Evaluation of lahar mitigation proposals at Mt Ruapehu

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ABSTRACT

This report summarises visits to the southern rim of Crater Lake, the Whangaehu Gorge, and the proposed site of the levée (also referred to as the 'bund') being proposed to prevent spillover of lahars from the Whangaehu channel into the upper Waikato River. The likely magnitude and flow characteristics of a lahar generated by a breakout from Crater Lake were calculated, and the suitability and likely reliability of the proposed Eastern Ruapehu Lahar Alarm and Warning System (ERLAWS) and of sites tentatively selected for deployment of acoustic flow monitors (AFMs) were assessed. Piping resulting from throughflow was considered the most likely mode of failure of the dam, but the worst-case scenario would result from the next most likely failure mode—overtopping and rapid downcutting. Peak discharge of the worst-case outbreak flood, estimated to be in the potential range of about 500–650 m^3/s, would release about 1.4×10^6 m^3 of water. It was considered that the ERLAWS had a very high probability of successfully mitigating the lahar that almost certainly would come down the Whangaehu River within the next few years. The two proposed AFM sites appeared to be excellent sites, but a lake-level sensor, which could be hooked up to the same station as the AFM sensor, was suggested to provide another layer of unambiguous redundancy to the system; redundancy in the human component of the system was also considered crucial, as was having well-rehearsed response procedures that leave little room for confusion or ambiguity. The proposed site for the levée appeared to be the best one available.

Keywords: Crater Lake, Mt Ruapehu, volcano, lake breakout, peak discharge, worst-case scenario, hazard mitigation, hazard warning.

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1. Introduction

On 19 and 20 February 2001, I visited field sites at Mount Ruapehu at the invitation of Harry Keys, New Zealand Department of Conservation. The first day involved a helicopter airlift to the crater rim at the summit, followed by a hike down the Whangaehu Gorge. The second day involved a hike into the proposed site of the levée (also referred to as the 'bund') being proposed to prevent spillover of lahars from the Whangaehu channel into the upper Waikato River.

1.1 OBJECTIVES

I was asked to offer opinions on the following issues:

- The hazards posed by the east and south-east rims of Crater Lake and the hydrothermally altered area in the upper Whangaehu valley relative to that posed by the natural dam at the former lake outlet.
- Likely magnitude and flow characteristics of a lahar generated by a breakout from Crater Lake.
- The suitability and likely reliability of the proposed Eastern Ruapehu Lahar Alarm and Warning System (ERLAWS) system.
- The suitability of sites tentatively selected for acoustic flow monitor (AFM) deployment.
- The suitability of an engineered levée (bund) to prevent avulsion of a lahar or lahars from the Whangaehu channel to the Waikato channel.

1.2 DISCLAIMERS

Although the timing of my visit and weather did not allow all sites to be visited in the field, I have addressed all of the issues noted above to the best of my ability, based on past research experience with lahars and observations of lahar-mitigation schemes in a number of different countries. I have also made several suggestions about construction methods and materials for the levée, based on levée failures that I have observed elsewhere. However, it must be underscored that I am not an engineer and these comments are not formal engineering recommendations.

2. Breakout of Crater Lake

2.1 PRESENT SITUATION

Explosive eruptions of Mt Ruapehu in 1995 and 1996 ejected large volumes of lake water that had been contained by the volcano's bedrock crater prior to volcanic activity. Prior to these eruptions the former lake overflowed through a natural spillway formed on the south-southwest side of the crater at about 2,530 m elevation. Following the eruptions, a new lake began refilling the crater, but the morphology and stability of the lake outlet had been modified by the eruption. An accumulation of unconsolidated, granular, pyroclastic debris (tephra) approximately 6.5 m thick now overlies the > 40 m-thick lava rock sill that formed the previous spillway, and its lowpoint (the anticipated new spillway location) is situated near but not directly over the old one. This layer of tephra will begin acting as a dam for the lake when the lake level rises. The lava sill below it is composed of well-jointed but relatively impermeable, unaltered andesite (G. Hancox pers. comm. 2001), and it is presumed that the sill will provide a stable base level when downcutting reaches it during a lake outbreak. The elevation of the top of the sill beneath the lowpoint in the tephra dam is 2536.5 m. At the time of my visit on 19 February, the lake level was very close to 2500 m.

