ability to model the direction, thickness and velocity of the active flows. This allowed a range of barrier and fanhead earthworks options to be compared in terms of performance, cost and impacts.

Keywords: debris-flow, Matata, RAMMS, ring-net, barrier

1 INTRODUCTION

On 18 May 2005, the township of Matata (population approximately 700) was impacted by several large debris-flows triggered by an intense band of rain passing over the catchments of the Awatarariki and Waitepuru Streams. The debris-flows and associated flooding destroyed 27 homes and damaged a further 87. Fortuitously no lives were lost, however some NZ$10M worth of property was damaged (McSaveney, 2007). The 2005 debris-flows were probably the most destructive to have occurred in New Zealand and only the second time that a populated area had been significantly impacted, after Te Aroha in 1985. A view of western Matata immediately after the Awatarariki debris-flows is presented as Figure 1.

The Whakatane District Council (WDC) is proposing to mitigate the consequences of future debris-flows within the Awatarariki Stream through a debris capture and diversion system. The published literature describes a multitude of active debris-flow management systems, including check dams, sabo dams, deflection dykes/walls, "shooting" channels, debris basins, bridges, sheds and flexible barriers. After an extensive assessment process, the WDC opted to construct a flexible "ring net" barrier within the lower Awatarariki Stream. A flexible barrier was selected over more traditional hard structures because of lower costs and a smaller streambed footprint.

Figure 1. View of western Matata in the immediate aftermath of the 2005 debris-flows. The Awatarariki Stream flows across recently deposited debris on the fanhead. The permanent stream channel is located in the left middle distance. In the right distance, State Highway 2 crosses beneath the East Coast Main Trunk railway via a narrow underpass.

At a height of 15 m, the proposed barrier would be the largest structure of its type ever constructed. Despite its unprecedented size, the barrier would be unable to fully retain the debris mobilised by the design event. It is therefore proposed to use a spillway to direct excess debris-flow material out of the Awatarariki Stream and onto the fanhead, where earth dykes would direct the flows away from populated areas. The mitigation system will be the most extensive to be constructed in New Zealand. This paper describes the use of numerical modelling to investigate the 2005 debris-flow event and to design the proposed mitigation works. Structural designs of the barrier and anchoring systems have been undertaken as part of the project but are not addressed here.

2 SETTING

Matata is located on a narrow strip of coastal land between Awaateatua Beach and the former sea cliffs of the Matata Escarpment. The coastal strip is formed from Holocene alluvium, intertidal, shallow marine and debris-flow deposits. The hills south of the Matata Escarpment are formed from Pleistocene estuarine to shallow marine sediments with interbedded rhyolitic airfall deposits originating from the Taupo Volcanic Zone. Mantling the Pleistocene sequence are airfall deposits from the Okataina Volcanic Centre and the 280-ka Matahina Ignimbrite.

The East Coast Main Trunk railway line runs along the toe of the Matata Escarpment. Prior to May 2005, State Highway 2 crossed beneath the rail line via an underpass located approximately 100 m west of the Awatarariki Stream. In the aftermath of the debris-flows, this narrow underpass was demolished and replaced by a significantly wider structure. This new underpass forms a critical part of the flow path for future debris-flows.

3 THE DEBRIS-FLOW HAZARD AT MATATA

With the notable exception of lahars, the New Zealand public, and many territorial authorities for that matter, are largely unfamiliar with debris-flows and their hazards. This has lead to a number of settlements, Matata included, being established within areas of debris-flow occurrence. The presence of large boulders within Matata confirms the occurrence of debris-flows prior to 2005. Historical records suggest that debris-flows or debris floods may have occurred in the general Matata area in 1869, 1906, 1939 and 1950 (McSaveney et al., 2005). Information concerning the nature and magnitude of these flows is very limited. They appear however to have been relatively small in volume and minor in consequence compared to the 2005 event.

Surveys of the Awatarariki Stream immediately after the 2005 debris-flows confirmed the presence of large volumes of alluvium capable of being mobilised in the future. Although the effect of future events could be mitigated through the abandonment of existing and future residential development on the Awatarariki Stream fanhead, the community and WDC have opted to retain the impacted area in predominantly private ownership, whilst constructing a debris-flow mitigation system centred on a large flexible barrier.

4 DEBRIS-FLOW MODELING

4.1 *General*

Debris-flow analyses were undertaken using the numerical continuum code RAMMS (Rapid Mass Movement), a state-of-the art software currently being developed by Swiss Federal Institute WSL. RAMMS models debris-flows as a two-dimensional, single-phase Voellmy-fluid whose bulk properties approximate those of the complex real-life flow. Flow across the digital elevation model (DEM) is a function primarily of basal friction (μ), internal turbulent flow resistance (ξ) and an internal "earth pressure" parameter (λ).

4.2 *Event characterisation*

The characteristics of the 2005 debris-flow event and its deposits have been described in a number of reports (McSaveney et al., 2005; Tonkin & Taylor, 2008; Harris, 2008). The salient points carried forward into the modelling are as follows:

- Fanhead deposition occurred as discrete pulses or surges
- The fanhead deposits had a volume of approximately 250,000 m^3, equivalent to an active flow of some 300,000 m^3
- Scour marks indicated peak surge heights of 4 m, increasing to 6 to 9 m on bends
- The fanhead deposits displayed clear grain-size differentiation (Figure 2).

4.3 *Calibration modelling*

The purpose of these initial analyses was to reproduce, within the limitations of numerical modelling, the flow and depositional characteristics of the 2005 Matata debris-flow event. Replication of observed behaviour would verify the ability of RAMMS to model Matata-type debris-flows as well as providing reliable estimates of design parameters for use in barrier and spillway design. A parametric study consisting of 36 separate analyses was undertaken on the same 2005 LiDAR-based digital topography. The results indicated that debris-flow movement and depositional characteristics are sensitive to the value of basal friction parameter μ, but are comparatively unresponsive to variations in the turbulent flow parameter ξ. Lambda (λ), the "earth pressure" parameter influenced the ability of a flow to spread. However, within the likely range of values for a granular-water mixture, the resultant flows were not greatly different.

The location and shape of the initiating debris avalanche has no meaningful impact on the form of the debris-flow, provided that the release area is not located immediately adjacent to the area of analytical interest. Modelling indicates that the primary difference between a single or multiple-surge event was, as would be expected, peak flow thickness and, to a lesser

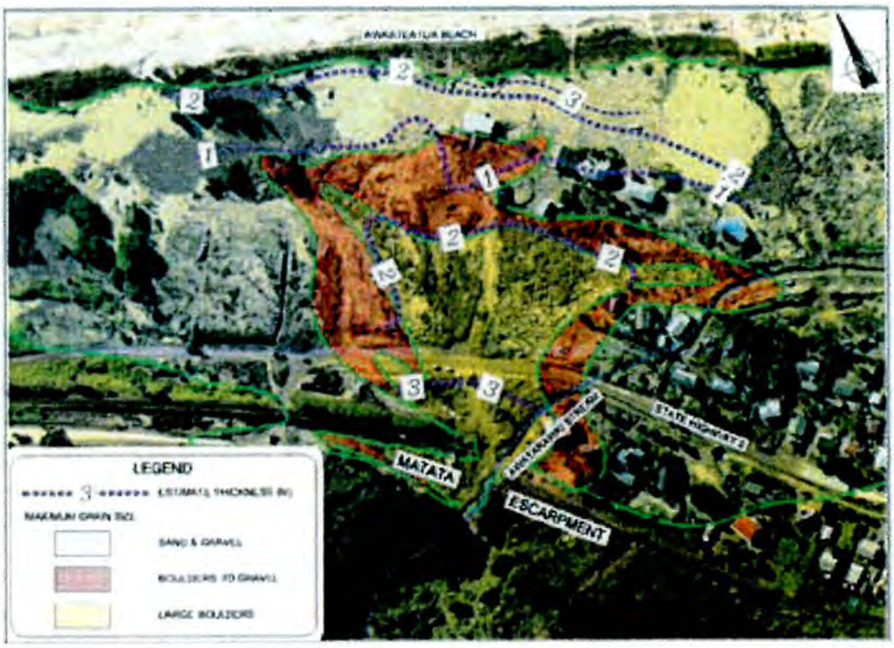


Figure 2. Western Matata immediately after the 2005 event. The estimated fanhead deposit distribution is shown.

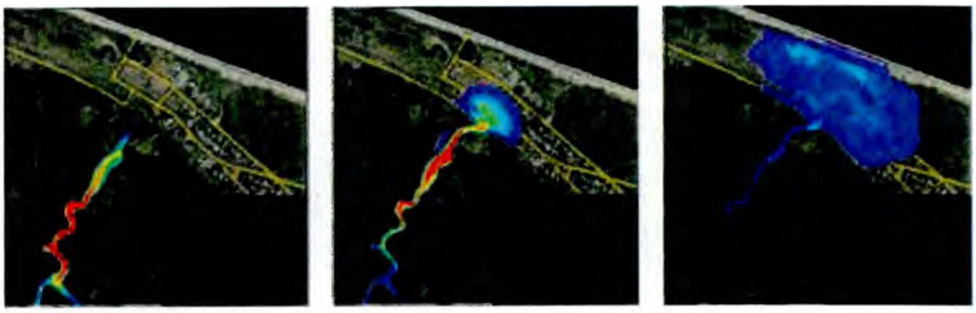


Figure 3. Output from the back analysis showing a large surge descending the Awatarariki Stream, emerging onto the fanhead and finally spreading across the coastal strip and western Matata. Colours indicate flow depths.

extent, flow velocity. The modelling supports the contention that the 2005 event consisted of multiple surges, as a single flow large enough to deposit 250,000 m^3 on the fanhead, would have flow heights well in excess of that indicated by streambank scour or deposition.

4.4 *Back analysis*

By undertaking multiple analyses covering the range of parameters and event configurations described above, it has been possible to recreate the fundamental behaviour of the 2005 event.

The best-estimate parameters were considered to be $\rho = 1700$ kg/m^3, $\mu = 0.05$, $\xi = 100$ m/s^2 and $\lambda = 1.75$. Based on flow heights, the largest single surge constituted approximately 40% of the total debris-flow volume. Output from RAMMS for this configuration is presented in Figure 3. Being a single-phase model, RAMMS was unable to replicate this differentiation, nor the final deposit thickness.

