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Reconnaissance studies of landslides caused by the M_L 5.4 Lake Rotoehu earthquake and swarm of July 2004

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CONTENTS

ABSTRACT	1
KEYWORDS	1
1. INTRODUCTION	2
1.1 Background	2
1.2 Field response.....	3
1.3 Scope of report	3
2. LOCATION AND REGIONAL SETTING	4
3. EARTHQUAKE DATA.....	7
3.1 Instrumental data	7
3.2 Field observations of earthquake effects.....	7
4. EARTHQUAKE-INDUCED LANDSLIDING AND GROUND DAMAGE	8
4.1 Landsliding and liquefaction effects	8
4.2 Landslide damage to roads	13
4.3 Significance of landsliding and liquefaction	16
5. CONCLUSIONS.....	18
6. REFERENCES	19
7. ACKNOWLEDGEMENTS.....	19
<i>Appendix: MM Intensity Scale (with revised Environmental Criteria 1997).</i>	20



Figures:

page

1.	Map showing the location and seismotectonic setting of the July 2004 Rotoehu earthquake swarm.	4
2.	Map showing location of earthquake swarm and other historical earthquakes.	4
3.	Map showing earthquake epicentres and landslide locations.	5
4-17.	Aerial and ground photos of significant landslides triggered by the earthquake.	9-16
18.	Area/magnitude plot showing the 2004 Rotoehu earthquake in relation to earthquake-induced landslide data in New Zealand and overseas.	17

*Note: Photos included as Figures 4–13 by G T Hancox, 24 July 2004;
Figures 14-16 - photos by M Mc Saveney, 19 July 2004;
Figure 17- photo by G Dellow, 23 July 2004*



ABSTRACT

The Rotoehu earthquake swarm began on 18 July 2004 (NZ Standard Time) with the largest event being a 5 km deep, magnitude 5.4 earthquake centred near Lake Rotoehu ~30 km northeast of Rotorua. From 18–25 July 2004 at least 40 earthquakes occurred in the same area, including another two of M 5, seven of M 4 – M 4.9, and many other smaller events. During the largest (M 5.4 and M 5.0) earthquakes on 18 July 2004 significant landsliding and ground damage occurred over a ~70–300 km² area in and around Lake Rotoehu and Lake Rotoma, with at least 100 landslides triggered. Most of these failures are very small (<10³ m³) to small (10³–10⁴ m³) superficial disrupted soil slides and falls of unconsolidated pyroclastics and tephra deposits around steeper parts of the lake shorelines, and on road cuts greater than 3 m high. No large or deep-seated landslides in rhyolitic lava bedrock occurred during the earthquakes.

The largest landslides observed were extensive but shallow soil slumps and falls of up to ~3000–5000 m³ on steep (45–75°) bush-covered headlands on the western and northern sides of both lakes, within ~10 km of the epicentre of the M 5.4 earthquake. The many landslides that fell into Lake Rotoehu may have caused or at least contributed to the ~600 mm ‘seiche’ (wave) observed around the lake shore. Apart from damaging and temporarily closing some roads in the area, including SH 30, the landslides and cracking and collapses of road edge fills did little significant damage. However, landslides that undermined two power pylons located unnecessarily close to a steep lake-edge cliff at Lake Rotoehu had the potential to disrupt electricity distribution in the area. Only minor liquefaction effects occurred in a few places in highly susceptible fine-grained sediments (saturated fine sands) around the shores of Lake Rotoehu and Lake Rotoma. Observed liquefaction features include a collapsed sand spit in Lake Rotoehu, and an underwater sand flow and sand boils, and ground cracking on the edge of Lake Rotoma. There was also an eye-witness report of a ‘water spout’ on Lake Rotoehu during the M 5.4 earthquake on 18 July 2004.

The area affected by landsliding during the 2004 Rotoehu earthquake fits well against the area/magnitude mean regression line for worldwide earthquake data, but is slightly above that for historical earthquakes in New Zealand. This is probably because slopes in the area were saturated when the 2004 earthquakes occurred, as the same slopes did not fail when shaken at least as strongly during the 1987 Edgecumbe earthquake. That earthquake occurred in summer when the slopes would have been drier and less susceptible to failure. Based on the type, size and number of landslides, and the minor soil liquefaction effects that occurred, the maximum Modified Mercalli (MM) felt intensity in the epicentral area during the two largest (M 5.4 and M 5.0) earthquakes of the swarm is estimated to have been about MM 7. This is generally consistent with the many felt intensity reports of MM 7 and few of MM 8 in the Lake Rotoehu and Lake Rotoma area.

KEYWORDS

Earthquakes, earthquake-induced landsliding, soil slides and falls, liquefaction effects, sand boils, ‘seiche’, MM intensity, Lake Rotoehu, Bay of Plenty, Edgecumbe, New Zealand.



1. INTRODUCTION

1.1 Background

At about 4.22 pm on Sunday 18 July 2004 (NZ Standard Time) an earthquake with a magnitude of M_L 5.4, and ~5 km deep, occurred in the Rotorua lakes area about 30 km northeast of Rotorua. It was the largest of a swarm of at least 40 earthquakes which occurred from about 18–25 July 2004, and also included another two earthquakes of M 5, seven of M 4 – M 4.9, and other smaller events. Most of the earthquakes were shallow (~5 km to < 40 km) and were mainly centred on the western and northern ends of Lake Rotoehu (Figure 1). Earthquake swarms are common in the Taupo Volcanic Zone of the central North Island, but the swarm that began on Sunday 18 July 2004 was bigger than usual (pers. comm. Warwick Smith). The largest event was a shallow (~5 km deep) M_L 5.4 earthquake. Two earthquakes of M_L 5.0 occurred before and after that event (see Table 1).

The Rotorua District Council's website (<http://www.rdc.govt.nz/news>) report that the Rotorua lakes area was shaken daily for at least six days. By Friday 23 July 2004 the area continued to be shaken by small earthquakes of up to M 3.4 – considerably smaller than the series of larger earthquakes (up to M 5.4) on 18 July, causing damage to roads and dwellings. The area had already suffered minor damage after the sustained period of heavy rainfall that affected the Bay of Plenty over the preceding forty eight hours. Rotorua District Council building inspectors were kept busy responding to requests to examine sites where potential safety or health issues were identified. Five homes were classed as uninhabitable, with less serious structural damage to at least 22 other properties, and superficial damage to another four. Council inspectors also checked out six dwellings where ground damage was identified. Many more homes suffered damage to fittings, furniture and other belongings as a result of the earthquakes.

The largest earthquakes on Sunday 18 July 2004 were reported in the news media to have triggered numerous landslides throughout the Rotorua-Rotoehu lakes area. These landslides closed or partly blocking many roads in the area, some of which took several days to reopen, with motorists restricted to a single lane in a number of locations. Several earthquake- triggered slips temporarily or partly blocked SH 30 along the southern shores of Lake Rotoehu and Lake Rotoma. Other local roads that were closed or had traffic reduced to one lane for several days included: Manawahe road; Rotoehu road; Pongakawa Valley road; and the Okataina road. Estimates of up to \$2M to repair damage to roads were reported on the Rotorua District Councils website, but it is uncertain how much of this damage was due to flooding and rain-induced landslides, or resulted from earthquake-induced slope failures.