2.2 TEPHRA DAM COMPOSITION AND POSSIBLE FAILURE MODES

At the new expected spillover point, the natural dam is about 6.5 m thick, approximately 90 m long above the lava sill, and more than 50 m wide (front to back). The width of the dam is expected to decrease to about 40–50 m as lake level approaches maximum capacity (G. Webby pers. comm. 2001). From field observations during our brief site visit, this outlet barrier appears to be composed of two basic units: a lower unit of approximately 4.5–5.0 m of unconsolidated, bedded, granular deposits that are predominantly of sand size but appear to contain some silt/clay-size particles; and an upper unit of approximately 1.5–2.0 m of coarser unconsolidated, granular deposits, ranging from sand- to cobble-size particles, but dominated by coarse sand with lenses or layers of gravel. Although there is some coherence to the sediments due to compaction, cohesion, and water tension, neither of these units appears to be cemented. The lower unit was deposited in 1995, the upper in 1996.

The lower unit is expected to be moderately permeable, while the upper unit is likely to be moderately to highly permeable. As the lake level rises above the level of the lava sill, lake water will begin to flow through the tephra dam to the head of the Whangaehu Valley, and the rate at which it flows will be controlled by the permeability of the material and by the level of the lake (pressure head).

Calculations by Hancox et al. (1997) suggest that piping[1] resulting from throughflow will be the most likely mode of failure of the dam, probably resulting in a flood release prior to the lake reaching the level of the spillway crest. If piping failure does not occur, the next most likely failure mode is by overtopping and rapid downcutting (the worst-case failure mode because it would allow the lake to achieve the highest possible water level prior to failure). This overtopping scenario (6.5 m drawdown of crater lake) would release about 1.4×10^6 m^3 of water (G. Webby pers. comm. 2001).

Other possible failure modes of the natural dam include liquefaction during an earthquake (assuming a high lake level and significant degree of saturation of the dam) and slope failure on the back of the dam (i.e. the side facing the valley). Whether pore pressures/seepage forces could ever be great enough to cause either of these failure modes would depend on lake level and the geotechnical properties of the material in the blockage. It should be noted that the M6.8 Nisqually Earthquake in Washington State in February 2001 (epicenter 105 km distant) did cause a liquefaction failure on the front side of a natural dam (composed of somewhat similar volcanic debris) that is presently damming Castle Lake near Mount St. Helens, although this did not cause the dam to fail. If failure were to occur by a means other than overtopping, the breakout flood could occur sooner than expected, but the flood volume would also be less than for the worst-case overtopping scenario because the lake would be less than completely full.

2.3 ESTIMATING PEAK DISCHARGE OF THE OUTBREAK FLOOD

A paper by Walder & O'Connor (1997) provides a method for extimating peak discharge of the worst-case outbreak flood from Crater Lake at Mt Ruapehu. The following values were used in the calculation:

Drop in water level	6.5 m
Water volume released	1.4×10^6 m^3
Erosion rate of dam	10 to 100 m/h (range of typical rates)

Assuming that the breach is relatively rapid but similar to other failures of natural dams and also assuming that the breach erodes all the way to the lava sill, application of their method (see Appendix 1) yields a potential range in peak discharge of about 500–650 m^3/s for the worst-case overtopping scenario. This range of values agrees well with the range 480–850 m^3/s determined by Hancox et al. (1998).

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[1] 'Piping' results from seepage velocities being sufficiently high (along zones of maximum permeability) to erode sediment grains from along the subsurface flow path, starting at the back side of the dam and moving forward towards the lake, leaving a gradually enlarging and lengthening cylindrical void in or beneath the dam. Failure occurs when the material in the dam collapses over the enlarging pipe, allowing lake water to spill through the breach.

2.4 BULKING FACTOR

During failure of the unconsolidated tephra dam, the water flood will erode and incorporate both material eroded from the dam itself, and loose sediment in the upper Whangaehu Valley (referred to as the Whangaehu Gorge), where tephra deposits 5–15 m thick have accumulated near the valley head since the 1995/96 eruptions (G. Hancox pers. comm. 2001). Because of the steep, narrow, and deeply incised nature of the Whangaehu Gorge, an outbreak flood from Crater Lake is almost certain to incorporate enough of the eroded sediment to change the rheology of much of the initial water flow to *debris flow*[2]. Other investigations of clear-water outbreak floods flowing down valleys filled with unconsolidated fragmental material demonstrate that full transformation can be achieved in valleys with channel gradients are as low as 3% (Pierson 1999), but 'bulking up' to debris-flow concentrations is generally observed only in reaches with gradients greater than 14% (Pierson 1999; O'Connor et al. 2001). The average gradient of the Whangaehu Gorge from the lake outlet down to the 1600 m level (4.5 km) is approximately 20% (computed from small-scale topographic map)—sufficiently steep for debris flows to form. High-concentration floods in channels draining volcanoes (that usually contain volumetrically significant debris-flow phases) are termed *lahars*.