5 PROPOSED DEBRIS-FLOW MITIGATION SYSTEM

Engineering solutions to debris-flow problems are rare in New Zealand. McSaveney and Davies (2005) describe small *ad hoc* raised dykes at Walter Peak, a "debris-flow proof" highway bridge at Waterfall Creek and a large earth dyke at Mt Ruapehu. Other examples include a concrete deflection wall and earth dykes at Aoraki Mt Cook Village (Skermer et al., 2002) and two debris fences and a small sediment trapping basin at Karaka Stream, Thames (McSaveney and Beetham, 2006). These structures were constructed fundamentally to encourage debris-flows to stay within their natural channels. Matata will be unique in New Zealand in that the proposed mitigation structures seek to stop and redirect significant debris-flow events away from the drainage channel in which they are initiated.

5.1 *Design philosophy*

Within New Zealand legislation (Building Act 2004; Resource Management Act 1991) it is usual when designing for structurally damaging hazards to adopt a 10% probability of occurrence in 50 years i.e. a 475-year return period (McSaveney et al., 2005). This is usually rounded to a 500-year return period. Although debris flows are not specifically mentioned in New Zealand legislation, Davies (2005) and McSaveney et al. (2005) both argue that since they can be both structurally damaging and life threatening, a 500-year return period is appropriate for design. Information regarding the frequency of debris-flows in the Awatarariki Stream is insufficient to estimate the return period of the 2005 event. As the triggering rainfall event had an estimated return period of between 200 and 500 years (Tonkin & Taylor, 2008), the return period of the 2005 debris-flows is likely to be in terms of hundreds of years, rather than either decades or millennia. Given the uncertainty as to what constitutes a 500-year return period event at Matata, the WDC has adopted a philosophy of designing the mitigation system to a specific event volume and resulting damage level. Specifically, the aim of the Awatarariki Stream mitigation system is to prevent an event of equivalent size to the 2005 event from again destructively impacting the town.

5.2 *General features*

A narrow gorge immediately upstream of where the Awatarariki Stream exits the Matata Escarpment was selected as the barrier location (Figure 4). This maximises the potential retained volume whilst minimising the width of the barrier. A section through the barrier location is presented as Figure 5. An abandoned gravel quarry located above the true left-hand side of the narrow gorge limits debris retention to approximately 15 m above stream level. Flows above this elevation would be able to bypass the barrier via the quarry saddle. Early discussions with barrier supplier Geobrugg AG indicated that 15 m was also the maximum viable height for the flexible barrier based on engineering and financial considerations. The height of the barrier was therefore set at 15 m. This would make it the largest flexible barrier ever constructed by quite some measure.

Although the barrier could structurally survive being overtopped, it is intended to maintain a nominal freeboard of 1 m. With a retained debris height at the barrier of 14 m, the stream valley would have an estimated maximum retainable volume of some 110,000 to 130,000 m^3. This is significantly less than the design deposit volume of 250,000 m^3. It is therefore proposed to direct excess material out of the Awatarariki Stream via a spillway located within the abandoned quarry. The diverted debris material would flow down the spillway, passing through the State Highway 2 underpass onto the fanhead west of the Awatarariki Stream. Determining the configuration of the spillway and the extent of diversion structures on the fanhead were two of the most important factors to be assessed by the modelling. Estimated flow directions are shown on Figure 4.

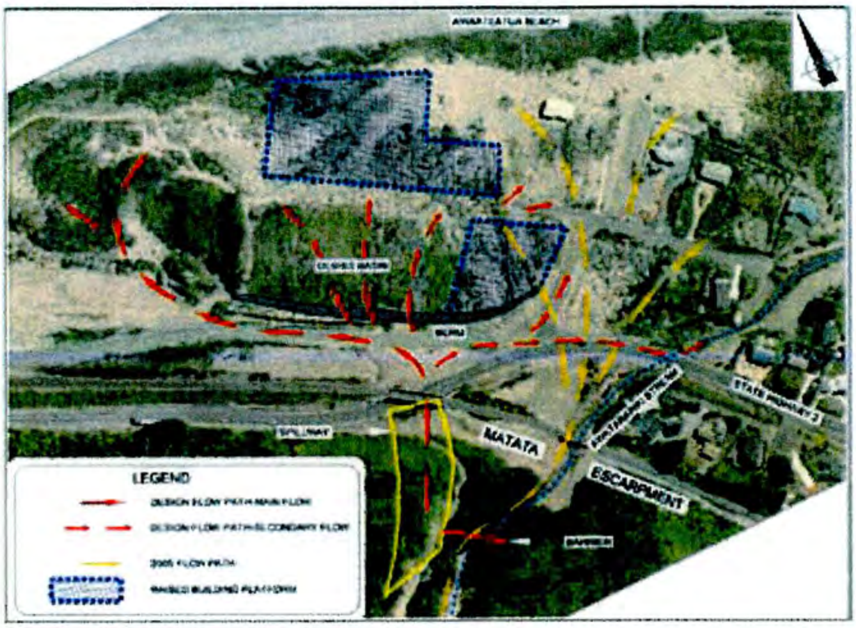


Figure 4. Aerial photo of western Matata indicating the location of the proposed debris-flow control system and dominant flow paths. Debris from the 2005 event is still clearly evident in this 2007 photo.

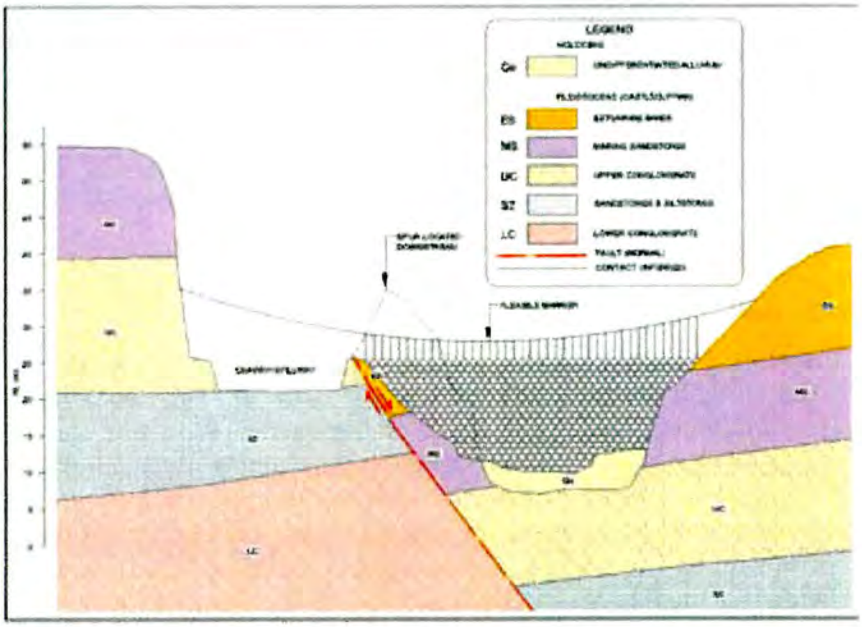


Figure 5. Section through the barrier location.

6 MODELLING OF THE PROPOSED MITIGATION SYSTEM

6.1 *Barrier and spillway elevation*

Barrier and spillway modelling was undertaken using three debris-flow types (water-like, best estimate and granular), single and multi-surge flow configurations and three spillway elevations. The modelling indicated that the spillway commenced to work whilst material continued to build up at the barrier and that the maximum height of debris at the barrier was equal to the elevation of the spillway entrance plus the peak flow thickness over it. These analyses determined that the peak elevation of the spillway should be 4 m lower than the top of the flexible barrier.

6.2 *Spillway gradient*

Partial or complete blockage of the spillway entrance with debris could conceivably result in redirection of material back towards the barrier, potentially resulting in overtopping. An excavated spillway with an overall gradient of 12° was included in the design as modelling showed that this generated sufficiently high flow velocities to prevent deposition from occurring on the spillway.

6.3 *Fanhead debris-flow control*

It is estimated that between 100,000 m^3 to 150,000 m^3 of material could pass down the spillway during the design debris-flow event. Without additional control measures, this material would spread out across the fanhead, inundating many of the same properties that were impacted in 2005. Numerous RAMMS models were undertaken as a means of assessing the effectiveness of several earth dykes and excavated channel configurations in modifying fanhead flows. These options were then able to be compared in terms of cost, physical impact and land acquisition requirements.

It was found that complete protection of western Matata from fanhead flows required an all enclosing dyke system at least 5 m in height. This level of protection required not only the construction of extensive earthworks but also a revised road layout, including a new road bridge. A substantial area of private land would also be required to accommodate the broad footprint of the dykes and the diverted flows. Land access limitations and a significant financial penalty associated with such a significant protection scheme made the full control option non-viable.

The WDC, in consultation with the community, opted for a partial control design, consisting of an earth dyke placed immediately north of State Highway 2 and raised earth building platforms (Figure 4). Limited land availability restricted the height of the dyke to only 1.5 m. If it was any taller, the volume of the dyke would rapidly start to infill the available space for redirected debris, requiring a correspondingly higher dyke. Modelling has shown that although the proposed dyke will slow down and partially redirect the debris material exiting the spillway, the structure will be overtopped by relatively small surges down the spillway.

Building platforms raised approximately 2 m to 3 m above the existing ground level will limit flow heights and velocities to non-destructive levels. They effectively form a second line of dykes that also define a large rectangular debris basin. The dykes would be constructed from existing debris-flow deposits in a manner similar to those described by Skermer et al. (2002) and Nasmith and Mercer (1979). RAMMS modelling of the complete mitigation system is shown in Figure 6. The output shows the concentration of debris within the stream and in front of the small berm. Secondary deposition occurs within the debris basin. Some relatively minor flows will occur to the east of the dyke and between the raised platforms. Given their tortuous routes, these flows are expected to be devoid of significant coarse-grained material, as well as being thinner than those associated with shorter return-period flood and coastal inundation hazards. The result is that although most of the fanhead is

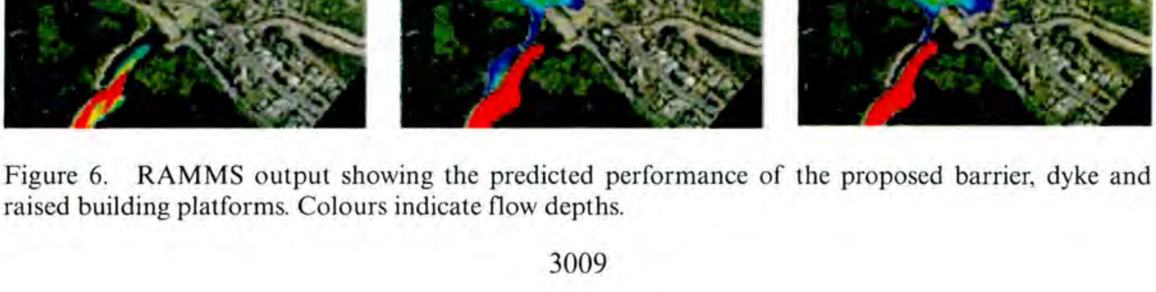


Figure 6. RAMMS output showing the predicted performance of the proposed barrier, dyke and raised building platforms. Colours indicate flow depths.

not fully protected from minor water inundation, existing and future dwellings are protected from potentially destructive fanhead flows.