There were several reports by local residents of landslides being triggered by the Rotorua-Rotoehu earthquake swarm, with slope failures observed on road cuttings and around the shores of Lakes Rotoma and Rotoehu. An eye-witness account from a resident of Otautu Bay at Lake Rotoehu established that landslides occurred during the two larger earthquakes (at around 3.00 pm and ~4.20 pm, Sunday 18/7/04, Dellow *et al.*, 2004).



1.2 Field response

A 'Landslide Rapid Response' was initiated by GeoNet¹ on 19 July 2004, with the objective of deploying a field team on the ground in the area affected by both the earthquake-triggered landslides, and those caused by heavy rainfall mainly in the coastal area of the Eastern Bay of Plenty. Heavy rainfall caused by a stalled weather system from Thursday 15 July to Sunday 18 July resulted in extensive flooding and thousands of landslides throughout the eastern Bay of Plenty. Anecdotal reports of the amount of rainfall indicate the highest intensity was 400 mm in 60 hours in the areas of most intense damage, with 200–250 mm in 60 hours common elsewhere in the Opotiki and Whakatane Districts (Dellow *et al.*, 2004).

Following these events, the GeoNet Project response activities by Geological and Nuclear Sciences staff have included:

- (1) Ground inspection of the landslide damage by Grant Dellow, Mauri McSaveney, and Joy Hoverd - 19–24 July 2004. [*Dellow et al., 2004; McSaveney et al., in prep, 2004*].
- (2) Deployment of portable seismographs (near lakes Rotoiti and Rotoehu) and some landslide observations by Brad Scott and Pilar Villamor - 19 July 2004.
- (3) Active Fault reconnaissance and some landslide observations by Pilar Villamor, Brad Scott, Grant Dellow, Mauri McSaveney - 21 July 2004.
- (4) White Island landslide hazard assessment by Brad Scott, Vern Manville, Mauri McSaveney, and Joy Hoverd - 23 July 2004.
- (5) Oblique aerial photography of earthquake-induced landslides in the Rotorua Lakes area, and rainfall-induced in the Bay of Plenty coastal area by Graham Hancox and Nick Boyens (Victoria University Wellington) on 24 July 2004.

1.3 Scope of report

This report provides a reconnaissance-level description of the types and extent of the landslides triggered by the Rotoehu earthquake swarm of 18–25 July 2003, and some discussion about their effects and significance in the context of earthquake-induced landsliding in New Zealand. The report is based mainly on studies of the oblique aerial photos (taken by G T Hancox) on the 24 July 2004 aerial reconnaissance. Information from ground observations of the landslides and damage effects to roads has also been used.

¹ GeoNet Project is a collaboration between the Earthquake Commission, the Institute of Geological & Nuclear Sciences, and the Foundation for Research, Science & Technology for the monitoring, data collection and rapid response to earthquake, volcano, landslide and tsunami hazards in New Zealand. It is managed by the Hazards Monitoring Section of GNS.



2. LOCATION AND REGIONAL SETTING

The Rotoehu earthquake swarm which began on 18 July 2004 was located within the Taupo Volcanic Zone (TVZ) of the central North Island about 30 km northeast of Rotorua (Figure 1). Shallow earthquakes of moderate size (M 5.0–6.0) are reasonably common within the Taupo Volcanic Zone (see Figure 2) as are earthquake swarms, but the July 2004 swarm was bigger than usual, with at least three earthquakes of magnitude 5 or greater.

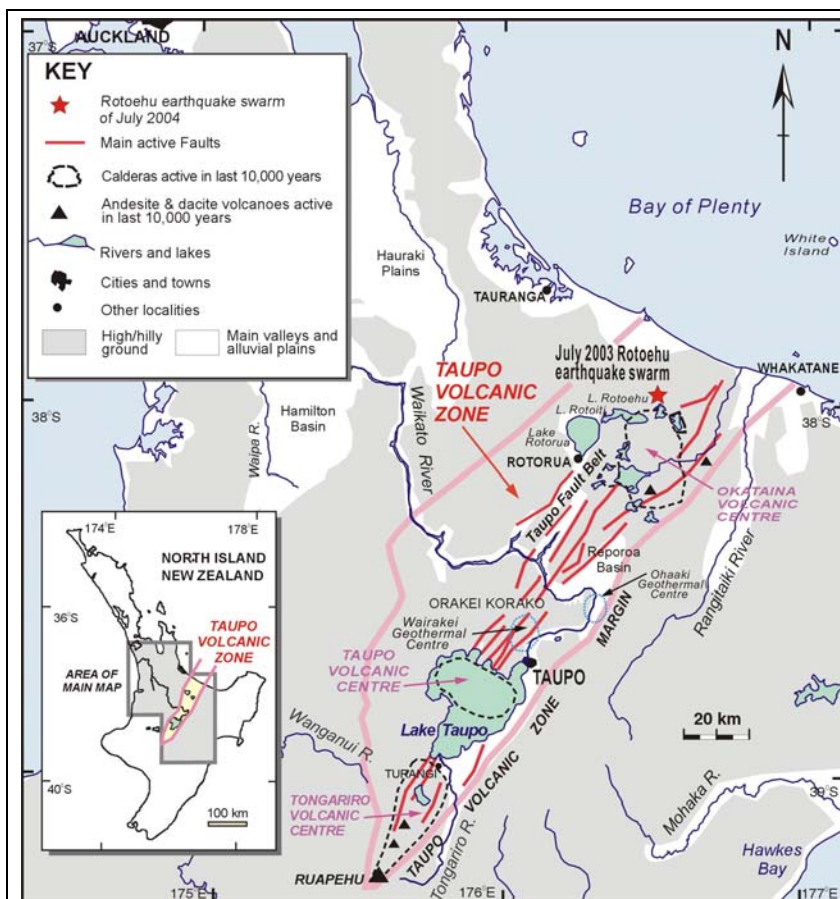


Figure 1. Map showing the location and seismotectonic setting of the July 2004 Rotoehu earthquake swarm, which was located within the Taupo Volcanic Zone of the central North Island, about 30 km northeast of Rotorua.

