Mt Ruapehu Crater Lake lahar hazard

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Published by
Department of Conservation
Head Office, PO Box 10-420
Wellington, New Zealand

This report was commissioned by Tongariro/Taupo Conservancy

ISSN 1171-9834

Reference to material in this report should be cited thus:

Webby, M.G., 1999
Mt Ruapehu Crater Lake lahar hazard *Conservation Advisory Science Notes No. 231,* Department of Conservation, Wellington.

Keywords: Mt Ruapehu, lahar hazard, hydraulic modelling

Summary

This report documents the results of some additional computational hydraulic modelling of the historic 1953 lahar event down the Whangaehu River (which caused the Tangiwai disaster) and a hypothetical lahar event generated by a future collapse of the Mt Ruapehu Crater Lake outlet barrier.

Based on the results of the additional work, the following conclusions were obtained regarding the lahar event generated by a future collapse of the Crater Lake outlet barrier:

- Peak discharge from the Crater Lake (assuming outlet barrier collapse occurs when the lake is full up to the top level of the barrier) is likely to be in the range 480-850 m^3/s.

- Bulking of the water flow (due to sediment entrainment) released by the outlet barrier collapse is likely to increase the peak discharge at the end of the Whangaehu Gorge to about 1540-2340 m^3/s.

- Overflows of the order of 50-290 m^3/s and 20-160 m^3/s into the southern "chute' channel and into the Waikato Stream system respectively are likely to occur.

- Attenuation of the lahar event due to sediment detrainment and channel friction effects will occur down the outwash fan and the Whangaehu River parallel to the Desert Road. Peak discharge at Tangiwai Bridge (38 km from the Crater Lake outlet) is estimated to be 910 ± 105 m^3/s giving an upper-bound credible discharge of about 1015 m^3/s.

- Peak discharge at Tangiwai Bridge will be up to 54-72% larger in magnitude than that for the historic 1953 event.

- The lahar event will also travel faster downstream than the historic 1953 event. Travel time to the Tangiwai Bridge is estimated to be 1.8-2.1 hours compared to about 2.3 hours for the 1953 event.

1. Introduction

This report extends some work described in a previous institute of Geological and Nuclear Sciences Limited report (Hancox *et al.* 1997) which simulated two historic lahar events down the Whangaehu River and a hypothetical future lahar event (given the current Mt Ruapehu Crater Lake outlet barrier situation) using a computational hydraulic modelling approach. One of the historic lahar events considered in this previous work was the 1953 event which caused the Tangiwai disaster. The current Mt Ruapehu Crater Lake outlet barrier situation mirrors the pre-1953 situation so that the 1953 event was used as an analogue for a hypothetical lahar event generated by a future collapse of the Crater Lake outlet barrier. Estimates of peak flood discharge for this event were obtained to enable an assessment of the potential flood hazard at the Tangiwai Bridge.

The IGNS report was reviewed by Dr Shane Cronin and Professor Vince Neall of Massey University, with particular scrutiny being given to the hydraulic model simulations of different lahar events. The review was carried out with the beneficial knowledge of recent field data obtained from lahar events which occurred during the course of the 1995/1996 Mt Ruapehu eruption sequence. The review arrived at different conclusions regarding the flood hazard at the Tangiwai Bridge posed by a lahar event resulting from a future Crater Lake outlet barrier collapse.

Following the Massey University review of the IGNS report, a technical review meeting hosted by DOC was held involving the Massey reviewers and two of the main contributors to the original IGNS report. The meeting explored possible reasons for the differences in conclusions regarding the magnitude of a likely future lahar event at Tangiwai rail bridge. As a result of the meeting it was resolved to undertake some additional hydraulic modelling of lahar events using the knowledge gained from the field data obtained from the 1995/1996 lahar events.

This report documents the results of the additional hydraulic modelling work. The additional work included simulations of the historic 1953 lahar event and a hypothetical lahar event generated by a future collapse of the Ruapehu Crater Lake outlet barrier. The specific objectives of the additional work were to:

- provide an estimate of the most credible peak discharge for the lahar event generated by a future collapse of the Ruapehu crater lake outlet barrier (given the 1997 situation),
- provide estimates of the maximum credible discharge for this event at the end of the Whangaehu Gorge and at the Tangiwai Bridge,
- list the uncertainties in these estimates and provide a final upper bound estimate of peak discharge.

2. Areas of uncertainty

Table 1 identifies a number of areas of uncertainty which affect the computational hydraulic modelling of lahar events. Pertinent comments are also made in relation to the simulation of the historic 1953 lahar event and a hypothetical lahar event generated by a future collapse of the Crater Lake outlet barrier.

3. Assumptions for revised lahar simulations

3.1 CRATER LAKE AND CRATER LAKE OUTLET BARRIER PARAMETERS

Table 2 summarises values of various Crater Lake and Crater Lake outlet barrier parameters assumed for the different lahar simulations. These parameters include:

- volume of water released from the Crater Lake,
- foundation level of outlet barrier,
- maximum depth of outlet barrier breach,
- maximum width of outlet barrier breach,
- breach development time.