7 CONCLUSIONS

Debris-flows are a significant yet commonly over-looked natural hazard within the New Zealand landscape. Historically, debris-flows have occurred in sparsely populated rural and alpine areas. The debris-flows that struck the town of Matata in 2005 were possibly only the second time a populated area in New Zealand has been impacted to a significant extent. Matata is to be provided a substantial degree of protected from future debris-flow events within the Awatarariki Stream through the construction of a mitigation system centred on a 15 m high flexible "ring net" barrier. This will be supplemented with a spillway, fanhead dykes, raised building platforms and a debris basin.

The design of what will be New Zealand's most extensive debris-flow mitigation system has been substantially aided by the use of RAMMS, a state-of-the-art numerical modelling code. RAMMS was successfully used to firstly back-analyse the 2005 event and then to configure the mitigation system through multiple option assessment and detailed design. Although the single-phase analysis method has some limitations in terms of estimating final deposit thickness and the spatial distribution of the different grain-size components of a real flow, nevertheless it successfully replicated observed active flow behaviour. The use of software like RAMMS is critical to the design of multi-component debris-flow mitigation systems such as that proposed for Matata.

ACKNOWLEDGMENTS

The authors would like to thank Haydn Read and Barbara Dempsey of the Whakatane District Council for their role in the development of the proposed mitigation system, as well as providing permission to publish the results of the analyses undertaken by Tonkin & Taylor. The primary author would like to thank Hannes Salzmann of Geobrugg AG for his invaluable advice on the performance and design of flexible barriers. The primary author would also like to acknowledge the assistance of the Swiss Federal Institute WSL in providing the latest version of RAMMS as well as being generous hosts in Switzerland.

REFERENCES

Davies, T. 2005. Debris flow emergency at Matata, New Zealand, 2005. Inevitable events, predictable disaster. Department of Geological Sciences; University of Canterbury.

Harris, N.I. 2008. Evidence to the Environment Court of New Zealand.

McSaveney, M.J. 2007. An introduction to sunny Matata and it's great debris-flows. Geological Society of New Zealand Miscellaneous Publication 123B.

McSaveney, M.J., Beetham, R.D. & Leonard, G.S. 2005. The 18 May 2005 debris-flow disaster at Matata: causes and mitigation suggestions. Institute of Geological and Nuclear Sciences. Report to Whakatane District Council.

McSaveney, M.J. & Beetham, R.D. 2006. The potential for debris-flows from Karaka Stream at Thames, Coromandel. Environment Waikato Technical Report 2006/17.

McSaveney, M.J. & Davies, T.R.H. 2005. Engineering for debris-flows in New Zealand. In M. Jacob & O. Hungr (eds.), *Debris-flow hazards and related phenomena*. Praxis Springer Berlin Heidelberg.

Nasmith, H.W. and Mercer, A.G. 1979. Design of dykes to protect against debris flows at Port Alice, British Columbia. *Canadian Geotechnical Journal*, 16: 748–757.

Skermer, N.A., Rawlings, G.E. & Hurley, A.J. 2002. Debris-flow defenses at Aoraki Mount Cook Village, New Zealand. *Quarterly Journal of Engineering Geology and Hydrogeology*, 35: 19–24.

Tonkin & Taylor. 2008. Matata regeneration project, Awatarariki Stream debris detention. Report to Whakatane District Council.

4/

Geomorphology 124 (2010) 75–84

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Assessing debris flows using LIDAR differencing: 18 May 2005 Matata event, New Zealand

J.M. Bull [a,*], H. Miller [a], D.M. Gravley [b], D. Costello [c,1], D.C.H. Hikuroa [c], J.K. Dix [a]

[a] School of Ocean and Earth Sciences, University of Southampton, National Oceanography Centre Southampton, Southampton SO14 3ZH, UK
[b] Department of Geological Sciences, University of Canterbury, Private Bag 4800, Christchurch, New Zealand
[c] School of Environment, The University of Auckland, Private Bag 92019, Auckland, New Zealand

ARTICLE INFO

Article history:
Received 24 March 2010
Received in revised form 16 August 2010
Accepted 20 August 2010
Available online 26 August 2010

Keywords:
LIDAR differencing
Slope failure
Debris flow
Sediment pathways
Matata
Hazard assessment

ABSTRACT

The town of Matata in the Eastern Bay of Plenty (New Zealand) experienced an extreme rainfall event on the 18 May 2005. This event triggered widespread landslips and large debris flows in the Awatarariki and Waitepuru catchments behind Matata. The Light Detection and Ranging technology (LIDAR) data sets flown prior to and following this event have been differenced and used in conjunction with a detailed field study to identify the distribution of debris and major sediment pathways which, from the Awatarariki catchment, transported at least $350{,}000 \pm 50{,}000$ m^3 of debris. Debris flows were initially confined to stream valleys and controlled by the density and hydraulic thrust of the currents, before emerging onto the Awatarariki debris fan where a complex system of unconfined sediment pathways developed. Here, large boulders, clasts, logs and entire homes were deposited as the flows decelerated. Downstream from the debris fan, the pre-existing coastal foredune topography played a significant role in deflecting the more dilute currents that in filled lagoonal swale systems in both directions. The differenced LIDAR data have revealed several sectors characterised by significant variation in clast size, thickness and volume of debris as well as areas where post-debris flow cleanup and grading operations have resulted in man-made levees, sediment dumps, scoured channels and substantial graded areas. The application of differenced LIDAR data to a debris flow event demonstrates the techniques potential as a precise and powerful tool for hazard mapping and assessment.

1. Introduction

High-resolution mapping techniques, such as Light Detection and Ranging technology (LIDAR) have the potential to precisely identify and quantify morphological change following a geomorphic event, predict hazard pathways, and map coastal evolution to a high level of accuracy (Revell et al., 2002; Stockdon et al., 2002; Sallenger et al., 2003; White and Wang 2003; Shrestha et al., 2005; Joyce et al., 2009). LIDAR technology has been applied in a number of scientific investigations to rapidly produce detailed topographic models which provide advancements in geomorphological and coastal research (Stockdon et al., 2007). LIDAR is an optical technique that uses the time taken for reflected light to return from objects or surfaces to determine the range, in a similar manner to radar.

In this paper, we present an analysis of LIDAR data flown prior to and following a debris flow event at Matata, Bay of Plenty, New Zealand, to identify, map and precisely quantify morphological change. In particular, the study proposes a methodology for LIDAR differencing and demonstrates this is an effective and valid approach for analysis of sedimentary processes and landscape evolution following a terrestrial slope failure event.

Debris flows are a type of terrestrial slope failure or landslide characterised by rapidly moving, water-saturated, non-plastic debris in a steep channel (Hungr, 2005; McSaveney et al., 2005). The principal factors controlling debris flow formation include the duration and intensity of rainfall, the geology and topography of the catchment, rock and soil types, climate, runoff, groundcover and moisture conditions (Manville et al., 2005). This form of slope failure has huge erosive and destructive potential due to its mass, volume, velocity, mobility and run out distance. Debris flows are typically initiated as a landslide on a steep slope before developing into a rapid flow confined by a steep channel, ultimately depositing material downstream on a debris fan (Davies, 2005). The debris fans that develop at the distal end of the depositional zone are often preferred sites for urban development and modification, and they consequently present an increasing hazard to human settlement (Wilford et al., 2004).

Geophysical mapping techniques have aided identification of such areas prone to debris flows; however, there is only a minor appreciation of the threat posed by such phenomena as a result of the

* Corresponding author. Tel.: +44 2380593078.
E-mail address: bull@soton.ac.uk (J.M. Bull).
[1] Now at: Aurecon, PO Box 9762, Newmarket, Auckland, New Zealand, N.Z.

0169-555X/$ – see front matter. Crown Copyright © 2010 Published by Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2010.08.011

infrequent nature of debris flows within any one stream (McSaveney and Davies, 2005). Scientific investigations using LIDAR have highlighted the broad applications of this technology; however, there currently is very little research applying this technology for debris flow hazard analysis and morphological change recognition. A recent study that was able to characterise 92% of the lahar (a similar gravity driven flow phenomena to debris flows) path from the 2007 Crater Lake breakout on Mt. Ruapehu in New Zealand revealed that LIDAR is most effective as a mapping and hazard analysis tool when used in combination with other remote sensing data such as satellite imagery (Joyce et al., 2009). The advantage of LIDAR over conventional geodetic techniques is that it can give a synoptic view over a large area.

LIDAR data sets flown before and after a debris flow event are compared in this paper and used for mapping morphological change and for identification of transport and sedimentary processes operating in a dynamic coastal zone. The paper aims to offer one of the first comprehensive assessments of morphological change using LIDAR differencing, to augment understanding of sedimentary transport processes from field and eyewitness accounts, and to more accurately determine the volume of the debris fan deposits and the post-event cleanup and rehabilitation measures. These components are important for land-use planning for future hazard mitigation.

2. Regional geologic setting

Matata is a small township, located at the coastal fringe in the Eastern Bay of Plenty, in the North Island of New Zealand (Figs. 1 and 2). It sits on the western edge of the Whakatane Graben which is a regional tectonic feature undergoing active extension and forms the northern part (both onshore and offshore) of the Taupo Volcanic Zone (TVZ) (e.g. Beanland et al., 1990; Beanland and Berryman, 1992; Wilson et al., 1995; Rowland and Sibson, 2001; Taylor et al., 2004; Lamarche et al., 2006; Rowland et al., 2009). The TVZ is a rifted volcanic arc (Wilson et al., 1995) that is the product of the coupling between the Pacific and Australian lithospheric plates at the Hikurangi subduction margin off the east coast of the North Island of New Zealand. Rifting in the TVZ is manifest in a series of fault systems, the most active of which is now within the Whakatane Graben. From offshore seismic reflection data, Lamarche et al. (2006) determined a crustal extension rate of 12.6 ± 3.5 mm year^{-1} for the last 20 kyr across the Whakatane Graben. The extension rate decreases to the southwest, along the axis of the TVZ, to <4 mm year^{-1} at the distal southern end of the zone (Villamor and Berryman, 2006).