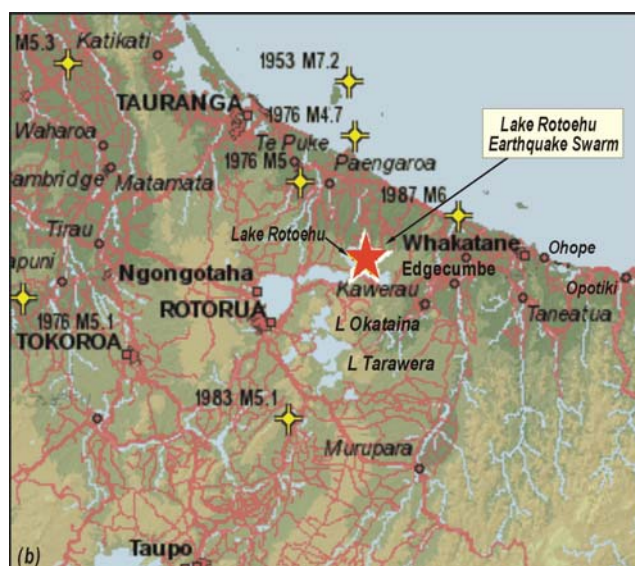
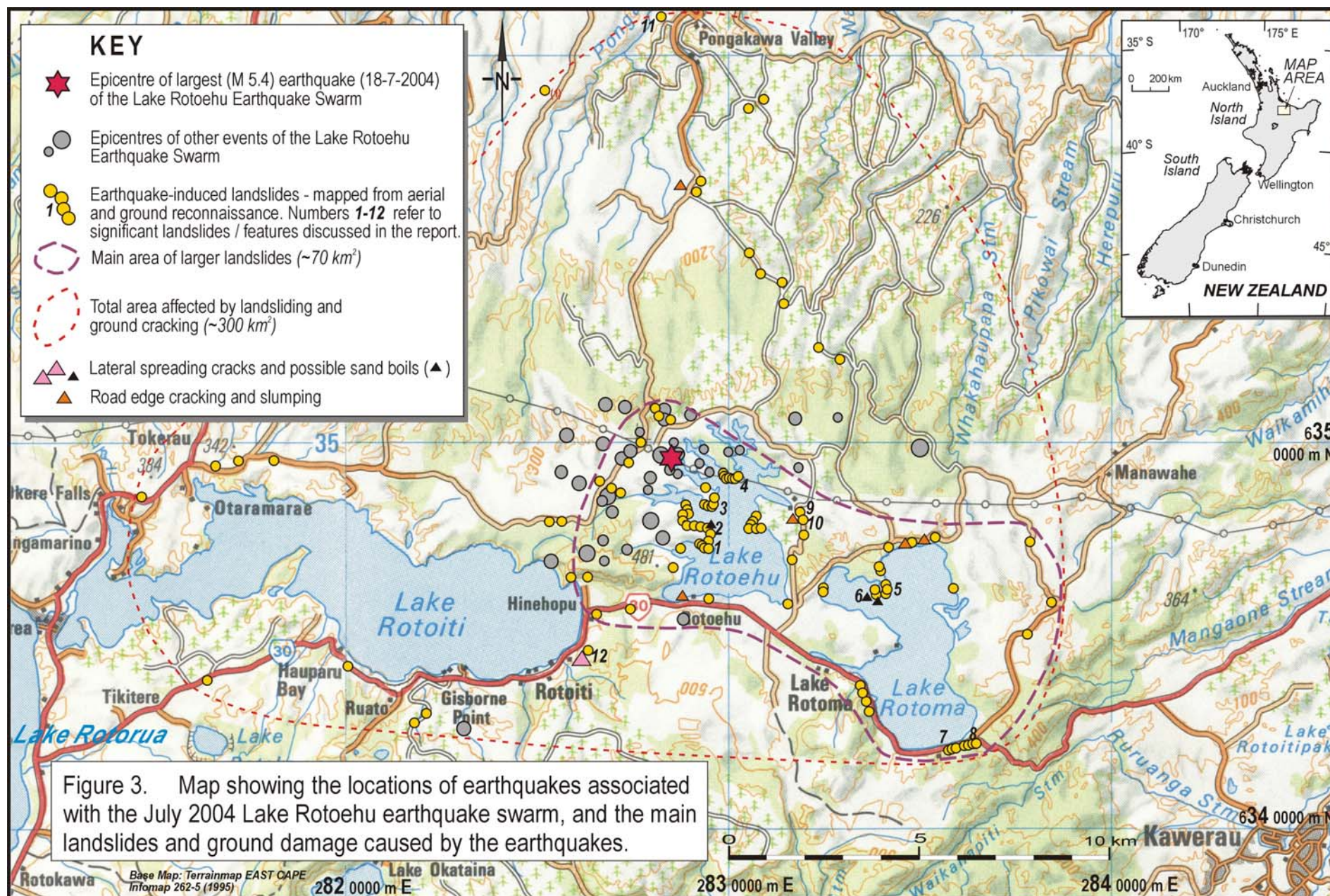


Figure 2. Map showing the location of the Rotoehu earthquake swarm in relation to local features and previous historical earthquakes greater than M 4 (yellow dots), including the M_w 6.6 Edgacumbe earthquake in March 1987.





Lake Rotoehu where the swarm was centred is a shallow lake which has existed for at least 9000 years. It has a surface area of $\sim 9 \text{ km}^2$ and occupies a closed basin formed by erosion of weak, unconsolidated rhyolitic pyroclastic deposits of Pleistocene age ($\sim 30,000$ – $45,000$ years), with its partly drowned shoreline giving the lake a pronounced digitate shape (Nairn, 2002). Lake Rotoma, a deeper and larger lake infilling an old explosion crater about 1 km to the east, is about the same age or older. Figure 3 shows the locations and extent of Lake Rotoehu, Lake Rotoma, and Lake Rotoiti, along with the epicentres of earthquakes recorded during the 2004 earthquake swarm and earthquake-induced landslides.

The western and northern shorelines of Lake Rotoehu are deeply indented with a series of narrow bays separated by grass and forest-covered headlands which rise steeply to flat-topped crests ~ 60 – 70 m above the lake surface (RL ~ 292 m). The topography in the area is gently hilly and rolling, with relief of 50 m to ~ 100 m in places. Slopes around the western and northern lake edge are mostly very steep (~ 45 – 75°), with flatter areas along the southern shoreline adjacent to SH 30 and the low divide between Lake Rotoehu and Lake Rotoma (Figure 3).

Previous moderately large ($M_5 - M_6$) earthquakes in the Taupo Volcanic Zone over the last 100 years have caused only minor to moderate landsliding and ground damage. For example, the 1922 Kaiapo earthquake swarm (largest earthquake $M_s 5.1$) was associated with regional subsidence of the central Taupo Fault Belt of 3–4 m, and local displacements of at least 0.8 m, and possibly up to 3 m on bounding faults (Grindley and Hull, 1986). The largest earthquake was reported to have caused ‘smallish’ debris slides on the white (pumice) cliffs at Hatepe, and also lake edge cliff collapses at Whakaipo Bay and Wairakei, indicating a shaking intensity of possibly MM 6 or MM 7. The 1983 Waiotapu earthquake ($M_L 5.1$) is reported to have produced intensities of MM 7 – MM 8 in the epicentral region near Waiotapu, based on damage to road edge fills, dislodgement of boulders up to 2 m in diameter from road cuttings on SH 5, and a landslide on the steep western face of Mount Paeroa (Smith *et al.*, 1984; Downes, 1995). Such relatively minor landslide damage has subsequently been considered to be more representative of MM 6–7 shaking rather than MM 7–8 (Hancox *et al.*, 1997).

Historically, the most significant earthquake-induced landsliding in the region was caused by the $M_w 6.6$ Edgecumbe earthquake on 2 March 1987, which was associated with up to 2.5 m ground surface faulting (Anderson & Webb, 1989; Smith & Oppenheimer, 1989). This earthquake (located ~ 25 km east-northeast of the 2004 Rotoehu swarm) caused moderate landsliding and ground damage over about 250 – 600 km^2 on hills and road cuts bordering the Rangitaiki Plains, in the MM 7–9 area within 10–20 km of the epicentre. However, no landsliding was observed around the shores of Lake Rotoehu, where the shaking intensity was inferred to have been \sim MM 7 (Franks *et al.*, 1989; Hancox *et al.*, 1997).