These parameter values are based on the assumption that outlet barrier collapse occurs when the Crater Lake water level is coincident with the crest of the outlet barrier (the worst case scenario). The maximum breach depth in the outlet barrier was assumed equal to the maximum barrier height.

The assumed range of breach development times is based on data from historical failures of man-made earthfill embankment dams (Froehlich 1987; Singh & Scarlatos 1988).

3.2 ICE TUNNEL DIMENSIONS

The following dimensions were assumed for the ice tunnel under the Whangaehu Glacier below the Crater Lake outlet for the simulation of the historic 1953 flood event.

• length	500 m
• average diameter	4-5 m
• characteristic wall roughness	0.15 m
• exit level	2460 m

3.3 WHANGAEHU RIVER GEOMETRY

The hydraulic model of the Whangaehu River was constructed assuming a simplified river channel geometry. Each distinctive reach (i.e. gorge, outwash fan, river parallel to Desert Road, entrenched channel downstream of Tangiwai Bridge) was approximated by a prismatic cross-section shape using available surveyed cross-section data and slope data obtained from standard NZMS 260 series 1:50,000 scale topographic maps. The model incorporated two overflow points: the first about 2 km above the end of the Whangaehu Gorge over a low ridge into the southern "chute" channel and the second immediately below the end of the Whangaehu Gorge into the Waikato Stream system (these overflow points were recently surveyed as part of the second stage of the previous IGNS study which has the objective of evaluating the hazard at specific locations posed by a future lahar event down the Whangaehu River). The overflow points are identified as sites M and D respectively in Figure 1(a) of Hancox et al (1998). The outwash fan from below the second overflow point was represented in the model by a series of multiple parallel channels. The model was terminated at the site of the Karioi hydrological gauging station, 54 km downstream from the Crater Lake outlet.

3.4 SEDIMENT CONCENTRATIONS

The physical processes by which a water flow released down a steep slope is transformed in a sediment-laden lahar flow and then back into a hyperconcentrated water flow (as the channel slope reduces and some of the transported sediment is deposited out) are poorly understood at present with no adequate theoretical model available. A simplified approach was, therefore, adopted for the revised lahar simulations.

The lahar events under consideration were assumed to be fully loaded with sediment at the end of the Whangaehu Gorge. Downstream of the gorge exit (i.e. as they flow across the outwash fan and down the Whangaehu River parallel to the Desert Road), they were assumed to gradually deposit sediment due the effects of channel friction and a decreasing channel slope causing them to slow down.

For the model simulations of the different lahar events, the sediment concentration by volume was assumed to vary spatially as in Table 3 based on field measurements of sediment concentration obtained from several lahar events during the 1995/1996 Mt Ruapehu eruption sequence (Dr Shane Cronin, personal communication).

The original water volume in each lahar event was assumed to be conserved. Table 3 also gives the bulking factors for the original water volume corresponding to the recommended sediment concentration values.

The spatial variation of sediment concentration was simulated using constant rates of volume loss over each distinctive channel reach.

3.5 CHANNEL ROUGHNESS (ENERGY DISSIPATION) PARAMETERS

The lahar simulations assumed a turbulent flow model which required the use of a channel roughness or energy dissipation parameter. Specifically, the Manning frictional resistance relationship was utilised, with Manning's n values for each distinctive channel reach selected on the basis of experience with water flows down similarly sloping channels (Hicks & Mason 1991). The Manning's n values assumed are given in Table 4.

3.6 STAGE/DISCHARGE RATING FOR KARIOI GAUGING STATION

The stage/discharge rating for the Karioi hydrological gauging station was assumed as the downstream boundary condition for the hydraulic model. This required considerable extrapolation, as the maximum flood discharge that has ever been gauged at the site is only 65 m^3/s. The other implicit assumption was that the stage/discharge rating developed for water flows is also valid for hyperconcentrated sediment-laden water flows as experienced during lahar events.

4. Results of revised lahar simulations

4.1 1953 LAHAR EVENT

The peak breach outflow generated by the 1953 collapse of the crater lake outlet barrier was assumed to be throttled by the ice tunnel under the Whangaehu Glacier. The model for this event was effectively calibrated by adjusting the size of the ice tunnel so that the magnitude of the lahar event at the Tangiwai Bridge and the travel time matched estimates of these parameters from actual field observations. The best estimate of the average tunnel diameter is 4.7 mm, giving a peak outflow (water only) of about 250 m^3/s.

Simulation of the historic 1953 lahar event based on the assumptions outlined in Section 3 produced the following estimates of downstream peak discharge (Table 5). The overall uncertainty in these discharge estimates is also given, this being determined by summing the estimated uncertainty values for the different sources of uncertainty (principally the tunnel diameter and sediment concentration in this case).

Some minor overflow (of the order of 5-10 m^3/s) into the southern "chute" channel (site M in Figure 1(a) of Hancox *et al.* (1998)) occurred which is consistent with observations from the actual event. However, no overflow into the Waikato Stream system at the end of Whangaehu Gorge (site D in Figure 1(a) of Hancox *et al.* (1998)) occurred.