The coastal zone in this part of the Bay of Plenty region is characterised by inland and coastal sand dunes, as evident at Matata, and also drained peat swamps and flood plains composed of pumiceous alluvium (i.e. the Rangitaiki Plains; Pullar and Selby, 1971; Nairn and Beanland, 1989). The town itself is situated between the former wetlands and the steeply rising hills behind, which are composed of mid to late Pleistocene fluvial gravels, marine sediments and interbedded rhyolitic airfall tephra deposits erupted from the TVZ. The stratigraphic sequence is capped by the Matahina ignimbrite, also erupted from the TVZ, which is ~300 ka (Bailey and Carr, 1994; Manning, 1996) and extends back into and above the Awatarariki and Waitepuru catchments behind Matata. The Matahina ignimbrite rests directly on marine/beach sediments at a maximum elevation of ~250 m above modern sea level which corresponds to significant uplift (c. < 1 mm year^{-1}) post c. 300 ka (Gravley et al., in preparation). The northern edge of the uplifted block experienced coastal erosion up until c. 7 ka with the remnant coastal cliffs visible today.

3. Eyewitness, photo and field observations of the Matata Debris Flows, 18 May 2005

Matata was originally settled on an elevated plateau in front of relatively stable and well-vegetated hills, and has since spread to a less safe and active depositional fan area. On the 18 May 2005, a band of intense rain passed over the hills behind Matata, generating several landslides that coalesced to form two large debris flows

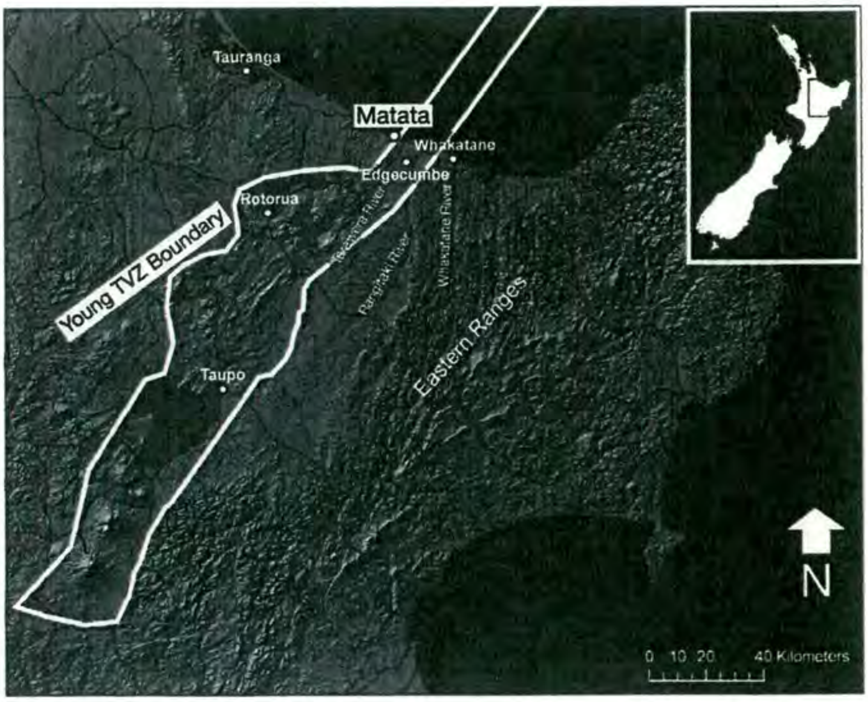


Fig. 1. Regional setting of Matata on the northern edge of the Taupo Volcanic Zone (TVZ), New Zealand. Major rivers are indicated draining northward into the Bay of Plenty.

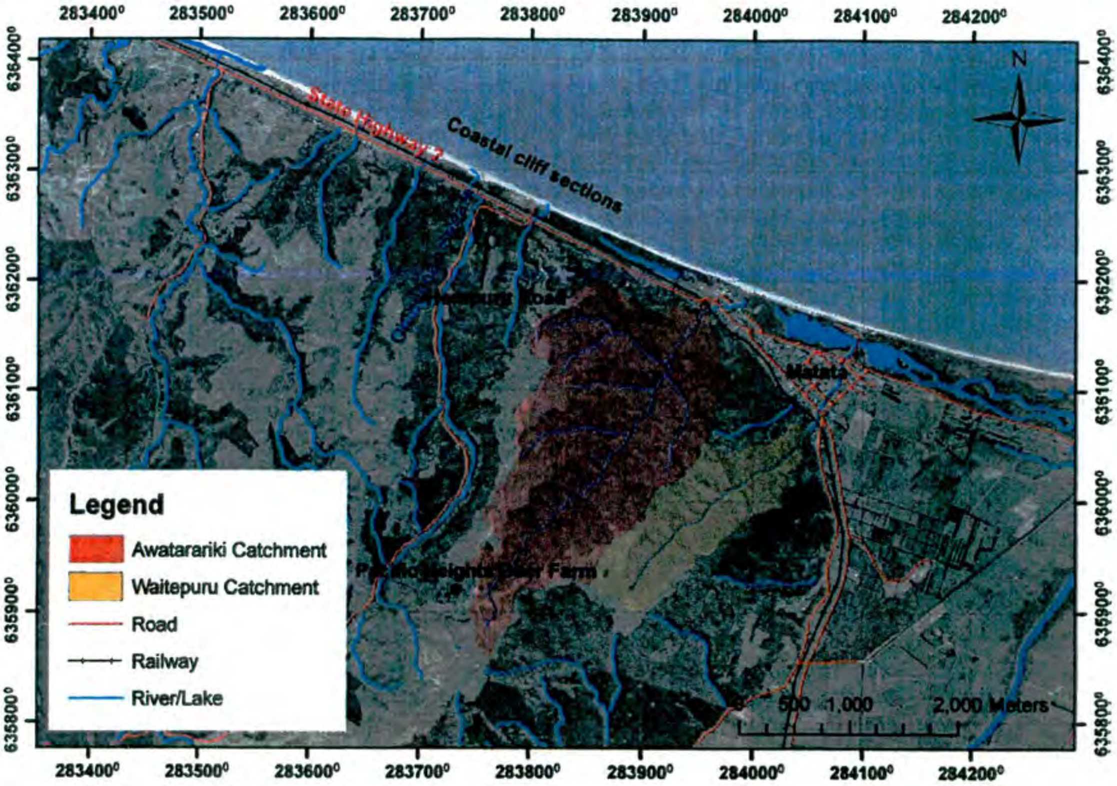


Fig. 2. Aerial photo (260-V15) showing location of the Awatarariki and Waitepuru catchments behind the coastal cliffs around Matata, Bay of Plenty, New Zealand. These catchments produced the damaging 18 May 2005 Matata debris flows. The image was taken prior to the debris flow and shows wetlands in the coastal strip west of the Awatarariki Stream which were covered by the debris flow.

within the Awatarariki Stream (catchment area 4.5 km^2) and Waitepuru Stream (catchment area 1.3 km^2) (Bassett, 2006) (Figs. 2 and 3). The closest automatic rain gauge to Matata is about 5 km SSE of Matata (V15: 412 555, near Awakaponga) and on 18 May 2005 this station recorded a 24-hour rainfall of 322 mm. The intensity of the rainfall event is further highlighted by a 1-hour rainfall of 94.5 mm, peaking at 30.5 mm in 15 minutes (McSaveney et al., 2005). Despite little data on past rainfall events of this intensity, 94.5 mm in an hour represents a c. 1 in 500 year return period event at this location based on an intensity (rate) that is 30% greater than the 1% annual exceedance probability (see McSaveney et al., 2005 and references therein). The debris flows ultimately emerged from the steep catchments and spread across a fan head at

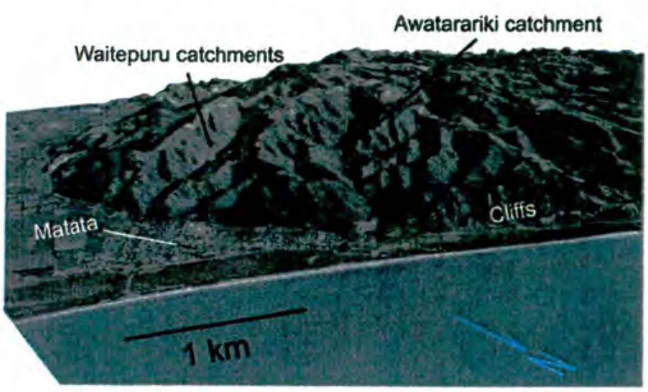


Fig. 3. The 3D perspective of the Awatarariki and Waitepuru catchments created using a 5-m DEM from LINZ 1:50,000 contours, and spot heights. The position of Matata and the coastal corridor seaward of the palaeo-cliffs are indicated.

the coastal fringe, destroying 27 homes and transport infrastructure within Matata (Hikuroa et al., 2006).

Rapid and recent uplift, combined with the presence of a resistant cap rock (the Matahina ignimbrite), has produced an immature landscape susceptible to debris flows. The Matahina ignimbrite is 20 to 30 m thick, forms vertical cliffs and has a uniform and relatively impermeable flat-topped surface that protects the underlying, weak to very weak mudstones and siltstones from pervasive erosion (Costello, 2007). From field observations, Costello (2007) modelled a scenario for slope failure whereby the mudstone and siltstones form over-steepened slopes with weathered surfaces that are susceptible to shallow, scallop-shaped slope failures that deliver debris to the stream valleys below. The head scarps from these failures subsequently undermine the overlying ignimbrite, triggering instability and toppling of large slabs of rock. These failure processes are compounded by the presence of unconsolidated sand beds lower in the stratigraphy and close to stream level, allowing for massive undercutting of thick mudstone. The result is massive rock failure and the development of near-vertical and boxed canyon-shaped cliffs with steep debris fans containing up to 100 m^3 of boulder to mud-sized grains (Costello, 2007). Together, these slope failures at different levels within the catchment stratigraphy occur on a semi-annual basis and the result is a continuous recharge and supply of boulders, gravels, sand, silt, mud and woody debris to the base of the stream valleys (recharge topple events have been witnessed and recorded by Costello, Gravley and Hikuroa since 18 May 2005 event). The debris then sits perched and ready to be mobilised in the next extreme rainfall event like the one that occurred on 18 May 2005.