Initial reports immediately following the largest events of 18 July 2004 earthquake swarm suggested that the landsliding associated with it was more extensive than had occurred during previous earthquakes, apart from the much (~ 30 times) larger 1987 Edgecumbe earthquake. The event therefore warranted a field response by GeoNet to look for surface faulting and examine the landslides. This response was initially undertaken along roads by Brad Scott and Pilar Villamor, but as many of the landslides were in inaccessible areas around the steep shores of Lake Rotoehu the landslides were best observed and photographed from the air.



3. EARTHQUAKE DATA

3.1 Instrumental data

The Rotoehu earthquake swarm began on 18 July 2004 with an M 3.8 event at 3:09 pm, with the largest earthquake of M 5.4 occurring at 4.22 pm (NZ Standard Time). The earthquakes continued spasmodically until 25 July 2004, and included two more events of M 5.0, seven of M 4.0 – M4.9, and many smaller events. Data on the main earthquakes recorded by GeoNet during the swarm are summarised in Table 1 and their locations are shown in Figure 3.

Reference Number	NZ Standard Time	Magnitude (M _L)	Focal Depth (km)	Location
2266205/G	18 July 2004, 3:09 p.m.	3.8	5 km	20 km north-west of Kawerau (38.01°S, 176.52°E)
2266230/G	18 July 2004, 3:57 p.m.	4.1	5 km	20 km east of Rotorua (38.07°S, 176.45°E)
2266782/G	18 July 2004, 3:58 p.m.	5.0	5 km	20 km north-west of Kawerau (38.01°S, 176.50°E)
2266243/G	18 July 2004, 4:22 p.m.	4.6	5 km	20 km north-west of Kawerau (37.99°S, 176.50°E)
2266243/G:	18 July 2004, 4:22 p.m.	5.4	5 km	20 km north-west of Kawerau (38.00°S, 176.53°E)
2266266/G	18 July 2004, 5:02 p.m.	4.0	5 km	20 km west of Kawerau (38.03°S, 176.49°E)
2266267/G	18 July 2004, 5:03 p.m.	4.0	5 km	10 km north-west of Kawerau (38.02°S, 176.60°E)
2266316/G	18 July 2004, 6:40 p.m.	5.0	5 km	20 km north-west of Kawerau (37.97°S, 176.54°E)
2266494/G	19 July 2004, 12:42 a.m.	3.3	5 km	20 km north-west of Kawerau (38.00°S, 176.48°E)
2266683/G	19 July 2004, 8:45 a.m.	3.6	5 km	20 km north-west of Kawerau (37.99°S, 176.49°E)
2268668/G	23 July 2004, 5:18 a.m.	3.4	5 km	20 km north-west of Kawerau (38.00°S, 176.50°E)
2269629/G	25 July 2004, 6:25 a.m.	3.9	5 km	20 km north-west of Kawerau (37.99°S, 176.50°E)

Table 1. Main earthquakes of the July 2004 Rotoehu earthquake swarm (*source GeoNet*).

3.2 Field observations of earthquake effects

In the immediate post-earthquake inspection carried out by Pilar Villamor and Brad Scott on 21 July 2004, no features were found that could be related to surface fault rupture or secondary fault movement. The observed ground cracking and damage along roads was attributed to collapse and spreading of road embankment fills, except in one case where a large section of the road and hillside slumped ~50 mm. Known active fault traces in the area were inspected (in road cut along Porter Road, 6 km east of Lake Rotoehu) but they showed no signs of fault movement. Other earthquake-related field effects observed in the epicentral area included a ‘seiching wave’ of up to 600 mm high and 8–10 m back from the lake shore at Otautu Bay on the east side of Lake Rotoehu. Landsliding into the lake may have contributed to the wave. Brad Scott also recorded an eye-witness account of a ‘*water spout*’, probably a liquefaction effect, on Lake Rotoehu during the M 5.4 earthquake, but found no ground evidence of liquefaction (e.g., sand boils, or lateral spreading fissuring and sand ejections).



4. EARTHQUAKE-INDUCED LANDSLIDING AND GROUND DAMAGE

4.1 Landsliding and liquefaction effects

Landsliding and ground damage effects of the July 2004 Rotoehu earthquake swarm were widely reported in the news media. On the ground landslides were observed in the distance around the shores of Lake Rotoehu and Rotoma, and on road cuttings, where the landslide debris was noted to be sandy and relatively dry, compared with the wet and muddy debris from the rainfall-generated slides in coastal parts of eastern Bay of Plenty (Dellow *et al.*, 2004). An eye-witness account from a resident at Otautu Bay clearly established that landslides occurred during at least the two larger earthquakes that occurred around 3 pm and 4.20 pm on Sunday 18 July (Dellow *et al.*, 2004). Most slope failures observed on the ground appeared to have affected steep ($>70^\circ$) road cuts greater than 3 m high on the southern side of Lake Rotoehu, with no failures seen on steep slopes in native bush or areas of pine forest.

Aerial reconnaissance allowed the main landslides around the shores of Lake Rotoehu and Rotoma to be located and the extent of landsliding to be determined more accurately. The main area affected by larger landslides covers about 70 km², centred mainly on the northern and western sides of Lake Rotoehu. The total area affected by earthquake-induced landsliding was about 200–300 km², with at least 100 landslides mapped so far (Figure 3). The largest landslides (all are small in accepted terminology* - Hancox *et al.*, 1997; 2002; INQUA, 2003) occur on steep headlands around the lake shores (numbered slides in Figure 3). These are illustrated by photos taken on the aerial reconnaissance (Figures 4–13). One of the largest slides (Slide 1, in Figures 3 and 4) was an extensive soil slump and fall of ~3000–5000 m³ on a steep (45–65°) scrub-covered slope at the south end of Waipuia Point near Maraua Pa on the western side of Lake Rotoehu (Figure 5). The sand spit at the northern end of the Waipuia point (2, Figure 3) also subsided within the lake, associated with what appears to be liquefaction-induced sand ejection ('boil') and cracking (Figure 4). Another extensive soil fall occurred on a very steep (~75°) bush-covered slope at the south end of Okahu Point (Slide 3 in Figure 3; Figure 6), while a number of similar falls occurred on a point ~700 m to the north (Slide 4 in Figure 3), undermining and threatening the foundations of two power pylons located unnecessarily close to the edge of a steep lake-edge cliff (Figures 7 and 8).

Similar but fewer landslides occurred around the northern shore line of Lake Rotoma, with the largest example being a ~4000–5000 m³ soil slump into the lake at the southern end of Otunarokura Point (Figures 9 and 10). Another similar failure occurred on the point ~300 m to the west (Slide 6 in Figure 3), in this case accompanied by a sub-aqueous sand flow and small underwater sand boils which provide evidence of minor liquefaction effects in highly susceptible fine-grained lake shore sediments (Figure 11). These liquefaction features are consistent with an eye-witness observation of a liquefaction-induced 'water spout' on Lake Rotoehu during the largest (M 5.4) earthquake.

*Terms used to describe size (m³) of earthquake induced landslides (Hancox *et al.*, 1997; 2002; INQUA, 2003) as follows:
Very small - $<10^3$; Small - 10^3 – 10^4 ; Moderate - 10^4 – 10^5 ; Large - 10^5 – 10^6 ; Very large - 1 – 50×10^6 ; Extremely large - $>50 \times 10^6$.