Figure 1 shows a plot of the peak discharge profile for the 1953 lahar event from the end of the Whangaehu Gorge down to the site of the Karioi hydrological gauging station. The calculated peak discharge at Tangiwai Bridge matches fairly well the discharge estimate of 540-620 m^3/s from a reanalysis of Harris' (1954) slope/area field data.

Table 6 presents estimates of travel times for the 1953 lahar event. Travel time to Tangiwai Bridge is consistent with evidence from the actual event which indicates a probable travel time of the order of 2.25 hours.

4.2 HYPOTHETICAL LAHAR EVENT FOR FUTURE COLLAPSE OF CRATER LAKE OUTLET BARRIER

Based on breach development times of 0.25-0.75 hours, peak outflows (water only) from the Crater Lake of 480-850 m^3/s are predicted for a future collapse of the outlet barrier.

Simulation of the hypothetical lahar event generated by this outlet barrier collapse produced the following estimates of downstream peak discharge (Table 7). The uncertainty in these discharge estimates is again determined by summing the estimated uncertainty values for the different sources of uncertainty (principally the outlet barrier breach development time and sediment concentration in this case).

A minor overflow of the order of 50-290 m^3/s into the southern "chute" channel (site M in Figure 1(a) of Hancox et al (1998)) occurs. Similarly, a further overflow of the order of 20-160 m^3/s into the Waikato Stream system occurs assuming no erosion at the crossover point. The duration of this latter overflow is up to 0.5 hours and the overflow event translates to a volume of 0.5-2.7% of the total volume of the lahar event at the end of the gorge.

Figure 1 also shows plots of the peak discharge profiles for a hypothetical future lahar event for the two crater lake outlet barrier breach times. The two peak discharge profiles gradually converge with distance downstream from the Crater Lake outlet indicating that self similarity of the flood discharge is achieved by about the Tangiwai Bridge (38 km downstream of the Crater Lake outlet). Self similarity describes the behaviour of a flood wave travelling downstream whereby, for the same initial volume released from an upstream reservoir, the peak discharge and travel times become independent of the rate of volume release or breach development time. An assumption of self similar behaviour is the basis of previous lahar modelling by Weir (1982) and Vignaux & Weir (1990).

The assumption of self similarity is also implicit in any attenuation model developed from estimates of peak discharge based on field measurements. Application of any attenuation model is only valid in the region where self similar behaviour occurs (i.e. downstream of the Tangiwai Bridge in this case).

The increase in the rate of attenuation of the peak discharge just downstream of Tangiwai Bridge observed in Figure 1 is due to the sharply contracted and entrenched nature of the river channel in this reach and the sharp-peaked nature of the flood hydrograph.

Comparison of the average peak discharge estimates at the Tangiwai Bridge from Tables 5 and 7 and Figure 1 indicates that the peak discharge for a hypothetical future lahar event will be up to 54-72% larger in magnitude than that for the historic 1953 event.

Table 8 presents estimates of travel time for a hypothetical future lahar event. Comparison of the travel times with those for the 1953 lahar event in Table 6 indicates that a hypothetical future lahar event will travel downstream faster than this historic event.

5. Peak flow depths

5.1 METHODOLOGY FOR ESTIMATING PEAK FLOW DEPTHS

As part of the second stage of the Ruapehu Crater Lake flood hazard study, the channel cross-section was surveyed at a number of specific sites along the Whangaehu River and the south and north branches of the Waikato Stream:

- at the overflow point to the southern "chute" channel in the Whangaehu Gorge (site M in Figure 1(a) of Hancox *et al* (1998)),
- at the overflow point to the Waikato Stream system below the end of the Whangaehu Gorge (site D in Figure 1(a) of Hancox *et al* (1998)),
- on the southward bend of the northern most channel at the bottom of Whangaehu outwash fan,
- at the Wahianoa aqueduct crossing of the Whangaehu River,
- at the TranzRail lahar warning gauge site on the Whangaehu River,
- at the Tangiwai rail bridge site on the Whangaehu River,
- at the SH49 road bridge site on the Whangaehu River,
- at the site of Strachan's bridge on the Whangaehu River,
- at the site of the Tirorangi Marae Road bridge on the Whangaehu River,
- at the electricity transmission line crossing point on the south branch of Waikato Stream,
- at the SH1 crossing of the south branch of the Waikato Stream,

- at the electricity transmission line crossing point on the north branch of Waikato Stream,

- at the SH1 bridge crossing of the north branch of the Waikato Stream.

In order to estimate flow depths at each of these sites for a hypothetical lahar event generated by a future collapse of the Crater Lake outlet barrier, local MIKE11 hydraulic models of each site were constructed. These models used the surveyed cross-section data supplemented by information obtained from NZMS 260 series 1:50,000 scale topographic maps and, in the case of two sites, additional topographic data dating back to the construction of the Tongariro Power Scheme. Input hydrographs for the models were obtained from the results of the lahar simulations with the coarse MIKE11 model of the whole Whangaehu River from the Crater Lake to the Karioi hydrological recording station.