On 18 May 2005, the peak rainfall event triggered several landslides within the Awatariki catchment. As described above, these landslides delivered a mixture of boulders, gravels, fines and large woody debris to a rapidly rising stream (McSaveney et al., 2005; Costello, 2007). The result was an increase in the mass and volume within the surging current which was then able to mobilise existing and perched ignimbrite boulder beds in the upper catchment and further scour and undermine the channel walls which created fresh debris downstream (Costello, 2007). Based on eyewitness accounts from the landowner adjacent to the stream channel, and oblique aerial photo interpretation (including Figs. 4 and 5), the following sequence of events have been re-constructed. The first surging, debris-laden currents to emerge from the hills passed beneath the railroad bridge and followed an existing stream channel that delivered fresh sediment to the south-eastern lagoon (see Fig. 4). As debris began to pile up behind the rail bridge, it became a sediment barrier that cut off flow into the aforementioned channel and ultimately failed from the back pressure of the subsequent debris flow pulses that were more voluminous and carried the large ignimbrite boulders. Following the failure of the bridge, the debris flows became unconfined, spread out across the pre-existing debris fan, and quickly decelerated which triggered rapid deposition of the heavy boulders and logs (Fig. 5). The rapid loss of mass created a transition from debris to hyperconcentrated flows that carried finer sediment 10's of metres further before it was deposited as smaller lobate fan structures (Fig. 5) and debris floods developed as the currents became even more dilute (Costello, 2007). The debris floods were topographically controlled by the coastal foredunes and followed pathways parallel to the coast, delivering sediment to the lagoon systems (Fig. 6).

The spatial distribution of boulders is not uniform over the debris fan: larger boulders of mudstone and ignimbrite are generally deposited on the seaward side of State Highway 2, and a less confined, c. 250 m stretch of the Awatarariki Stream prior to reaching the debris fan. Smaller and less dense boulders of material were transported further and can be found in the distal areas of the fan. Fines and gravels can be found in all areas of the debris fan and provided the material strength to transport larger boulders. Further evidence of the ability of the flow to transport objects is the presence of large woody debris. Whole-sized trees make up c. 10% of the debris and were particularly deposited in the lagoon and distal parts of the fan where flow momentum decreased. Anthropogenic debris such as cars, sheds and houses etc are present throughout the debris flow, and some of the larger objects have been transported several hundred metres. While the debris flow deposits from the Waitepuru Stream have a similar lithologic content they lack the abundance of large boulders present in the deposits of the Awatarariki Stream. In this paper, we focus primarily on the depositional fan and associated sedimentation from the Awatarariki debris flows.

4. Methods

This study is based on three high-resolution LIDAR data sets (Fig. 7) which surveyed the coastal zone and wider Rangitaiki Plains in the Bay of Plenty, New Zealand in 2000 and 2006. Prior to the Matata debris flow event, a LIDAR data set was collected on the 31 May and 1 June 2000 covering the coastal strip at Matata (Run 5 and Run 6—an area of 7.4 km^2). After the Matata event, LIDAR data were acquired on the 26 June 2006 specifically over the debris fans. These data image a 3.2-km^2 swath of ground which covers Matata town and the adjacent coastal and lagoonal environments. Finally, a component (Rang 3 and Rang 4) of the larger Rangitaiki Plains LIDAR data set flown on 14 December 2006 that covers the coastal strip and Rangitaiki Plains adjacent to Matata (an area of 5.2 km^2) was used. In the following section we describe analysis of the different data sets, the formation of a single year (pre-debris flow) 2000 data set and a single year (post-debris flow) 2006 data set, and the differencing of the 2006 and 2000 data sets. Begg and Mouslopoulou (2009) describe the complete December 2006 data set, but do not discuss the Matata debris flow event.

The LIDAR data were collected using different systems at different times, and therefore there was an initial stage of pre-processing and inspection of the data to determine the point density/spatial resolution, and comparability. Point density was calculated in areas where the data sets overlapped by analysis of 50 m^2 bins. This analysis indicated that Krigging of the data onto a 4-m spaced grid was appropriate. In the vast majority of the survey area there were between 2 and 5 data points within each 4-m bin (Miller, 2008).

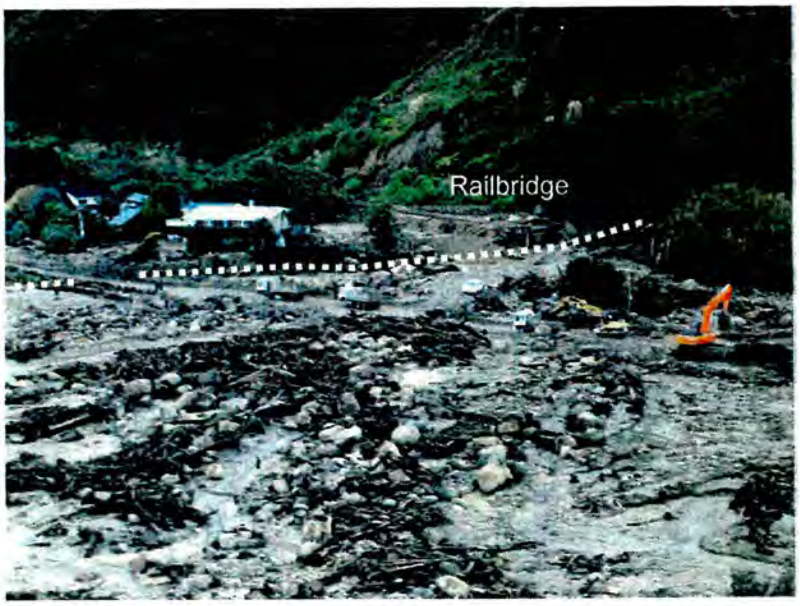


Fig. 4. Aerial Photograph (courtesy Terrain Consultants) showing in detail where the debris flow emerged from the confinement of the Awatarariki Stream. The first debris-laden currents passed beneath the railroad bridge and followed an existing stream channel (indicated by the white dotted line). After debris buildup behind the bridge and its failure, the main debris flow bypassed the channel and spread out in an unconfined way across the pre-existing fan with huge truck-sized boulders visible in the proximal fan. Remediation efforts had just commenced when this photograph was taken.

Fig. 5. Aerial photograph (courtesy Whakatane Beacon, taken 18 May 2005) showing the debris flow from the Awatarariki Stream. The emergence of the Awatarariki Stream onto the flat coastal plain is visible, as is the lobate boulder train. This photograph was taken before any remediation activity and is a good record of the immediate aftermath of the debris flow. Large boulders were limited to the area between the line of the buildings and the base of the hill. Fine debris was deposited as a debris flood in the foreground, while the dashed white lines indicate small lobate fan structures.

Testing of the vertical accuracy of the LIDAR data can be achieved by comparing RTK (real-time kinematic) terrestrial topography data from the Matata region with the recently acquired LIDAR data (details are described by Miller 2008). Due to the sporadic nature of the bench mark sites, only one point is found in a location of both 2000 and 2006 data coverage. The differences between the ground point and LIDAR data in this instance range between $+0.34$ m and $+0.4$ m. Although this is slightly higher than best-case vertical accuracy estimates for the LIDAR data (± 0.15 m), the difference suggests that the LIDAR data sets are comparable to surface topography data.

In order to check on the validity of combining the different gridded LIDAR data sets, a comparison of the vertical height differences was made between the different data sets (Fig. 7) in areas of overlap away from man-made features, where topography was relatively subdued, and away from the dynamic coastal fringe. We examined areas of overlap between Run 5 and Run 6 for the 2000 LIDAR data. For the 2006 data, Rang 3 and Matata, Rang 4 and Matata and the overlap between Rang 3 and Rang 4 were analysed.

From the vertical difference of the selected area, an error range was selected to represent the mean differenced value ± 1 standard deviation (Table 1). The largest error range is calculated to be ± 0.2 m (Table 1), which means that when differencing the LIDAR data sets elevation changes less than ± 0.4 m are meaningless.

Following vertical accuracy testing of the data, the two separate runs from the 2000 data (Run 5 and 6) were combined. A composite file was also produced for the 2006 data using the Matata, Rang 3 and Rang 4 data sets. The two composite rasters (gridded at 4 m) were differenced and the output image interpreted. Drawing upon the results above, data values which fell within the defined error range of ± 0.4 m were excluded.

Georeferenced aerial photography provided a high-resolution collection of images covering Matata town, the coastal zone and the

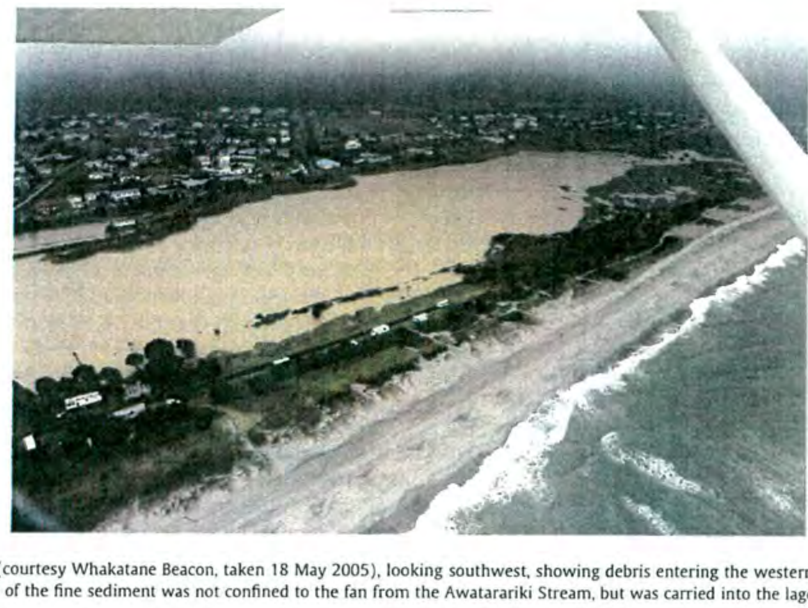


Fig. 6. Oblique aerial photograph (courtesy Whakatane Beacon, taken 18 May 2005), looking southwest, showing debris entering the western portion of the Matata lagoon, and associated silt-laden waters. Much of the fine sediment was not confined to the fan from the Awatarariki Stream, but was carried into the lagoon.