The proportional volume increase of the flood from its point of initiation to some downstream point is referred to as the *bulking factor*. Assuming a 6.5 m drop in lake, the volume of lake water released in the breakout flood would be about 1.4 million m^3. If a water flood picks up just enough loose, dry sediment to transform totally to debris flow, the new volume would be about three times its initial volume, or about 4.2×10^6 m^3 (bulking factor of three), because debris flows containing poorly sorted volcaniclastic sediment characteristically are composed of about one-third water and two-thirds sediment by volume. However, valley-fill sediments in deeply incised valleys on the flanks of volcanoes in temperate climates (such as Mt Ruapehu) are likely to be partially water-saturated and contain active streams and/or accumulations of snow, at least for part of the year. In such cases, bulking factors can be greater than three, because additional water can be ingested with the eroded sediment, and although the volumetric sediment concentration stays at a sediment/water ration of about 2 : 1, the bulking factor can become greater than three because, by definition, it is the ratio of the *final* volume (sediment + water) to the *original* volume (water only). Furthermore, the lahar can additionally increase its volume by pushing a 'wedge' of relatively clear stream water ahead of itself (as the leading edge of the flood wave), as lahars did in the Whangaehu River in 1995 (Cronin et al. 1999). In the case of the 1982 North Fork Toutle lahar at Mt St Helens, peak discharge for the lahar was actually the result of the passage of such a clear-water wedge prior to the arrival of the highly concentrated lahar (Dinehart 1999).

Several case studies demonstrate the range of bulking factors that might be expected at Mt Ruapehu. In the following examples, bulking factors were not computed from the sediment/water ratios of grab samples, because sediment/

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[2] A *debris flow* is a rapidly flowing, high-concentration mixture of sediment and water that has the approximate consistency of wet concrete.

water ratios can only give maximum concentration and cannot account for any water added to the lahar through in-transit incorporation. Instead, the bulking factors were obtained from the ratio of final bulk volume to the initial bulk volume, computed either (a) directly from the volumes preserved in the depositional zones and the volumes of the initial water floods or landslides, or (b) indirectly from flow volumes computed from near-source hydrographs compared to hydrograph volumes near the point where significant deposition begins. Both methods assume that transformation to debris flow has occurred for the entire flood wave (the entire hydrograph), thus giving a maximum possible bulking factor. In cases where the front or the back of the flood wave is more dilute (the case of the clear-water wedge being pushed ahead, for example), the bulking factor would be less.

2.4.1 Lake breakout lahar at Mt St Helens

A lake-breakout flood from the crater of Mt St Helens, USA, on 19 March 1982 was initiated by the complete drainage of a transient meltwater lake having a volume of about 4×10^6 m^3 and draining through two outlets at an estimated rate of between 2600 and 4400 m^3/s (Pierson & Scott 1985; Pierson 1999). Within the first 5 km (average gradient 18%), the water flood transformed fully to a debris flow, and rough volume estimates indicated a bulking factor of about 3.0 for this reach. However, the lahar continued to be dominantly erosive for another 20 km (average gradient 3.3%), and in doing so increased its volume by a factor of 4.5–5.0 (computed by two independent methods using data in Pierson & Scott (1985) and Pierson (1999)).