In the case of the MIKE11 model of the Tangiwai rail bridge and SH49 road bridge reach, the model was calibrated and verified against estimated flow depth data from the 1953 and 1975 historic lahar events. In the case of other local MIKE11 models, calibration was not possible due to the unavailability of any flow depth data for historic lahar events. It was necessary, therefore, to exercise judgement in assigning appropriate values for the channel roughness (energy dissipation) parameter.

5.2 PEAK FLOW DEPTHS AT TANGIWAI RAIL BRIDGE AND SH49 ROAD BRIDGE

The MIKE11 hydraulic model of the Whangaehu River covered the reach between the Tangiwai rail bridge and the SH49 road bridge and the uniform 1953 slope/area measurement reach upstream of the rail bridge. The model was constructed using the surveyed channel cross-section data with the assistance of an RNZAF photo of the Tangiwai rail bridge site immediately following the 1953 collapse of the bridge. The model used input hydrographs for the rail bridge location with average values of peak discharge obtained from the coarse MIKE II model of the whole Whangaehu River. Scaled hydrographs with peak discharge values reflecting the uncertainty in the average peak discharge estimate were also run through the model to obtain uncertainty estimates for the peak depth.

The model was calibrated against peak flow depth observations from the 1953 lahar event and then verified against observations from the 1975 event. Harris (1954) estimated a flow depth of 4.6-5.2 m at the site of the rail bridge for the 1953 event, while Healy (1954) quotes a depth of 6.1 m at the same location. Harris (1954) also gives average flow depths of 1.9-2.2 m for the slope/area measurement site upstream of the rail bridge. Photographs of the SH49 road bridge following passage of the 1975 lahar event show a distinct tide mark along the side of the piers. From recent measurements on the piers, the flow depth is estimated to have been 3.9 m, although the stream bed was 0.7-0.8 m lower than the present level. These observations are summarised in Tables 9 and 10.

The discharge hydrograph at Tangiwai for the 1975 lahar event was estimated by applying the concept of self similarity discussed in Section 4.2 to the flood hydrograph recorded at the downstream Karioi gauging station (for which the peak discharge was estimated to have been 310 m^3/s). Assuming self similarity of the flood hydrograph from the Tangiwai rail bridge downstream, the peak discharge at Tangiwai for the 1975 event was estimated to have been about 470 ± 55 m^3/s (the uncertainty value for this estimate is based on the percentage uncertainty value in Table 7 for the peak discharge estimate at Tangiwai for a hypothetical future lahar event).

The discharge hydrograph for the hypothetical future lahar event was assumed to have a peak discharge of 910 ± 105 m^3/s (Table 7).

The local MIKE11 hydraulic model was successfully calibrated against Harris' (1954) observations of peak flow depth at the rail bridge site and the upstream slope/area measurement reach and then verified against the estimated flow depth at the SH49 bridge for the 1975 event. The predicted flow depths are shown in Tables 9 and 10 for comparison with the observed values. The uncertainties in the predicted flow depths reflect the uncertainties in the peak discharge estimates (as shown in Table 5 for the 1953 event).

Note that it proved impossible to calibrate the model against Healy's (1954) peak flow depth observation at the rail bridge site for the 1953 lahar event with realistic values of the channel roughness (energy dissipation) parameter. Calibration against this observation would only have been successful if the peak discharge was significantly larger than estimated (but this would cause average flow depths at the slope/area site to be greater than observed) or if there was a channel constriction between the two bridge sites (photographs indicate that this is not the case). Healy (1954) did not indicate where or how his observation was made. The only explanation for the inability to calibrate the model against Healy's observation was that it was made at a location affected by either wave runup or superelevation or bow wave effects.

Because of the uncertainty in the measured peak depths at the rail bridge site for the 1953 event, Healy's (1954) depth measurement of 6.1 m has been taken into account by applying an "observational uncertainty" factor of +17%. This factor is obtained from the difference between Harris's (1954) observed maximum depth of 5.2 m and Healy's observation of 6.1 m. This additional uncertainty factor has been added to the model predicted peak depth estimates at both the rail and road bridge sites for a future lahar event to obtain maximum credible peak depth estimates for hazard and damage assessment purposes.

Following the successful calibration of the local model of the Tangiwai reach, it was applied to the case of a hypothetical future lahar event. The results are summarised in Table 11. At the rail bridge (Site I), a peak depth of 5.8 m is predicted for the average peak discharge estimate and 6.0 m for the maximum credible peak discharge estimate. Adding on the +17% "observational uncertainty" factor increases the maximum credible depth estimate at the rail bridge site to 7.05 m. This depth is considered to be an appropriate value to use for the estimation of potential hazard and possible damage to the bridge.

A similar approach is used for the road bridge site (Site H). A peak flow depth of 4.0 m is predicted for the average peak discharge estimate and 4.2 m for the maximum credible peak discharge estimate. The maximum credible depth estimate increases to 4.95 m when allowance is made for the "observational uncertainty" factor.

The reason for the relatively small increases in model predicted flow depth at both sites between the average and maximum credible peak discharges is the relatively large width of the river channel (60-80 m) at these flow depths. The same reasoning explains the relatively modest increase in depth at the Tangiwai rail bridge between the 1953 event and the future event compared to the 54% and 72% increase in the average and maximum credible peak discharge estimates, respectively.