Figure 4. Aerial view of several moderately large 'soil' slumps and falls on steep slopes of Waipuia Point, near Maraua Pa (pa) site on the western side of Lake Rotoehu. It also shows a collapse area with sand ejections and cracking (due to liquefaction) at the end of the sand spit (sp). [Photo: GH-BOP0725]

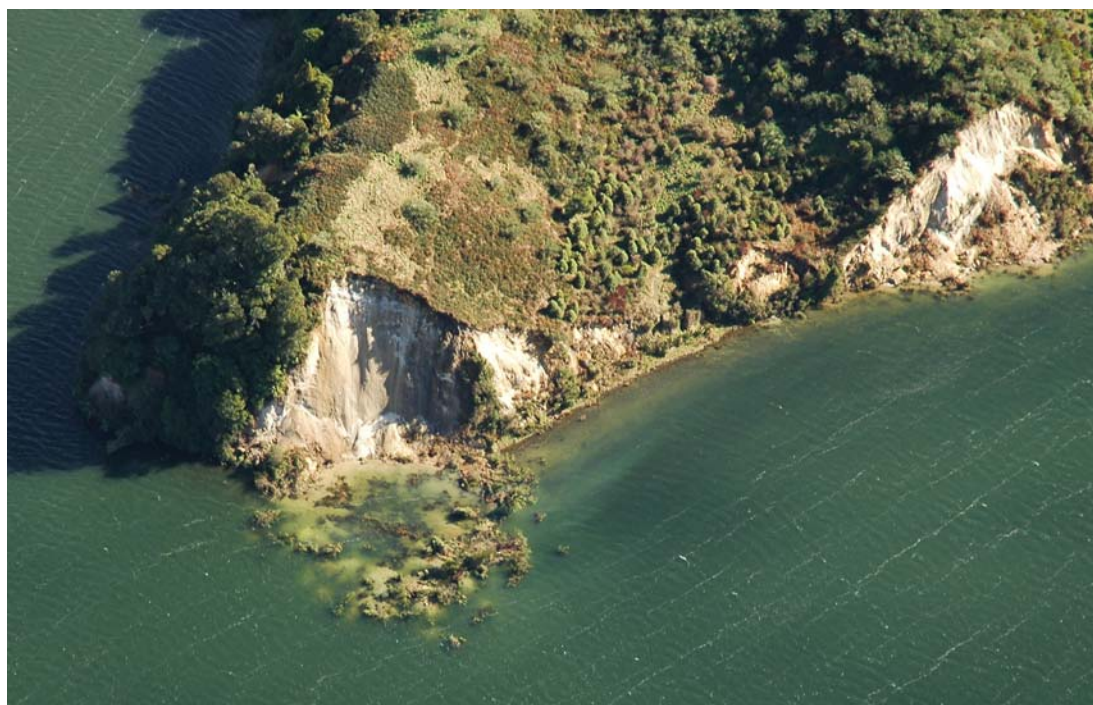


Figure 5. Aerial view of moderately large (~3000-5000 m³) soil slump (Slide 1, Figure 3) from steep ~25 m high slope in weak, unconsolidated rhyolitic pyroclastic deposits ~400 m south of the Maraua Pa site shown in Figure 4. The landslide is about 60 m wide and 25 m high and the slide debris has travelled at least 50 m out into the shallow lake. [Photo: GH-BOP0718]

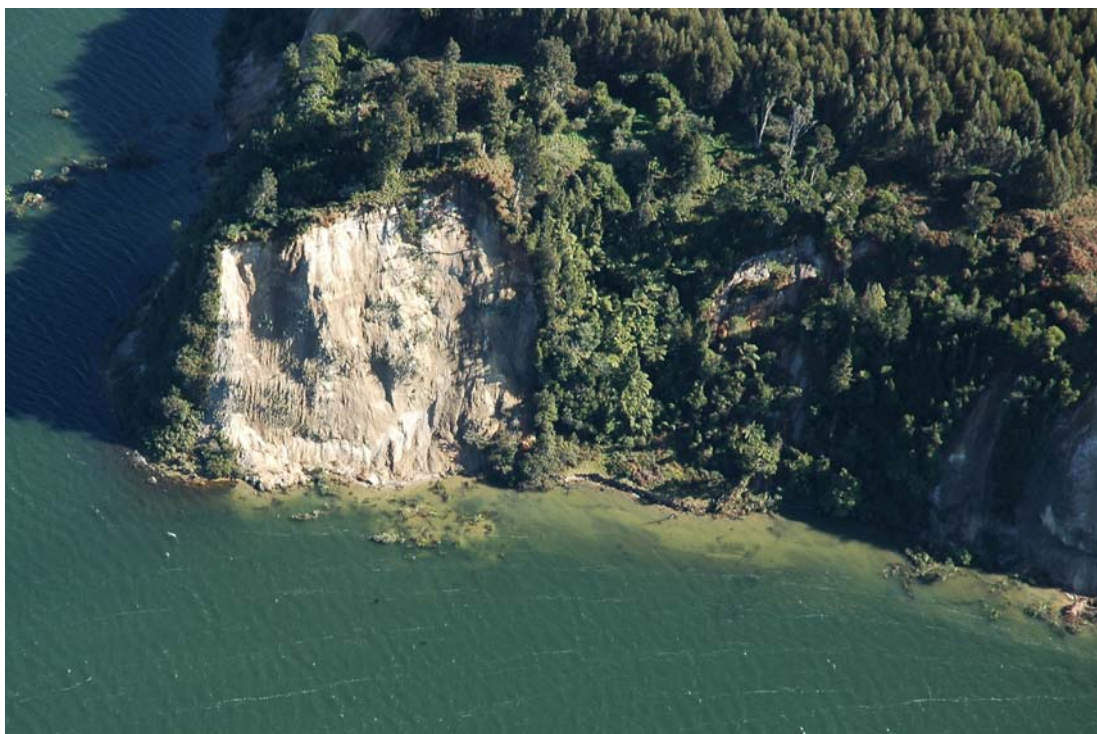


Figure 6. Extensive (~45 m high x 100 m wide) but superficial soil fall on a very steep (~75°) bush-covered slope at the south end of Okahu Point on the western side of Lake Rotoehu (Slide 3 in Figure 3).
[Photo: GH-BOP0715].



Figure 7. Moderate size (~50 m high x 20 m wide) soil fall from this steep bush-covered slope threatens a power pylon on a major transmission line at the northern end of Lake Rotoehu (Slide 4 in Figure 3). The pylon is clearly located unnecessarily close to edge of the steep cliff edge.
[Photo: GH-BOP0714]



Figure 8. More distant view of power pylons threatened by several large soil slides on steep bush-covered slope at the northern end of Lake Rotoehu.

Photo: GH-BOP0924]



Figure 9. Aerial view of some of the large soil falls and slumps on Otunarakura Point at the northwest corner of Lake Rotoma (Slide 5 in Figure 3 bottom left). The scale in the foreground shows the approximate size of these landslides. In the distance the numerous landslides scarring steep headlands on the western shoreline of Lake Rotoehu can also be seen (top right). Note that the landsliding is restricted to very steep slopes around lake edges (whether or not they were bush-covered) and local road cuts, with few if any failures on other slopes in the area.