2.4.2 Lahars initiated by rapid snowmelt at Nevado del Ruiz volcano

Prior to the eruption that rapidly melted part of the snow/ice cap at Nevado del Ruiz, Colombia, on 13 November 1985 there was no snow in the steep upper channels draining the volcano (average gradients 40–80%), but it was raining heavily. Within about 15 minutes, the eruption produced more than 10^7 m^3 of meltwater, which rapidly flowed downhill in three separate drainages. The lahars produced from these floods had the following maximum bulking factors (from Pierson et al. 1990, table 5):

Rio Guali	>2.7	Over distance of 74 km (ave. gradient 6.5%)
Rio Azufrado	4.0—5.0	Over distance of 69 km (ave. gradient 7.2%)
Rio Molinos/Nereidas	4.0—6.4	Over distance of 69 km (ave. gradient 6.6%)

2.4.3 Landslide-triggered lahar at Mt Hood

In a channel cut into pyroclastic deposits on the east flank of Mt Hood, USA, warm and extremely heavy rains falling on a widespread snowpack on 25 December 1980 triggered a landslide of approximately 4000 m^3 that immediately liquefied into a debris flow. This lahar flowed about 8 km down a steep channel (average gradient 14%) that was experiencing a major flood, and in doing so increased its total volume by about a factor of about 20 (Gallino & Pierson 1985). This is an extreme example, but it serves to indicate that under very wet conditions, bulking factors can be significantly higher than 4 or 5.

2.4.4 Relevance to Mt Ruapehu

Given that snow can accumulate in the upper Whangaehu channel during winter and early spring months and that a lake breakout cannot be guaranteed to occur during a dry, snow-free time, I would consider a reasonable and conservative estimate of the maximum bulking factor of the anticipated breakout flood to be 5. Therefore, the probable maximum volume of the lahar at the downstream end of the erosional reach (before deposition begins significantly reducing flow volume) could be as much as about $5 \times (1.4 \times 10^6)$, or 7.0×10^6 m^3.

2.5 MAXIMUM PEAK DISCHARGE

Conversion of this probable maximum volume to a probable maximum peak discharge (Q_p) is more problematic. Lahar discharge peaks typically become amplified (rather than attenuated) in steep upstream channel reaches because of (a) coalescence of flow surges, (b) sloughing of undercut banks into the flow, and (c) flow resistance encountered at the front of the flow due to accumulation of coarser debris, which allows flow to 'pile up' behind the flow front (Pierson et al. 1990), but there is no standard way to estimate the amplification factor. Several empirical approaches provide some guidance:

- A large-scale debris-flow experiment carried out in Kazakhstan in 1991 released 4.5×10^5 m^3 of clear water in a steep channel filled with unconsolidated glacial sediment (Khegai et al. 1992). Peak discharge at the lake outlet (artificially controlled) was 22 m^3/s, but within about 1 km, Q_p was amplified nine times to about 200 m^3/s.
- Pierson et al. (1990) and O'Connor et al. (2001) have documented amplifications of peak discharge by factors of at least 2.4 to about 5 over distances of several hundred metres to several tens of kilometres (the lower values being associated with the shorter distances).
- The 1982 lahar at Mt St Helens was triggered by rapid drainage of a transient meltwater lake through two outlets (Pierson 1999). Two distinct lahars occurred, so the outflows were not synchronous, but some overlap in the hydrographs could have occurred. Therefore the outflow Q_p could have ranged from 2600 to perhaps 3500 m^3/s. About 5 km downstream, the flood had transformed to a debris flow, and Q_p was estimated to be about 9000 m^3/s, which gives an amplification factor of between 2.6 and 3.5.

These examples provide a fairly wide range of amplification factors. It would seem that the peak-discharge amplification ultimately depends on: (1) volume and erodibility of sediment available in the flood channel; (2) dynamic interaction of the flow with channel topography; (3) partial or temporary damming of the flow by bank collapses; and (4) slowing of the flow by friction at the bouldery flow front. Channel conditions that might play a role in these processes were not evaluated during my brief visit to the Whangaehu Gorge. Given the estimated maximum initial peak discharge at the breach of about 600 m^3/s and the attendent uncertainties, it seems likely that Q_p for a crater lake outbreak flood could be amplied anywhere from 3 to 8 times. Given that range, the estimated maximum peak discharge for a worst-case Mt Ruapehu lahar flowing out of the Whangaehu Gorge could be between 1800 and 4800 m^3/s. Note that this estimated range is in fairly good agreement with the revised peak discharge estimate of 3550 m^3/s for a crater lake outbreak lahar (for a bulking factor of 5) by G. Webby (pers. comm. 2001).