The model predicted peak flow depths assume no obstruction across the channel conveying the lahar event. The piers and abutments of both bridges will, however, cause significant bow wave action on the upstream side due to the viscosity of the hyperconcentrated water flow. Cronin et al. (1997) show a photograph of the TranzRail lahar warning gauge lower during the passage of the largest lahar event in the 1995/1996 Ruapehu eruption sequence. The flow depth for this event was about 2.5 m and the bow wave height on the leading edge of the tower appears to be a similar order of magnitude to the depth. The "observational uncertainty" factor added to obtain the maximum credible depth estimates would probably allow for some bow wave action on the upstream side of the rail and road bridge piers.

5.3 PEAK FLOW DEPTHS AT OTHER WHANGAEHU RIVER SITES

Estimated peak flow depths for other Whangaehu River sites for a hypothetical lahar event generated by a future collapse of the Crater Lake outlet barrier are summarised in Table 11 also. These estimates were generally obtained by constructing local MIKE11 hydraulic models for each site using the surveyed channel cross-section data and other supplementary topographic data. Other estimates, particularly within the Whangaehu Gorge and down the multichannel outwash fan, were obtained from the coarse MIKE11 model of the whole Whangaehu River between the Crater Lake outlet and the Karioi hydrological recording station.

Generally, no calibration data were available for these other sites. However, Healy (1954) measured a peak flow depth of 6.7 m at the end of the Whangaehu Gorge for the 1953 lahar event. The coarse MIKE11 model peak flow depth prediction of 6.6 ± 0.4 m at this location (Table 9) compares very well with Healy's observation.

Flow depth for the average peak discharge estimate for a hypothetical future lahar event at the overflow point to the Waikato Stream system below the end of the Whangaehu Gorge is estimated to be 4.0 m (Table 11). Similarly flow depth for the maximum credible discharge estimate for the same event and location is estimated to be 4.5 m. These flow depths result in an estimated overflow of 20-160 m^3/s into the Waikato Stream system (Section 4.2).

Site F is located at the end of the multi-channel outwash fan on a southward bend of the northernmost channel. Aerial photographs after the 1953 lahar event show this channel to have carried the bulk of the flow during the event. This is estimated to have been of the order of 50% of the total flow based on the extent of the debris trail left behind by the event. Using the 1953 event as an analogue for a hypothetical future lahar event, the discharge down the northernmost channel at this location is estimated to be 50 +20/-10% of the total discharge at the bottom end of the outwash fan. This translates to average and maximum peak discharge estimates of 770 m^3/s and 1200 m^3/s, respectively (Table 11).

The flow round the bend at site F will be subject to superelevation effects (where the flow depth on the outside of the bend is higher than on the inside due to radial acceleration acting on the flow). The bend radius is estimated to be of the order of 150 m from the NZMS 260 series topographical plan. The estimated flow depth values given in Table 11 for Site F include the estimated amount of superelevation of the transverse flow surface profile.

5.4 PEAK FLOW DEPTHS AT WAIKATO STREAM SITES

Overflow into the Waikato Stream system from a hypothetical future lahar event is estimated to be of the order of 20-160 m^3/s (Section 4.2). The upper bound overflow value has been taken as the maximum credible discharge down the Waikato Stream system in order to estimate peak flood depths at Sites C and E on the south branch and Sites B and A on the north branch. The path of any overflow event would initially follow the course of the south branch down the outwash fan. The south branch is normally a dry channel. At a point approximately 3.2 km from the initial breakout point from the Whangaehu River, any overflow event could easily break out again into the north branch of the Waikato Stream. Peak flow depth estimates in the south and north branches were, therefore, evaluated for the following scenarios:

(a) overflow event down south branch only,

(b) overflow event down both south and north branches,

(c) overflow event down south branch initially and then breaking out into north branch.

Separate MIKE11 hydraulic models were constructed for each of these scenarios allowing for peak discharge attenuation due to sediment deposition and channel friction effects as outlined in Section 3.4.

SH1 crosses both the south and north branches of the Waikato Stream. Because the south branch is normally dry, there is only a 700 mm diameter culvert under the road (Site E). There is a bridge across the north branch at Site A.

Maximum credible discharge and flow depth estimates for Sites A, B, C and E on the Waikato Stream from the system hydraulic model simulations are summarised in Table 12.

SH1 crosses the south branch (Site E) at a minimum level of 1.65 m above stream bed levels. Under a worst case scenario, the flow depth estimates in Table 12 indicate that SH1 could be overtopped by up to 1.2 m by a lahar overflow from the Whangaehu River below the end of the gorge.

At the north branch crossing (Site A), the bridge waterway under a worst case scenario appears to have enough freeboard to convey the estimated peak discharge with an estimated peak depth of 2.7 m. However, the geometry of the crossing, with the bridge being sited immediately downstream of a sharp 90 degree bend, makes the north abutment particularly vulnerable to scouring (and hence collapse of the bridge) during the passage of a lahar breakout event.

The maximum duration of the breakout event is estimated to be approximately 0.75 hours at both the south branch and north branch crossing points for SH 1.