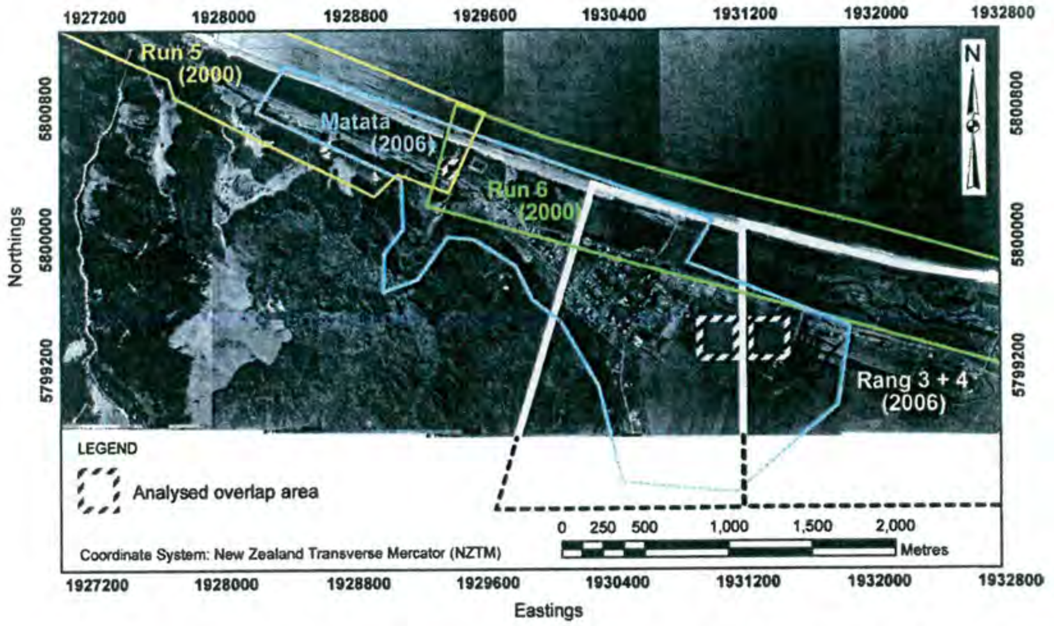


Fig. 7. Location of LIDAR data files—Run 5, Run 6, Matata, Rang 3 and Rang 4. Aerial photographs for context were flown in March 1987 by New Zealand Aerial Mapping Ltd. Areas of overlap used for analysis in producing the integrated pre-debris flow (2000) and post-debris flow (2006) topography are indicated.

wider Rangitaiki Plains, which helped validate the findings of the LIDAR data, and enabled further insights into the terrain, sedimentary processes and hazard assessment.

5. Results

The topographic maps using the LIDAR data record the land surface pre- and post-event (Fig. 8). The spatial extent of these maps range from the base of the steeply rising hills located behind Matata to the coastal and dune system. This region fully covers the area where the Awatarariki Stream channel loses confinement and also maps the township of Matata and the surrounding coastal flats and lagoon environment. The more recent 2006 LIDAR data set also includes data mapping the Awatarariki Stream and catchment, which extends into the hills behind Matata.

The quality of the pre-event LIDAR data is reduced in comparison with the 2006 data set, the latter having higher point density and greater vertical accuracy and horizontal resolution. This accounts for the sporadic data gaps in the 2000 topography (Fig. 8). Despite this, change in topography over the intervening period is clearly visible, and areas where previous low elevation has preferentially increased in height are identifiable. The changes in topography show a general increase in elevation across the coastal flats, with up to 2 m of height increase in certain locations. This sediment deposition is in the form of a fan, the apex of which is at the point where the Awatarariki Stream loses confinement (i.e. the drainage point of the Awatarariki Stream catchment). The topographic data further illustrates that a more defined channel flowing into the lagoon has developed in the intervening period between 2000 and 2006 (Fig. 8). This channel is characterised by flanking levee deposits of increased elevation (see later discussion for the origins of this change). In addition, the lagoon environment which this channel flows into is also well defined by the LIDAR data.

The LIDAR data in the topographic plots are used primarily to examine the key region of interest and have demonstrated significant change in topography following the Matata debris flows. This can be further assessed and built upon through comparison with the differenced plots, which precisely map the distribution of morphological change following the debris flow event in 2005. These plots illustrate quantifiable areas of erosion and deposition in the form of sedimentary features and geomorphic landforms associated with the Awatarariki Stream course. Erosion scarps and pockets of deposition are captured in the differenced image along the coastal hill slopes west of the Awatarariki catchment (Fig. 9A, area A).

The Awatarariki Stream, which conveyed a large proportion of the debris flow, can be identified in the differenced plot as an S-shaped channel traversing the coastal flats from west to east and connecting with the lagoonal depositional environment (Fig. 9A, B, Line B–B′). There is evidence for 1–2 m removal of material at the channel bed and a further removal of up to 2 m to the east of the channel (Fig. 9A, B, areas C and D, respectively). Elongated levee deposits flank this channel and are approximately 10 m in width (although this is variable and can be as wide as 20 m) and have a mean height of around 1 m, with a maximum height of 4.5 m (Fig. 9B, Line B–B′). These mapped changes in elevation are comparable to the findings of the topographic plots.

Deposition of material on the coastal flats in the vicinity of Matata is in the general form of a fan, with sediment deposition taking place at the point where the Awatarariki Stream loses confinement (Fig. 9A, Point E). We define the main depositional fan as the area between the point of flow expansion (Point E) and the lobate fan structures (J–J′; Figs 5 and 10), where the transition between debris flows/hyperconcentrated flows and debris floods occurs (see Section 3).

Table 1
Vertical height comparison in areas of data overlap (Fig. 7).

Year flown	Data sets compared in overlap area	Range of vertical height differences (m)	Error range (m) Mean ± 1 SD	Overall max error range
2000	Run 5 + Run 6	−1.44 to 0.76	−0.07 ± 0.18	± 0.4 m
2006	Rang 3 + Matata	−0.31 to 1.00	0.18 ± 0.125	
	Rang 4 + Matata	−0.87 to 0.86	0.1 ± 0.16	
	Rang 3 + Rang 4	−0.02 to 0.20	0.1 ± 0.1	

The range of vertical height difference of clipped areas is biased by the inclusion of outliers, and therefore a better measure of the differences is the mean ± 1 standard deviation.

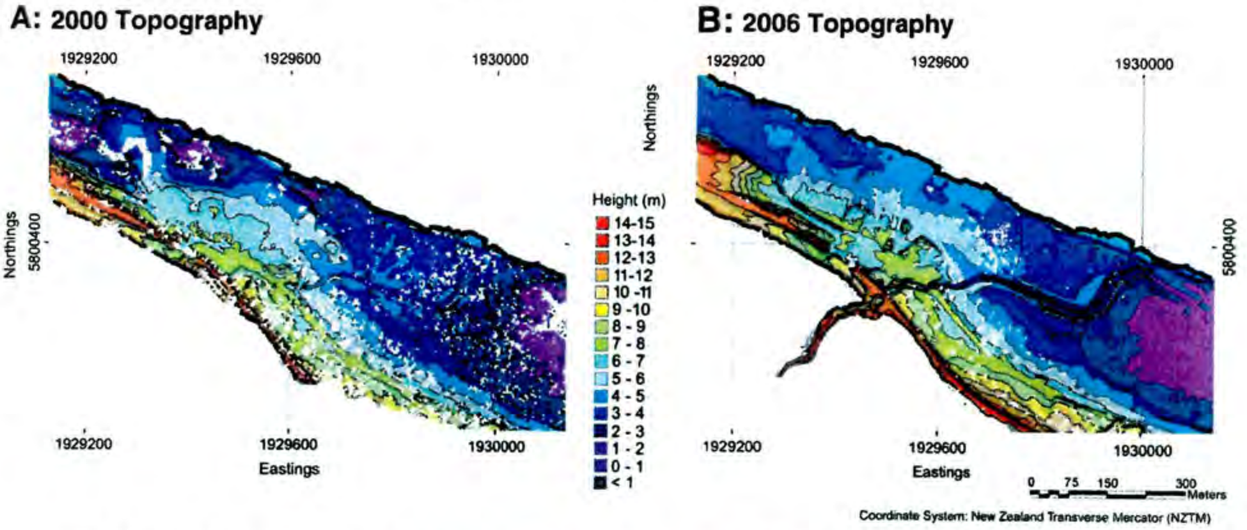


Fig. 8. Composite figure of a selected area affected by the debris flow. (A) 2000 topography; (B) 2006 topography. All contours at 1-m intervals.

Both the topographic plots and the differenced data show that at point E, there is an increase in depositional area due to lateral flow expansion and material expelled onto the debris fan in a process which built topography. The same data clearly show, beyond the debris fan, infilling of topography that parallels the coastline to the northwest (where a wetland existed, Fig. 2, prior to the flow event) and to the southeast towards the lagoon (Fig. 10). Another factor characterising fan development is the presence of irregular fingers of higher elevation (Fig. 9, area F). At the margins of the debris fan is an anomalously large, oval-shaped deposit approximately 200 m in length, 50 m in width and of a maximum height of 11 m (Fig. 9A, area G).

The lagoonal system is characterised by patchy data coverage because the water prevents consistent reflected LIDAR returns and no elevation can be calculated. However where water depth is particularly shallow then some elevation data (e.g. bathymetry) could be obtained. Despite these issues, there are a number of data points which map elevation in the western lagoon section which show that there is a net increase in residual silt levels following the debris flow and subsequent debris flood. The differenced plot suggests the silt level equals, and in places is up to 0.7 m higher than the original bathymetric level (Fig. 9B, area H). The difference plots delineate the lateral extent of deposition within the lagoon (Fig. 9B, area I). This coincides with the presence of a causeway which bisects the lagoon and appears to have effectively acted as a barrier to the spread of debris further to the east.

6. Discussion

The LIDAR data have successfully identified, mapped and precisely quantified morphological change following the terrestrial slope failure event at Matata. The differenced data identified the location of sediment deposition and erosion and has been used to confirm the sediment transport and deposition processes described by eye witnesses and subsequent field observation. However it is important to recognise that the differenced data delineates landscape change due to both the debris flow and flood, but also the subsequent cleanup operations. The post-event clear up operations are best shown by the oval-shaped sediment deposit (area G, Fig. 9A), which is the largest positive elevation in the differenced plot in an area of previously low topography and was the site where material was moved to and dumped during cleanup operations. Additional anthropogenic modification detected in the LIDAR data include the buildup of levees (B–B′, Fig. 9A,B) from material (up to 2 m deep) excavated from the stream channel floor (Fig. 9A, area C). These levees have been constructed to augment a confined flow path within the excavated channel and, thus, constitute the surface morphology visible today. These examples of post-event modification of morphology demonstrate LIDAR differencing can be a valid and effective tool to identify mass movement and precise changes in the landscape over a small area. However, LIDAR cannot be used in isolation, and complementary field studies are required to validate anthropogenic modification. Furthermore, it is desirable that LIDAR data should be flown immediately following an event (i.e. before cleanup operations) if the natural landscape-modifying processes are to be fully understood.