2.6 ESTIMATED LAHAR TRAVEL TIMES

According to the scoping report, lahar modelling by Grant Webby has provided estimated travel times for a lake-breakout lahar moving down the Whangaehu River. This model predicts that the lahar will take 0.85–1.1 hours to reach the end of the outwash fan near the power transmission lines and 1.8–2.1 hours to reach Tangiwai. Empirical data on lahars of similar magnitude suggest that a lake-breakout lahar could reach the end of the outwash fan much sooner. Figure 1 shows that, from an expanded plot of a best-fit regression for measured travel times of actual lahars with peak discharges in the range 10^3 to 10^4 m^3/s (Pierson 1998), travel time to the end of the outwash fan is expected to be only about 0.3 hours (range 0.2–0.5). However, the empirical data suggest that travel time to Tangiwai should be about 1.8 hours (range 1.2–2.7), which is in agreement with Webby's values. For these estimates, I scaled distances off the map on the scoping report and got travel distances of about 15 km to end of the outwash fan and 37 km to Tangiwai. If these distances are not accurate, estimated travel times should be adjusted. It should be noted that the empirical method of Pierson (1998) lumps together channels of different geometries, but for this particular range in magnitude (10^3–10^4 m^3/s), actual examples in the study were taken from multiple lahar events from only two volcano-draining channels, and both channels were narrow and steep near source and relatively flat and quite wide at distances of more than about 20 km from source—similar to the situation at Mt Ruapehu.

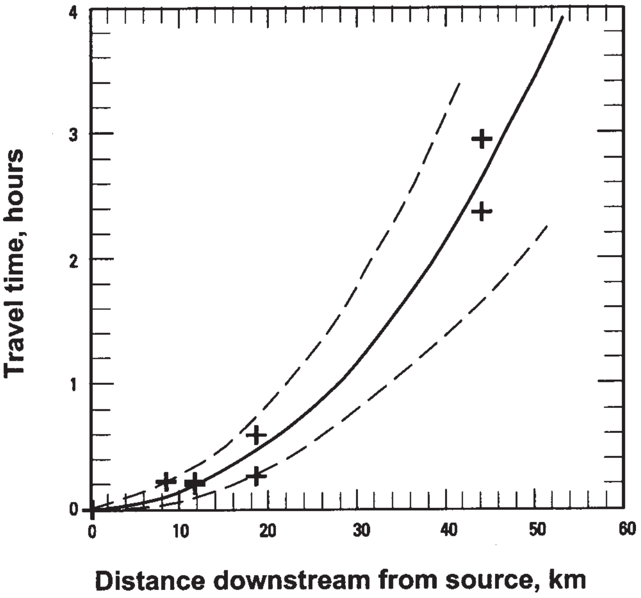

Figure 1. Best-fit regression curve (2nd degree polynomial) for measured flow-front travel times for individual lahars having peak discharges (Q_p) between 1000 and 10 000 m^3/s in the Drift River (Redoubt Volcano, Alaska) and the North Fork Toutle River (Mt St Helens, Washington). Each + represents a different lahar. This is an enlargement of part of fig. 3 ('large' mass flows) in Pierson (1998, p. 105), with the addition of high and low limiting envelopes.

2.7 CRATER RIM AND HYDROTHERMALLY ALTERED AREA

The condition of the crater rim on the east and south-east sides of Crater Lake was not evaluated during this visit. I have been told that the crater wall is relatively thin in this sector, and that some concern has been voiced about its stability there. If this is a serious concern, movement of this part of the crater wall could be monitored using continuous GPS, so that any acceleration of movement could be used as an indicator of impending failure. Failure of part of the crater wall could lead to a much bigger lahar than would occur by overtopping at the low point in the crater rim.

The hydrothermally altered area south-west of Crater Lake at the head of the Whangaehu drainage was only observed briefly at a distance during our field visit. Colouration of the rock making up this steep ridge suggests that the alteration is fairly extensive, which further suggests that the shear strength of the rock (or at least parts of it) is less than that of unaltered andesite. Whether it is now particularly vulnerable to failure (other than surficial rockfall), I cannot say.