Table 13 presents estimates of travel time for breakout into the Waikato Stream System for a hypothetical future lahar event down the Whangaehu River. Travel time to the SHI crossing points of the north and south branches of the Waikato Stream is estimated to be of the order of 1 hour from the commencement of failure of the Crater Lake outlet barrier.

6. Conclusions

Based on the results of the revised simulations for the historic 1953 lahar event and a hypothetical lahar event generated by a future collapse of the crater lake outlet barrier, the following conclusions can be drawn:

1. The ice tunnel under the Whangaehu Glacier, through which the 1953 flood event exited into the Whangaehu River, had a significant throttling effect on the peak discharge. The tunnel is anticipated to have been enlarged during the passage of the flood event due to the erosion of the ice walls by the high velocity flow of warm water. The best estimate of ice tunnel average diameter is 4.7 m, giving a peak outflow (water only) of about 250 m^3/s.

2. Bulking of the water flow (by entrainment of sediment) released in the 1953 event down the steep Whangaehu Gorge would have increased the peak discharge at the end of the gorge to about 800 m^3/s.

3. Attenuation of the 1953 event down the multi-channel outwash fan below the Whangaehu Gorge and then down the wide bed of the Whangaehu River would have occurred because of redeposition of sediment (and hence the reduction in sediment concentration by volume) and the effects of channel friction. Peak discharge at Tangiwai Bridge is calculated to have been about 590 m^3/s which matches fairly well the

estimated discharge based on a reanalysis of some slope/area measurements made by Harris (1954) following the 1953 event.

4. The flood event resulting from a future collapse of the Crater Lake outlet barrier (given the 1997 situation) will be unconstrained by any ice tunnel as in the 1953 event because of the disappearance of the Whangaehu Glacier below the outlet. The rate of outflow will be controlled by the rate of breach development. Breach development times in the range 0.25-0.75 hours are expected, based on evidence from data for the historical failure of constructed earthfill embankment dams. This range of breach development times gives peak outflows (water only) of 480-850 m^3/s.

5. Bulking of the water flow (by entrainment of sediment) released down the steep Whangaehu Gorge by a future collapse of the Crater Lake outlet barrier will increase the peak discharge at the end of the gorge to about 1540-2340 m^3/s. Overflows of the order of 50-290 m^3/s and 20-160 m^3/s into the southern "chute" channel and into the Waikato Stream system, respectively, are predicted to occur.

6. Attenuation of the hypothetical lahar event generated by a future collapse of the Crater Lake outlet barrier will occur down the outwash fan below the gorge and down the Whangaehtt River for the same reasons as for the historic 1953 event. Peak discharge at Tangiwai is estimated to be 910" 105 m^3/s, giving an upper bound credible discharge of 1015 m^3/s.

7. The peak discharge at Tangiwai Bridge for a hypothetical future lahar event will be up to 54-72 % larger than that for the historic 1953 event.

8. A hypothetical future lahar event will also travel downstream faster than the historic 1953 event. A travel time to the Tangiwai Bridge of 1.8-2.1 hours is predicted for a future lahar event.

9. At Tangiwai Bridge, a peak depth of 5.8 m is predicted for the average peak discharge estimate for a hypothetical future lahar event and 6.0 m for the maximum credible peak discharge estimate. Application of an "observational uncertainty" factor (which allows for some bow wave action on the upstream side of the bridge piers) increases the maximum credible depth estimate to 7.05 m.

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Table 1. Areas of uncertainty regarding lahar event simulation.

Area of Uncertainty	Comment
breach development time for crater lake barrier	not significant for 1953 event if ice tunnel acted as a throttle very significant for hypothetical future lahar event
ice tunnel diameter	not relevant for future lahar event very significant for 1953 event - lake outflow controlled by narrowest diameter along tunnel length current estimates of tunnel diameter are based on visual observations from photographs of the tunnel outlet after the 1953 event tunnel diameter would have probably increased in size during the course of the 1953 event due to effect of warm lake water melting the ice walls
transformation of water flow into lahar flow/transformation of lahar flow back into hyperconcentrated water flow	very poor understanding of processes at present no theoretical model available simplified approach is most practical one available in view of limited understanding of transformation processes and unavailability of an adequate theoretical model
spatial and temporal variation of sediment concentration by volume of lahar event	sediment concentration values of 0.38 and 0.85 obtained for two reconstituted sediment deposit samples from 1953 event field data from 1995 lahar events is best available guide for hypothetical future lahar events
fluid mechanics behaviour of lahar event	turbulent flow model seems most reasonable model to apply turbulent flow model requires use of channel roughness/friction parameter as energy dissipation parameter
channel roughness (energy dissipation) parameter for lahar event	values based on experience with water flows are best available guide
channel geometry	generic cross-section shapes and dimensions for discrete reaches of Whangaehu River provide reasonable approximation due to steepness of channel slope channel slope determined from standard NZMS 260 series 1:50,000 scale topographic mapping
slope/area measurement of 1953 event at Tangiwai	physical measurements of channel dimensions accurate prediction of peak discharge values using measured channel dimensions requires an assumption of a turbulent flow model and an assumption of a suitable channel roughness (energy dissipation) parameter value choice of channel roughness parameter value based on experience with water flows
flood discharge estimates from rating curves for hydrological gauging sites	conversion of water level data to discharge data implicitly assumes turbulent flow behaviour and that stage/discharge rating curve for water flows is valid also for lahar events. stage/discharge rating for Karioi gauging site requires considerable extrapolation to higher flows as largest gauged flow is only about 65 m^3/s

Table 2. Assumed values for Crater Lake and Crater Lake outlet barrier parameters.