Eyewitness and field observations were used to determine the spatial variations in flow processes (Section 3), but the differenced plot (Fig. 9A) clearly detects mini finger-like levee structures on top of the debris fan (from point E to Line J–J′) and the lobate boulder train deposit at the edge of the fan. This arcuate-shaped feature in the differenced LIDAR data marks the point at which the boulder front stalled and the more dilute material from the main body of the flow broke through (Hungr, 2005), developing smaller subsequent fans and feeding an area of low topography to the northwest (the elongate wetlands seen in the coastal strip northwest of the Awatarariki debris fan in Fig. 2). Comparison of topographic maps (Fig. 8) of the land surface pre- and post-event reveal that this area, of previous low elevation, preferentially increased in height due to deposition of material that was transported along identifiable pathways controlled by pre-existing topography (Fig. 10). This is the most obvious example of topography-driven flow.

The topographic and differenced LIDAR data further identify a sediment pathway to the southeast (Fig. 10), where a proportion of material was transported to the lagoon system via a pre-existing channel. The presence of debris including large trees at the exit of this channel in the lagoon (Fig. 9B, area H) suggests that to begin with, this channel provided a conduit to the lagoon. It can be inferred that this channel was infilled relatively quickly following the initiation of the debris flow event, given the volume of material and the clast rich and boulder bearing surges which characterised the event. Hard to very hard (welded) ignimbrite boulders from the Matahina formation and weak siltstone and silty sandstone boulders which originate from the Pleistocene marine sediments found in the catchments behind Matata are the source of these clast rich and boulder-bearing surges (McSaveney et al., 2005). Eye

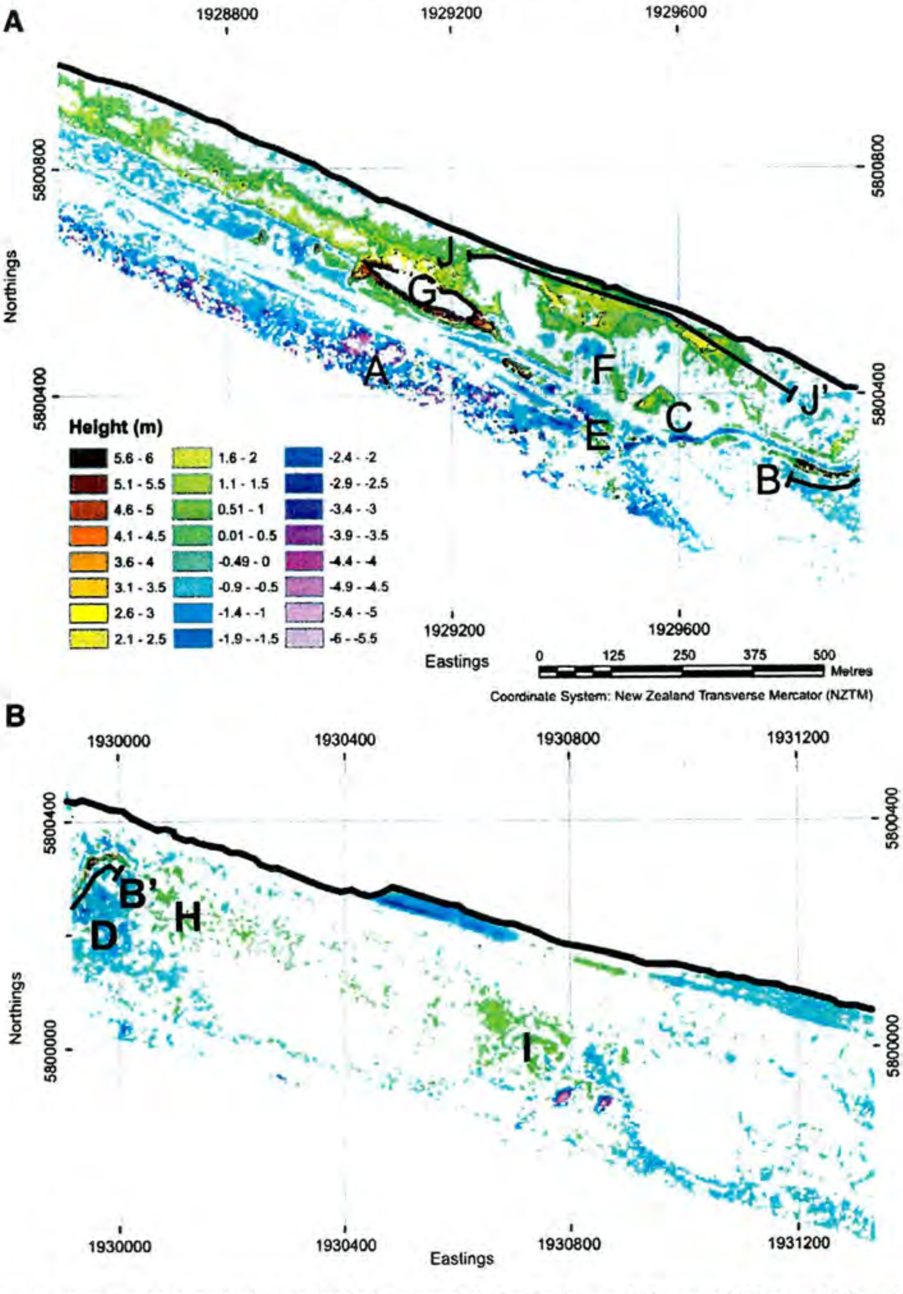


Fig. 9. Difference in vertical height between the 2000 and 2006 LIDAR data for (A) an area including the Awatarariki Stream and (B) an area to the east including the Matata Lagoon (locations shown in Fig. 2). Contours are at 1-m intervals. Lettered areas are referred to in the main text. Classification of heights around the mean has resulted in high values assigned no colour, as at area G. In this location, the maximum height is 11 m.

witness studies suggest that the channel was subsequently bypassed after the rail bridge initially trapped material, and then failed allowing the debris fan to become unconfined (Fig. 10).

The differenced LIDAR data can be used for precise quantification of morphological change following the terrestrial slope failure event at Matata but it has some limitations. The raised foredune system prevented loss of material to the sea; however, a substantial amount of material entered into the lagoon system, and this material was not fully detectable by the LIDAR differencing due to the water layer absorbing the light. Recently collected core data acquired within the lagoon as part of Matata Regeneration works by Tonkin and Taylor Ltd. found that between 0.4 and 1.8 m of debris from the 2005 event was deposited in the lagoon with an average thickness of 1.0 m. Our approach is to use the differenced LIDAR data to calculate the volume of the debris flow outside of the lagoon, and the core data to calculate the amount deposited within the lagoon. These volumes can then be compared to the estimates of Costello (2007) who used field surveying to estimate the amount of material outside of the lagoon.

In our calculations we divide the area of deposition into the main debris fan and the area of the debris flood to the northwest of the fan. We add in the material moved as part of the cleanup operation into our estimate where this was easily identified. Table 2 summarises the total volumes calculated from the field observations, and from the LIDAR data. For the areas outside of the lagoon we find 300,000 m^3 derived from field observations, and 260,000 m^3 from the LIDAR

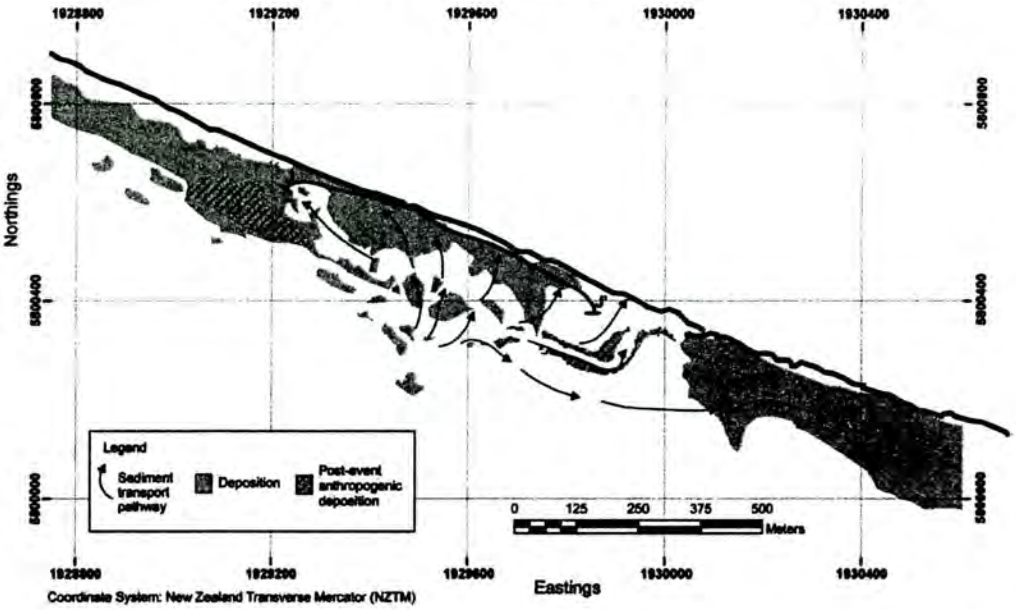


Fig. 10. Sediment pathways map, showing deposition following the 2005 Matata debris flow event. Arrows show the sediment transport pathways. Line J–J′ is discussed in the main text.

differencing. Errors on these estimates are large, perhaps $\pm 50{,}000\ m^3$, and therefore the estimates from the two different approaches are broadly consistent. Any systematic difference is most likely to be due to difficulties in estimating the thickness of deposits in areas of low lying relief in the field observations.

The 27 boreholes acquired were concentrated within the centre of the lagoon system, and therefore we do not have good control on deposition at the margins of this area which were flooded during the event. Taking a conservative approach we find that a minimum of $90{,}000\ m^3$ was deposited within the lagoon, beyond the detection limits of the LIDAR data (under water). We therefore find a total debris flow volume of $390{,}000 \pm 50{,}000\ m^3$ estimated by field observations and $350{,}000 \pm 50{,}000\ m^3$ estimated by the LIDAR data. These figures are both substantially higher than the estimate made by rapid reconnaissance immediately after the debris flow of c. $250{,}000\ m^3$ (McSaveney et al., 2005). The major reasons for this discrepancy are likely to be underestimates of the material deposited by the debris flood in areas of originally low topography.

Table 2
Estimates of volume of debris flow produced by the Awatariki Catchment in Matata.