3. Potential lahar spillover into Waikato River

At the site of the proposed levée ('bund'), which appears to be about 8–10 km downstream from Crater Lake, a high lateral moraine on the left side of the stream terminates and the valley widens considerably. Significant deposition by lahars during the 1995/96 eruption occurred at this point (evidenced by fresh deposits), owing to the decrease in channel slope and decrease in valley confinement. Debris flows typically spread out, become shallower, encounter more frictional resistance, and slow down or stop at such channel expansions. Although the moraine on the left side of the channel terminates at the proposed levée site, the eroded margin of a higher, older fan surface continues downstream on the right side, effectively blocking the stream from moving in that direction. Thus any channel shifting has to occur to the left of the present channel. A low divide of only 1–2 m separates the Whangaehu Valley from the Waikato Valley to the north. Given these topographic realities, I would consider the Waikato River drainage to be very susceptible to capturing lahar flow from the Whangaehu Valley during flow of a large lahar.

4. Evaluation of proposed mitigation solutions

4.1 LAHAR ALARM AND WARNING SYSTEM

Given that engineering intervention at the crater rim to mitigate the lahar hazard is not feasible politically, the lahar alarm and warning system, ERLAWS, is the next best alternative. AFM systems detect ground vibrations from passing lahars and have been shown to be effective in detecting the passage of lahars in several different countries over the last decade. As opposed to trip-wire systems, they can detect multiple events without having to be re-set and can indicate relative magnitude of the flows. Furthermore, AFMs can discriminate lahar signals from other noise, such as earthquakes, volcanic explosions, rockfall, and high wind. It is a robust, effective, and economical technology. Redundancy from multiple sensors at single stations and multiple stations in series are ways to increase system reliability, as well as allow gleaning of additional information such as lahar travel times.

In lahar warning systems using AFMs or other technologies, the weakest link in the system is usually the part that involves human beings sending an alarm after a lahar has been detected by instruments. As with the instruments themselves, redundancy is crucial, as is having well-rehearsed response procedures that leave little room for confusion or ambiguity. I do not know how many 'first-order' responders will be carrying pagers, but problems happen—one or more responders could be out of town, one could have left his/her pager on the bedside table on the critical day, batteries could be low in someone else's pager, another responder could be in the field in a cell-phone 'dead zone' and never get the page or be unable to call out, etc. Whatever response system is decided on, it should be able to deal with all kinds of unexpected contingencies.

4.2 PROPOSED SITES FOR AFM SENSORS

The two proposed AFM sites that I saw in the field on 19 February (the crater-rim site and the 'lava bluff' site near the Alpine Club hut) both appeared to be excellent sites. We did not have the opportunity to see the Tukino Ski Field site. Although I realise there are substantial technical challenges involved in getting a site to function year-round at the crater rim, I believe there are substantial advantages in having a functional, real-time site there:

- It provides the earliest possible warning. Given the possible overestimation of lahar travel times noted above, this may be of real importance.
- Signal duration can be used to determine the rapidity of breaching, which can be used to roughly estimate the relative magnitude of flow peak discharge.
- Lake level and flow-induced ground vibrations can be simultaneously monitored from the same station, and lake level provides another layer of unam-

biguous redundancy to the system—one can be sure that the signal is from a lake breakout (not a nearby rock avalanche, for example)—and the magnitude of the drop in lake level can allow estimates of lahar volume (and thus travel time and potential impact) to be adjusted.

- Deformation of the dam can be independently monitored by the same station using tiltmeters, achieving yet another level of redundancy.

If the crater rim site is abandoned eventually for technical reasons, I would recommend that a third site be established downstream to complement the Alpine Hut and Ski Field sites, in order to achieve the desired redundancy.

Experience in operating AFMs under varied conditions in a number of different locations has led to the following recommendations for instrument set up:

- Geophone sensors ideally should be 50–75 m away from the channel (100 m is about the maximum before signal begins to be lost, but this also depends on how solidly the sensor is connected to the ground). At the Alpine Club 'lava bluff' site, this means that the sensor could be located above the channel at the top of the bluff, so long as it is in good contact with the bedrock.
- Up to 100 m of cable can be run from the instrument station to the geophone sensor.
- Clear line-of-sight paths from instrument sites to repeaters are critical.
- A battery cache having power to last a year is needed if solar recharging of batteries is problematic.
- Relative ease of access is helpful for installation and servicing.

4.3 PROPOSED SITE FOR LEVÉE (BUND)

The proposed site for the levée appears to be the best one available. The medium- to long-term success of such a structure depends on: the material it is constructed of; the duration of erosion against it by lahars; and the amounts of degradation (leading to undercutting) and aggradation (leading to burial) experienced by the adjacent channel. I have observed that in areas where multiple lahars may be expected, levée structures tend to last for only a few years. In the Whangaehu River where only one lahar is expected in the foreseeable future, there is a good likelihood of a levée lasting for many years.