[Photo: GH-BOP0739]

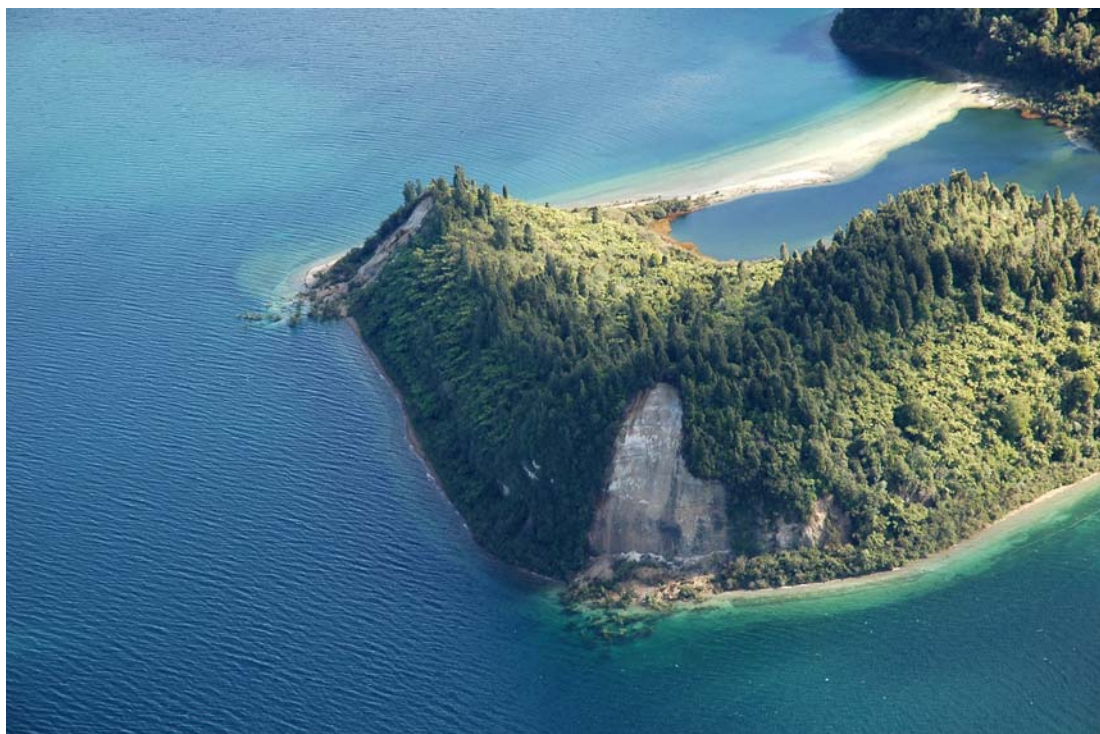


Figure 10. Closer view of the large ($4000\text{--}5000\text{ m}^3$) soil slump on steep, 40 m high bush-clad lake shore on Otunarokura Point (west side of Lake Rotoma - Slide 5 in Figure 3). *[Photo: GH-BOP0740]*



Figure 11. Moderately large soil slide and sub-aqueous sand flow with small sand boils in shallow water on the southwest end of Otunarokura Point (Slide 6 in Figure 3). The underwater sand boils (*sb*) are minor liquefaction effects in fine-grained, highly susceptible lake shore sediments. There is also some cracking around the lake edge just above water level (*left, c*). *[Photo: GH-BOP0734]*



4.2 Landslide damage to roads

The aerial reconnaissance also showed the after-effects of several significant landslides road cut along SH 30 on the south side of Lake Rotoma, as shown in Figures 12 and 13. These failures, which were mainly shallow soils slides of ash and regolith sliding off harder rhyolitic lavas, partly blocked the road for a day or so. Other ground damage and landslides affecting roads are shown in Figures 14–16. Most of the failures observed were disrupted soils falls and slides of relatively dry sandy debris (Figures 14 and 16). Ground cracking on the Pongakawa Valley Road ~1 km east of Lake Rotoehu (Slide 10 in Figure 3 was associated with an incipient failure of the largest (~10,000 m³) earthquake-induced landslide observed (Figure 15).

Several smaller (1,000-5,000 m³) landslides blocked SH30 at several places between the SH33 turnoff at Te Ngae on the eastern shore of Lake Rotorua and the SH34 (Kawerau west) turnoff. Within 24 hours of the earthquake traffic was moving again, albeit reduced to a single lane in places. SH33 had some very small soil falls (<10 m³) near Okere. The worst affected of the local roads was the Manawahe Road on the north side of Lake Rotoma which lost parts of the road in under-slips. This was the only road that was closed for several days. Other roads that were blocked by landslides (often reduced to a single lane 24 hours later) included Maniatutu Road, Rotoehu Road as far as Pongakawa Valley, Lake Okataina Road and the Pongakawa Valley Road. Forestry roads southeast of Pongakawa Valley were also slightly affected.



Figure 12. Shallow regolith failure which temporarily blocked SH 30 at the southern end of Lake Rotoma (Slide 7 in Figure 3), but had been cleared when this photo was taken. *[Photo: GH-BOP0742]*



Figure 13. Other shallow regolith failures at the south end of Lake Rotoma (Slide 8 in Figure 3) which partly blocked SH 30 but were quickly cleared. *[Photo: GH-BOP0743]*



Figure 14. Typical disrupted soil fall on Pongakawa Valley Road just east of Lake Rotoehu (Slide 9 in Figure 3). This landslide was reported by local residents to have occurred during the largest earthquake (M 5.4 at 4.22pm on 18 July 2004) while they were walking past. Note the relatively dry nature of the sandy landslide debris. *[Photo: M.J. McSaveney, 19/7/04]*



Figure 15. Ground cracking on the Pongakawa Valley Road ~1 km east of Lake Rotoehu (Slide 10 in Figure 3). The crack in the foreground crossing the road can be traced across a low spur to re-cross the road several metres past the vehicle. This incipient landslide was the largest observed landslide caused by the earthquake ($\sim 10,000 \text{ m}^3$). [Photo: M.J. McSaveney, 19/7/04]



Figure 16. Disrupted soil slide affecting a farm track near the Pongakawa Valley village (Slide 11 in Figure 3). This landslide, on a slope predisposed to failure by the cutting of the track, was one of the few observed on farmland. Note the relatively dry nature of the debris. [Photo: M.J. McSaveney, 19/7/04]



Figure 17. Ground cracking observed in a sidling fill for a track to water reservoirs above Lake Rotoiti village (Feature 12 in Figure 3). Cracking in sidling fills was observed along this track for a distance of 200-300 m *Photo: G Dellow, 23/7/04].*

4.3 Significance of landsliding and liquefaction

As already discussed, the July 2004 Rotoehu earthquake and swarm caused numerous landslides over a wide area. The main landslides occurred over a $\sim 70 \text{ km}^2$ area in and around Lake Rotoehu and Lake Rotoma, while the total area affected by earthquake-induced landsliding covered approximately $200\text{--}300 \text{ km}^2$ (Figure 3).