Field observations	Location	Volume (m^3)
	Main debris fan	110,000
	Debris flood (to the north-west)	190,000
	Total field	300,000
LIDAR differenced data		
	Main debris fan	120,000
	Debris flood (to the north-west)	80,000
	Material moved before LIDAR acquired	60,000
	Total LIDAR	260,000
Sediment cores in lagoon		
	Sediment deposited in lagoon (minimum)	90,000
Total LIDAR-based (Minimum)	Field observations + lagoon	390,000
Total field-based (Minimum)	LIDAR + lagoon	350,000

The 2005 debris flow calculated from field observations (Costello, 2007) and using LIDAR differencing (this paper), and using thicknesses of 27 sediment cores within the lagoon. Some of differences seen in estimates of debris fan and debris flood deposits between the field observations and LIDAR data could be due to cleanup prior to the second LIDAR flight. Where known, the volume of material removed (e.g. to location G, Fig. 9A) has been incorporated in the estimates.

These findings demonstrate the capabilities and huge potential of LIDAR to precisely quantify change following a mass movement event, and build upon field observations to calculate volumetric change. Such accurate measurements of morphological change are vital in precise hazard assessment studies. In particular, accurate calculations for the volume of debris that came from the Awatarariki catchment during the 2005 event are essential to making future land-use planning decisions and mitigating damage to infrastructure and lifelines (i.e. rail and road bridges) through appropriate engineering and design. The frequency of debris flows emanating from the Awatarariki catchment is poorly understood, but what is known is that the catchment has been destabilised and landslips continue to deliver fresh sediment to the valley floor today. As a consequence, the triggering of a future debris flow event of a similar magnitude may not require a 500-year rainfall event. If and/or when the next debris flow event occurs, it is clear that LIDAR could be used to accurately assess volumetric change and significantly aid cleanup operations.

7. Conclusions

A terrestrial slope failure event in New Zealand has been successfully mapped and investigated using a LIDAR differencing technique. This investigation confirms the capabilities and validity of using high-resolution differenced LIDAR data sets as a geophysical mapping tool for coastal science and mass movement assessments. LIDAR differencing permits precise quantification and accurate mapping of a dynamic environment following a terrestrial slope failure event, and is useful for hazard assessment.

The LIDAR differencing technique estimated a minimum volume of $350{,}000 \pm 50{,}000\ m^3$ for the debris flows which is comparable to estimates from detailed field observations $390{,}000 \pm 100{,}000\ m^3$. The LIDAR data give a comprehensive overview of the deposit, and identified volumes deposited by both the debris flow, but also the debris flood. The infilling of pre-existing low topography by the debris flood was notable in the Matata event.

While LIDAR differencing can be successfully used to study landscape evolution and make volumetric estimates of change, it is important that the post-event survey occurs immediately following the event, and before any major site remediation has taken place.

Acknowledgements

We are grateful to Environment Bay of Plenty Regional Council, New Zealand, for provision of the LIDAR and terrestrial topography data, and thank Peter West and Mark Langridge for their assistance. Helen Miller was supported by the University of Southampton (Richard Newitt Bursary) and the Society for Underwater Technology (Educational Support Fund). Without the ground support of Anthony Olsen and the Matata Community Centre, the field work would not have been possible. In addition, the eyewitness accounts provided by Neville Harris were invaluable to this research. We thank David Bouma of Tonkin and Taylor Ltd. for making available core information within the lagoon. We thank Colin Wilson, Julie Rowland and Pierre Cazenave for their support.

References

Bailey, R.A., Carr, R.G., 1994. Physical volcanology and eruptive history of the Matahina Ignimbrite, Taupo Volcanic Zone, New Zealand. NZ J. Geol. Geophys. 37, 319–344.
Bassett, T., 2006. The Matata debris flows, 18 May 2005. Monitoring, simulation, prevention and remediation of dense and debris flows. WIT Trans. Ecol. Envir. 90, 363–370.
Beanland, S., Berryman, K.R., 1992. Holocene coastal evolution in a continental rift setting: Bay of Plenty, New Zealand. Quatern. Int. 15/16, 151–158.
Beanland, S., Blick, G.H., Darby, D.J., 1990. Normal faulting in a back arc basin: geological and geodetic characteristics of the 1987 Edgecumbe earthquake, New Zealand. J. Geophys. Res. 95, 4693–4707.
Begg, J.G., Mouslopoulou, V., 2009. Analysis of late Holocene faulting within active rift using lidar, Taupo Rift, New Zealand. J. Volcanol. Geoth. Res. 190, 152–167.
Costello, D.A., 2007. Slope failures and debris flow assessment at Matata, Bay of Plenty, New Zealand. Masters Thesis, Univ. Auckland, New Zealand.
Davies, T., 2005. Debris flow emergency at Matata, New Zealand, 2005. Inevitable events, predictable disaster. Internal Report Natural Hazards Research Centre, Department of Geological Sciences, Univ. Canterbury, New Zealand.
Hikuroa, D.C.H., Gravley, D.M., Wilson, C.J.N., Browne, P.R.L., Olsen, A.W., 2006. Recent stratigraphic studies at Matata: implications for Kawerau geothermal field modelling and subsurface interpretation. Proceedings, 28th New Zealand Geothermal Workshop.
Hungr, O., 2005. Classification and terminology. In: Jakob, M., Hungr, O. (Eds.), Debris-flow Hazards and Related Phenomena. Springer and Praxis Publishing, Berlin, pp. 9–23.
Joyce, K.E., Samsonov, S., Manville, V., Jongens, R., Graettinger, A., Cronin, S.J., 2009. Remote sensing data types and techniques for lahar path detection: a case study at Mt. Ruapehu, New Zealand. Remote Sens. Environ. 113, 1778–1786.
Lamarche, G., Barnes, P.M., Bull, J.M., 2006. Faulting and extension rate over the last 20,000 years in the offshore Whakatane Graben, New Zealand continental shelf. Tectonics 25, TC4005. doi:10.1029/2005TC001886.
Manning, D.A., 1996. Middle-late Pleistocene tephrostratigraphy of the eastern Bay of Plenty, New Zealand. Quatern. Int. 34-36, 3–12.
Manville, V., Newton, E.H., White, J.D.L., 2005. Fluvial responses to volcanism: resedimentation of the 1800a Taupo ignimbrite eruption in the Rangitaiki River catchment, North Island, New Zealand. Geomorphology 65, 49–70.
McSaveney, M.J., Davies, T.R.H., 2005. Engineering for debris flows in New Zealand. In: Jakob, M., Hungr, O. (Eds.), Debris-flow Hazards and Related Phenomena. Springer and Praxis Publishing, Berlin, pp. 635–657.
McSaveney, M.J., Beetham, R.D., Leonard, G.S., 2005. The 18 May 2005 debris flow disaster at Matata: causes and mitigation suggestions. Institute of Geological & Nuclear Sciences, Client Report 2005/71, pp. 1–50.
Miller, H., 2008. Examination of terrestrial slope failures, sedimentary processes and coastal evolution using LIDAR data around Matata, Bay of Plenty, New Zealand. MSc Thesis. Univ. Southampton, U.K., 65p.
Nairn, I.A., Beanland, S., 1989. Geological setting of the 1987 Edgecumbe earthquake, New Zealand. NZ J. Geol. Geophys. 32, 1–13.
Pullar, W.A., Selby, M.J., 1971. Coastal progradation of Rangitaiki Plains, New Zealand. NZ J. Sci. 14, 419–434.
Revell, D.L., Komar, P.D., Sallenger Jr., A.H., 2002. An application of LIDAR to analyses of El Niño erosion in the Netarts littoral Cell, Oregon. J. Coast. Res. 18, 792–801.
Rowland, J.V., Sibson, R.H., 2001. Extensional fault kinematics within the Taupo Volcanic Zone, New Zealand: soft-linked segmentation of a continental rift system. NZ J. Geol. Geophys. 44, 271–283.
Rowland, J.V., Wilson, C.J.N., Gravley, D.M., 2009. Spatial and temporal variations in magma-assisted rifting, Taupo Volcanic Zone, New Zealand. J. Volcanol. Geoth. Res. 190, 89–108.
Sallenger Jr, A.H., Krabill, W.B., Swift, R.N., Brock, J., List, J., Hansen, M., Holman, R.A., Manizade, S., Sontag, J., Meredith, A., Morgan, K., Yunkel, J.K., Frederick, E.B., Stockdon, H., 2003. Evaluation of airborne topographic lidar for quantifying beach changes. J. Coast. Res. 19, 125–133.
Shrestha, R.L., Carter, W.E., Sartori, M., Luzum, B.J., Slatton, K.C., 2005. Airborne laser swath mapping: quantifying changes in sandy beaches over time scales of weeks to years. J. Photogram. Rem. Sens. 59, 222–232.
Stockdon, H.F., Sallenger Jr, A.H., List, J.H., Holman, R.A., 2002. Estimation of shoreline position and change using airborne topographic lidar data. J. Coast. Res. 18, 502–513.
Stockdon, H.F., Lillycrop, W.J., Howd, P.A., Wozencraft, J.M., 2007. The need for sustained and integrated high-resolution mapping of dynamic coastal environments. Mar. Technol. Soc. J. 40, 90–99.
Taylor, S.K., Bull, J.M., Lamarche, G., Barnes, P.M., 2004. Normal fault growth and linkage during the last 1.3 million years: an example from the Whakatane Graben, New Zealand. J. Geophys. Res. 109, B02408. doi:10.1029/2003JB002412.
Villamor, P., Berryman, K.R., 2006. Late Quaternary geometry and kinematics of faults at the southern termination of the Taupo Volcanic Zone, New Zealand. NZ J. Geol. Geophys. 49, 1–21.
White, S.A., Wang, Y.W., 2003. Utilizing DEMs derived from LIDAR data to analyse morphologic change in the North Carolina coastline. Remote Sens. Environ. 85, 39–47.
Wilford, D.J., Sakals, M.E., Innes, J.L., Sidle, R.C., Bergerud, W.A., 2004. Recognition of debris flow, debris flood and flood hazard through watershed morphometrics. Landslides 1, 61–66.
Wilson, C.J.N., Houghton, B.F., McWilliams, M.O., Lanphere, M.A., Weaver, S.D., Briggs, R.M., 1995. Volcanic and structural evolution of Taupo Volcanic Zone, New Zealand: a review. J. Volcanol. Geoth. Res. 68, 1–28.

Whakatane District Council

WHAKATĀNE District Council

www.whakatane.govt.nz

Awatarariki Fanhead Intolerable Risk Area

reference - Supplementary Risk Assessment Debris Flow Hazard Matatā Report, Tonkin and Taylor Ltd, November 2013, Figure 15.

Scale: 1:1,500

Path: G:\DATA\GIS\ArcGIS\Maps\DevelopmentandCompliance\MatataIntolerableRisk.mxd

Author: SMO

Date of issue: 12/12/2013

N