From what I have seen of levées in other countries following lahar occurrence and the relative degrees of success the structures have had, constructing the levées out of heavy-duty gabion baskets seems to be the most successful approach. Undercutting of a levée during part of a lahar event itself or by smaller preceding floods is almost certain to happen and will undermine a concrete structure, causing it to break under its own weight and perhaps even topple over. If rows of gabion baskets are used, the first row or two may drop into the channel, but the baskets maintain structural integrity and thus armour the foundation under the remainder of the original rows. In this way, a gabion structure is self-adjusting. However, a sufficient number of rows must be employed to achieve enough overall width for such adjustments to not compromise the whole structure. For gabion baskets to survive under highly erosional lahar conditions, the wire forming the baskets must be of the heaviest possible gauge and the baskets must be strongly wired together.

Burial of the levée during periods of aggradation is also a possibility, and to guard against the overtopping that could result, the levée must have sufficient height. I do not know how much aggradation occurred at this location during the 1995/96 events, but I would not be surprised if 5–10 m of aggradation occurred. Similar amounts could occur again if some small eruptions caused minor lahars to precede a major lake breakout. On the other hand, a levée could be designed with a sufficiently wide base so that additional layers of gabion baskets could be added if aggradation were to become a long-term problem.

5. Conclusions

The ERLAWS has been very well thought out, and I am extremely impressed by the attention to detail, the degree of cooperation among involved agencies and parties, the breadth of planning, and the knowledge and abilities of the involved individuals that I met. In terms of overall strategy and approach, I believe that the system has a very high probability of successfully mitigating the lahar that almost certainly will come down the Whangaehu River within the next few years. In terms of a few additional details to be covered, I would suggest the following:

- Double-check the estimated lahar travel times using one or more other methods, in order to ensure that the lahar does not arrive at critical locations before it is expected.
- In addition to an AFM station at the crater rim, install a lake-level sensor, which can be hooked up to the same station as the AFM sensor. Lake level provides another layer of unambiguous redundancy to the system, i.e. one can be sure that the signal is in fact from a lake breakout. Detection of the rate and magnitude of the drop in lake level can also allow estimates of initial peak discharge and lahar volume (and thus travel time and potential impact) to be adjusted.
- Do geotechnical tests and computer modelling to see if the dam is likely to fail by a scenario other than piping or overtopping, i.e. slope failure or liquefaction. The gullies and embayments that are currently eroded into the front face of the dam will shorten the subsurface seepage pathways and could significantly affect stability calculations.

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Appendix 1

ESTIMATION OF PEAK DISCHARGE OF CRATER-LAKE OUTBREAK FLOOD

This calculation uses methodology of Walder & O'Connor (1998):

Assumptions:

Drop in water level of lake (d)	6.5 m
Water volume released (V_0)	1.4×10^6 m^3
Erosion rate of dam (k)	10–100 m/h (typical rates from literature)

Step 1:

Calculate value of n, where

$$n = (k \times 1/3600 \times V_0)/(g^{1/2} \times d^{7/2})$$

For $k = 10$ $\quad n = (10/3600)\,(1.4 \times 10^6)/(9.81^{1/2} \times 6.5^{7/2})$

$= 1.8$

For $k = 100$ $\quad n = (100/3600)\,(1.4 \times 10^6)/(9.81^{1/2} \times 6.5^{7/2})$

$= 17.7$

Step 2:

For values of n between 0.6 and 5, the peak discharge Q_p is determined from the graph of Q^*_p v. n (Walder & O'Connor 1998, p. 2343, 2344), and then Q^*_p is converted to Q_p by the relation

$$Q_p = g^{1/2} \quad d^{5/2} \quad Q^*_p$$

After doing so, $\quad Q^*_p = $ c.1.5

and $\quad Q_p = 1.5 \times 3.13 \times 107.7$

$= 505$ m^3/s

For values of $n >> 1$,

$$Q_p = 1.94\, g^{1/2}\, d^{5/2}\, (D_c/d)^{3/4}$$

(where D_c is height of dam)

$= 1.94 \times 3.13 \times 6.5^{5/2} \times 1$

$= 654$ m^3/s