When plotted on an area/magnitude graph (Figure 14) the main and total areas affected by landsliding during the 2004 Rotoehu earthquake fit well against the mean regression line for worldwide earthquake data, but are slightly above the mean regression line for historical earthquakes in New Zealand (Hancox *et al.*, 2002), especially the 1987 Edgecumbe earthquake. This is thought to reflect the higher susceptibility of slopes in the Rotorua Lakes area to landsliding in July 2004 because of the very heavy rainfall over the preceding two days. Slopes around the shoreline of Lake Rotoehu and Lake Rotoma did not fail during the March 1987 Edgecumbe earthquake (MM 7 at Lake Rotoehu and MM 8 at Lake Rotoma), which occurred in summer when the slopes would have been much drier.

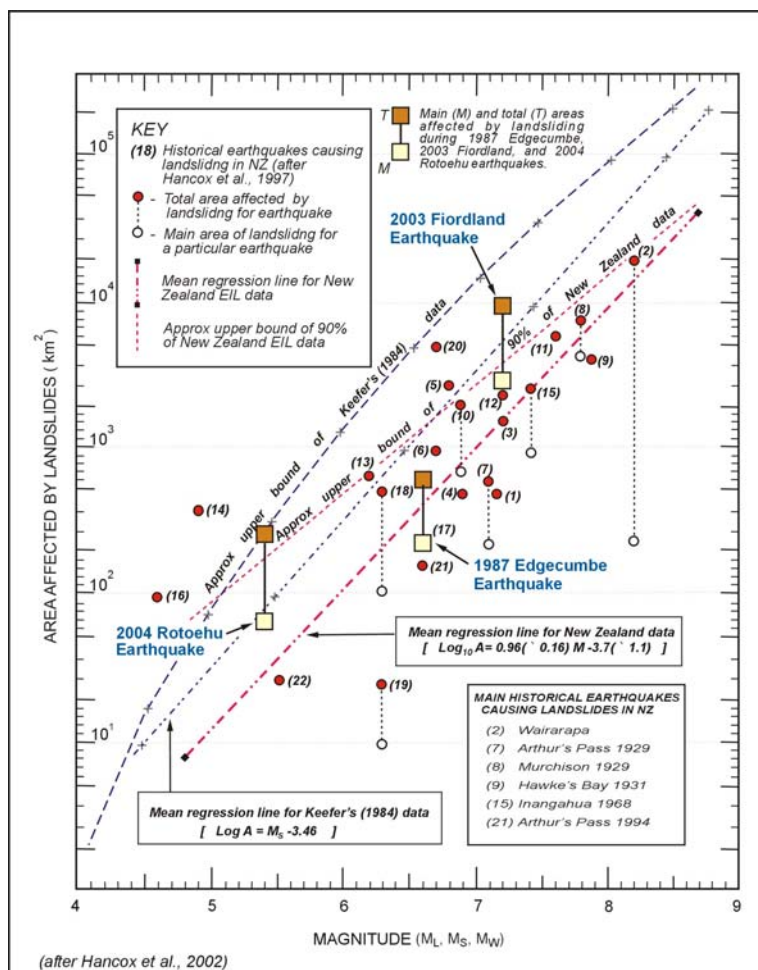


Figure 18. Plot showing relationship of the main and total areas affected by landslides during the 2004 Rotoehu earthquake swarm, here compared to the 2003 Fiordland earthquake, the 1987 Edgecumbe earthquake (the largest historical earthquake in the Bay of Plenty area), and other historical earthquakes of different magnitude in New Zealand (Hancox *et al.*, 2002) and overseas (Keefer 1984).

It was notable that the landslides interpreted to be earthquake-induced (and supported by eye-witness accounts) were restricted to very steep slopes around the lake shorelines, whether or not they were bush-covered, and steep road cuts higher than 3 m. There were few if any significant failures on other slopes in the area (Figure 9). No wet and highly mobile soil and debris flows were observed in the earthquake area that could be attributed with certainty to the heavy rainfall that preceded the earthquake swarm. In general the earthquake-induced failures were all much drier failures, typically located on very steep (oversteepened) natural and man-made slopes.

The intensity of earthquake shaking can be estimated indirectly from environmental effects, including the type, size and number of landslides produced, and the extent of the area over which landslides occur (Keefer, 1984; Hancox *et al.*, 1997, 2002; Crozier *et al.*, 1995; INQUA, 2003). Based on the superficial and relatively small-scale nature of the landsliding, and the minor liquefaction effects that occurred during the two largest (M 5.4 and M 5.0) earthquakes, the maximum Modified Mercalli (MM) felt intensity in the epicentral area during these events is estimated to have been about MM 7 (*see Appendix*). This is generally consistent with many felt intensity reports of MM 7 and few of MM 8 in the Lake Rotoma area (GNS Online felt reports database). There was one felt report of MM 10 but it is regarded as anomalous. It is not supported by other felt reports, or by the general level and extent of the landslide damage.



5. CONCLUSIONS

- (1) Significant landsliding and ground damage occurred during the largest (M 5.4 and M 5.0) events of the July 2004 Rotoehu earthquake swarm, over a ~70–300 km² area in and around Lake Rotoehu and Lake Rotoma, with at least 100 landslides triggered. Most of these failures are very small (<10³ m³) to small (10³–10⁴ m³) superficial disrupted soils slides and falls of unconsolidated pyroclastics and tephra deposits around steeper parts of the lake shorelines, and on steep road cuts greater than 3 m high. No large or deep seated landslides in rhyolitic lava bedrock occurred during the earthquakes.
- (2) The largest landslides observed were extensive but shallow soil slumps and falls of up to ~3000–5000 m³ on steep (45–75°) bush-covered headlands on the western and northern sides of both lakes within ~10 km of the epicentre of the M 5.4 earthquake. The many landslides that fell into Lake Rotoehu may have caused or contributed to the ~600 mm ‘seiche’ (wave) observed 8–10 m back from the lake shore. Apart from damaging and temporarily closing some roads in the area including SH 30, the landslides and minor cracking and collapses of road edge fills did little real damage. However landslides that undermined two power pylons two power pylons located unnecessarily close to a steep lake-edge cliff at Lake Rotoehu had the potential to disrupt electricity supply in the area.
- (3) A collapsed sand spit in Lake Rotoehu and underwater sand flow and small sand boils with cracking in one location on the edge of Lake Rotoma suggest that small-scale soil liquefaction occurred in a few places in highly susceptible fine-grained lakeshore sediments (saturated fine sands). These minor liquefaction features are consistent with an eye-witness observation of a ‘*water spout*’ on Lake Rotoehu during the largest M 5.4 earthquake.
- (4) The area affected by landsliding during the 2004 Rotoehu earthquake fits well against the area/magnitude mean regression line for worldwide earthquake data, but is slightly above that for historical earthquakes in New Zealand. This is probably because slopes in the area were saturated when the 2004 earthquakes occurred, as they did not fail when shaken at least as strongly during the 1987 Edgecumbe earthquake, which occurred in summer when the slopes would have been drier and less susceptible to failure.
- (5) Based on the type, size and number of landslides and liquefaction effects that occurred during the maximum Modified Mercalli (MM) felt intensity in the epicentral area during the two largest (M 5.4 and M 5.0) earthquakes of the swarm is estimated to have been about MM 7. This is generally consistent with the many felt intensity reports of MM 7 and few of MM 8 in the Lake Rotoehu and Lake Rotoma area.