Parameter Volume	Historic 1953 Flood Event	Hypothetical Future Flood Event
Volume of water released (m^3)	1.82×10^6	1.45×10^6
foundation level of outlet barrier (m)	2530	2530
maximum breach depth (m)	8	6.5
maximum breach width (m)	60	60
breach development time (hrs)	0.25-0.75	0.25-0.75

Table 3. Assumed spatial variation of sediment concentrations for lahar simulations.

Location	Sediment Concentration By Volume (%)	Bulking Factor on Original Water Volume
end of Whangaehu Gorge	70	3.3
end of outwash fan	55-60	2.2-2.5
Tangiwai Bridge	45±5	1.8±0.2

Table 4. Assumed Manning's n channel roughness values.

Channel Reach	n value
Whangaehu Gorge	0.150
outwash fan	0.100
southern "chute" channel	0.100
Whangaehu River parallel to Desert Road	0.035-0.040
Whangaehu River below Tangiwai Bridge	0.040

Table 5. Esimates of peak discharge for 1953 lahar event.

Location	Peak Discharge (m^3/s)	Uncertainty (m^3/s)
end of Whangaehu Gorge	805	±180 (22%)
Tangiwai Bridge	590	±110 (19%)

Table 6. Estimates of travel time for 1953 lahar event.

Location	Distance from Crater Lake Outlet (km)	Travel Time (hrs)
end of Whangaehu Gorge	8.8	0.4
Tangiwai Bridge	38.1	2.3

Table 7. Estimates of peak discharge for hypothetical future lahar event.

Location	Peak Discharge (m^3/s)			Uncertainty (m^3/s)
	0.75 hour breach time	0.25 hour breach time	Average	
end of Whangaehu Gorge	1540	2340	1940	±400 (20.6%)
end of outwash fan	1345	1725	1535	±300 (19.5%)
Tangiwai Bridge	890	930	910	±105 (11.5%)

Table 8. Estimates of travel time for hypothetical future lahar event.

Location	Distance from Crater Lake Outlet (km)	Travel Time (hrs)
end of Whangaehu Gorge	8.8	0.35
end of outwash fan	15.5	0.85-1.1
Tangiwai Bridge	38.1	1.8-2.1

Table 9. Peak depths for 1953 lahar event.

Location	Assumed Peak Discharge (m^3/s)	Peak Depth (m)	
		Measured	Model prediction
end of Whangaehu Gorge	805	6.7 (from Healy (1954))	6.6 ± 0.4
slope/area measurement reach	590 ± 110	1.9-2.2 (from Harris (1954))	2.1 ± 0.2
Tangiwai rail bridge	590 ± 110	4.6-5.2 (from Harris (1954)) 6.1 (from Healy (1954))	5.1 ± 0.3

Table 10. Peak depths for 1975 event.

Location	Assumed Peak Discharge (m^3/s)	Peak Depth (m)	
		Estimated	Model prediction
SH 49 road bridge	470 ± 55	3.9 (measured 1998 to tide mark level shown in 1975 photograph)	3.75 ± 0.15

Table 11. Peak discharges and depths for future event in Whangaehu River.

Site	Location	distance from crater lake outlet (km)	average peak discharge estimate (m^3/s)	uncertainty (m^3/s)	maximum credible discharge (m^3/s)	depth for average peak discharge (m)	depth for maximum credible discharge (m)	maximum credible depth** (m)
M	Whangaehu Gorge - overflow point to southern chute channel	6.8	2140	±550	2690	10.4	12.0	
D	below Whangaehu Gorge - overflow point to Waikato Stream system	8.9	1940	±400	2340	4.0	4.5	
F	Whangaehu Fan - southward bend of northern most channel	12.0	770	+430 -230	1200	4.0*	5.15*	
G	Whangaehu River - Wahianoa aqueduct crossing	22.6	1305	±230	1535	7.65	7.85	
K	Whangaehu River - TranzRail lahar warning gauge site	25.7	1215	±165	1380	4.0	4.25	
I	Whangaehu River -Tangiwai rail bridge	38.1	910	±105	1015	5.8	6.0	7.05
H	Whangaehu River - SH49 road bridge	38.4	910	±105	1015	4.0	4.2	4.95
J	Whangaehu River - Strachan's bridge	45.2	645	±72.5	718	5.8	6.7	
L	Whangaehu River - Tirorangi Marae Road bridge	52.2	590	±65	655	5.0	5.9	

*includes allowance for superelevation on outside of bend

**allows for "observational uncertainty" in peak depth measurements at Tangiwai rail bridge for 1953lahar event

Table 12. Peak discharges and depths for future event breaking out into Waikato Stream system (assuming 160 m^3/s maximum overflow).

Site	Location	distance from crater lake outlet (km)	Scenario (a)		Scenario (b)		Scenario (c)	
			maximum credible discharge (m^3/s)	depth for maximum credible discharge (m)	maximum credible discharge (m^3/s)	depth for maximum credible discharge (m)	maximum credible discharge (m^3/s)	depth for maximum credible discharge (m)
C	South Branch - power transmission line crossing point	6.05	80	1.45	29	1.00	-	-
E	South Branch - SH1 crossing	6.8	72	2.85	25	2.35	-	-
B	North Branch - power transmission line crossing point	5.85	-	-	50	2.6	78	3.15
A	North Branch - SH1 crossing	6.9	-	-	48	2.1	75	2.7

Table 13. Estimates of travel time for breakout event into Waikato Stream system.

Site	Location	Distance from Crater Lake Outlet (km)	Travel Time (hrs)		
			Scenario (a)	Scenario (b)	Scenario (c)
C	South Branch Waikato Stream - electricity transmission line crossing point	6.05	1.0	1.1	-
E	South Branch Waikato Stream - SH1 crossing	6.8	1.1	1.2	-
B	North Branch Waikato Stream - electricity transmission line crossing point	5.85	-	0.95	0.95
A	North Branch Waikato Stream - SH1 crossing	6.9	-	1.05	1.05

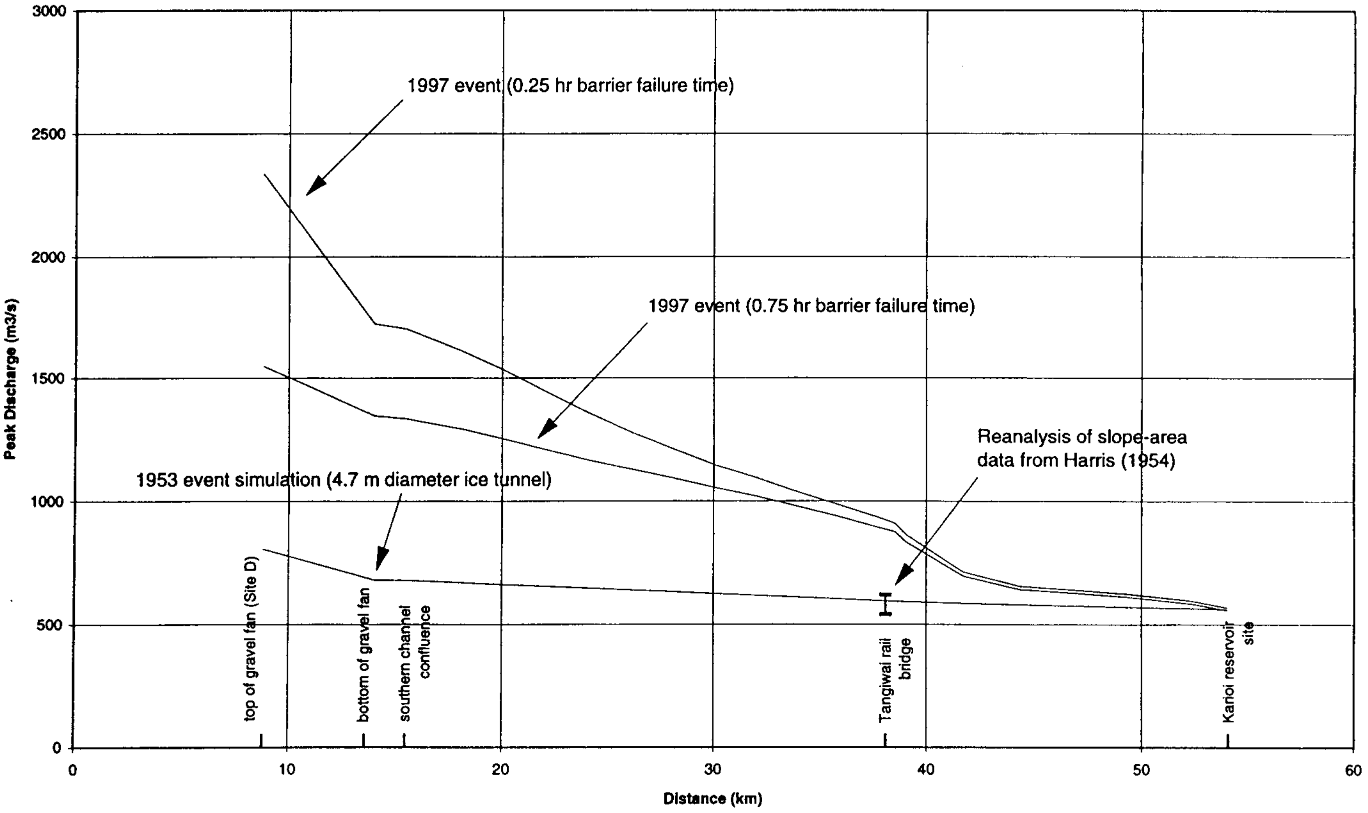

Figure 1. Predicted peak discharge values for different lahar simulations.