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Appendix

Environmental criteria for the N Z Modified Mercalli Intensity Scale

MODIFIED MERCALLI INTENSITY SCALE - N Z 1996 (<i>Dowrick, 1996</i>) <i>1996 Environmental Criteria</i>	REVISED MODIFIED MERCALLI INTENSITY SCALE – N Z 1997 (<i>Hancox et al., 1997</i>) ¹¹ <i>Proposed Environmental Criteria</i>
<p>MM6 Trees and bushes shake, or are heard to rustle. Loose material may be dislodged from sloping ground, e. g. existing slides, talus slopes, shingle slides.</p>	<p>MM6 Trees and bushes shake, or are heard to rustle. Loose material dislodged on some slopes, e.g. existing slides, talus and scree slope.</p> <p>A few very small (10^3 m^3) soil and regolith slides and rock falls from steep banks and cuts.</p> <p>A few minor cases of liquefaction (sand boil) in highly susceptible alluvial and estuarine deposits.</p>
<p>MM7 Water made turbid by stirred up mud.</p> <p>Small slides such as falls of sand and gravel banks, and small rock falls from steep slopes and cuttings. Instances of settlement of unconsolidated or wet or weak soils.</p> <p>Some⁽¹⁾ fine cracks appear in sloping ground. A few¹ cases of liquefaction (e.g. small water & sand ejections).</p>	<p>MM7 Water made turbid by stirred up mud.</p> <p>Very small (10^3 m^3)⁽⁴⁾ disrupted soil slides and falls of sand and gravel banks, and small rock falls from steep slopes and cuttings are common.</p> <p>Fine cracking on some slopes and ridge crests.</p> <p>A few small to moderate landslides (10^3–10^5 m^3), mainly rock falls on steeper slopes ($>30^\circ$) such as gorges, coastal cliffs, road cuts and excavations.</p> <p>Small discontinuous areas of minor shallow sliding and mobilisation of scree slopes in places.</p> <p>Minor to widespread small failures in road cuts in more susceptible materials.</p> <p>A few instances of non-damaging liquefaction (small water and sand ejections) in alluvium.</p>
<p>MM8 Cracks appear on steep slopes and in wet ground.</p> <p>Small to moderate slides in roadside cuttings and unsupported excavations.</p> <p>Small water and sand ejections, and localised lateral spreading adjacent to streams, canals, and lakes etc.</p>	<p>MM8 Cracks appear on steep slopes and in wet ground.</p> <p>Significant landsliding likely in susceptible areas.</p> <p>Small to moderate (10^3–10^5 m^3) slides widespread; many rock and disrupted soil falls on steeper slopes (steep banks, terrace edges, gorges, cliffs, cuts etc). Significant areas of shallow regolith landsliding, and some reactivation of scree slopes.</p> <p>A few large (10^5–10^6 m^3)⁽⁴⁾ landslides from coastal cliffs, and possibly large to very large (10^6 m^3) rock slides and avalanches from steep mountain slopes.</p> <p>Larger landslides in narrow valleys may form small temporary landslide-dammed lakes.</p> <p>Roads damaged and blocked by small to moderate failures of cuts and slumping of road-edge fills.</p> <p>Evidence of soil liquefaction common, with small sand boils and water ejections in alluvium, and localised lateral spreading (fissuring, sand and water ejections) and settlements along banks of rivers, lakes, and canals etc.</p>
<p>NOTES:</p> <p>(1) "Some or 'a few' indicates that threshold for a particular effect or response has just been reached at that intensity.</p> <p>(2) Intensity is principally a measure of damage. Environmental damage (response criteria) occurs mainly on susceptible slopes, and in certain materials, hence the effects described above may not occur in all places, but can be used to reflect the average or predominant level of damage (or MM intensity) in a given area.</p> <p style="text-align: right;">[Page 1 of 2]</p>	



Appendix continued:

<p>MODIFIED MERCALLI INTENSITY SCALE - N Z 1996 (Dowrick, 1996) 1996 Environmental Criteria</p>	<p>REVISED MODIFIED MERCALLI INTENSITY SCALE - N Z 1997 (Hancox et al., 1997)¹¹ Proposed Environmental Criteria</p>
<p>MM9 Cracking on ground conspicuous. Landsliding general on steep slopes. Liquefaction effects intensified and more widespread, with large lateral spreading and flow sliding adjacent to streams, canals, and lakes etc.</p>	<p>MM9 Cracking on flat and sloping ground conspicuous. Landsliding widespread and damaging in susceptible terrain, particularly on slopes steeper than 20°. Extensive areas of shallow regolith failures and many rock falls and disrupted rock and soil slides on moderate and steep slopes (20-35° or greater), cliffs, escarpments, gorges, and man-made cuts. Many small to large (10³-10⁶ m³) failures of regolith and bedrock, and some very large landslides (10⁶ m³ or greater) on steep susceptible slopes. Very large failures on coastal cliffs and low-angle bedding planes in Tertiary rocks. Large rock/debris avalanches on steep mountain slopes in well-jointed greywacke and granitic rocks. Landslide-dammed lakes formed by large landslides in narrow valleys. Damage to road and rail infrastructure widespread with moderate to large failures of road cuts slumping of road-edge fills. Small to large cut slope failures and rock falls in open mines and quarries. Liquefaction effects widespread with numerous sand boils and water ejections on alluvial plains, and extensive, potentially damaging lateral spreading (fissuring and sand ejections) along banks of rivers, lakes, canals etc). Spreading and settlements of river stop banks likely.</p>
<p>MM10 Landsliding very widespread in susceptible terrain, with very large rock masses displaced on steep slopes. Landslide dammed lakes may be formed. Liquefaction effects widespread and severe.</p>	<p>MM10 Landsliding very widespread in susceptible terrain⁽³⁾. Similar effects to MM9, but more intensive and severe, with very large rock masses displaced on steep mountain slopes and coastal cliffs. Landslide-dammed lakes formed. Many moderate to large failures of road and rail cuts and slumping of road-edge fills and embankments may cause great damage and closure of roads and railway lines. Liquefaction effects (as for MM9) widespread and severe. Lateral spreading and slumping may cause rents over large areas, causing extensive damage, particularly along river banks, and affecting bridges, wharfs, port facilities, and road and rail embankments on swampy, alluvial or estuarine areas.</p>
<p>NOTES:</p> <p>(1) "Some or 'a few' indicates that the threshold for a particular effect or response has just been reached at that intensity.</p> <p>(2) Intensity is principally a measure of damage. Environmental damage (response criteria) occurs mainly on susceptible slopes and in certain materials, hence the effects described above may not occur in all places, but can be used to reflect the average or predominant level of damage (or MM intensity) in a given area.</p> <p>(3) Environmental response criteria have not been suggested for MM11 and MM12, as those levels of shaking have not been reported in New Zealand. However, earlier versions of the MM intensity scale suggest that environmental effects at MM11 and MM12 are similar to the new criteria proposed for MM9 and 10 above, but are possibly more widespread and severe.</p> <p>(4) Terms used to describe size (volume, m³) of earthquake induced landslides in NZ and overseas (after Hancox et al., 1997; 2002; INQUA, 2003) as follows:</p> <p>Very small - <10³; Small - 10³-10⁴; Moderate - 10⁴-10⁵; Large - 10⁵-10⁶; Very large - 1-50 x 10⁶; Extremely large - >50 x 10⁶.</p> <p style="text-align: right;">[Page 2 of 2]</p>	