2.22  Arthur's Pass earthquakes of 18 June 1994 (21) and 29 May 1995 (22)

The $M_w$ 6.8 (previously $M_L$ 6.6) Arthur's Pass earthquakes of 18 June 1994 caused widespread landsliding over a 170 km$^2$ area around the epicentre of the main shock and the largest aftershock (on 19 June 1994). The area affected by very minor, surficial landsliding and failure of cut and fill slopes is about 950 km$^2$. Figure 17 shows the locations of landslides that occurred during the 1994 and 1995 Arthur's Pass earthquakes, with isoseismals based on landsliding as there was insufficient building damage for a standard intensity map to be prepared. Most of the landsliding caused by the 1994 earthquake was located within the main aftershock zone. The $M_L$ 5.5 earthquake of 29 May 1995 caused only minor landsliding along SH 73 closest to the epicentre (Figure 17). Several of the 1994 slides were reactivated in the 1995 event, and some new failures occurred north of Arthur's Pass township.

A total of about 70 landslides attributed to the 1994 earthquake were mapped during this study, mostly very small to moderate in size. Data on the main landslides (numbered 1-20 in Figure 17) are presented in Table 8. There was a marked topographic effect in the landslide distribution, especially along Camp Spur where the largest slides (in the order of 1 to 2 x $10^6$ m$^3$) are located, see Figure 17.1. Two minor landslide dams were formed by slides in Basin Creek. Most of the larger slope failures were first-time rock falls, avalanches and rock slides, while the smaller ones were mainly regolith failures, or small rockfalls in the heads of the retrogressively-eroding headwaters of some streams. Other ground damage included cracks forming near terrace edges, and partially buried boulders were ejected from the ground in river terraces and valley bottoms. Minor failures affecting the road included individual large rocks falling on the road, subsidence below the road on places, and a small to moderate rock fall that blocked SH 73 near the Zig-Zag and temporarily dammed the Otira River for a few days (Figure 17.2).

Currently there are no published isoseismal maps for the 1994 and 1995 Arthur's Pass earthquakes. As already mentioned, the isoseismals shown in Figure 17 are based on the few observations in the area for M 6 and MM7, and landslide distribution for MM8. All the landslides triggered by the 1994 event are all within the MM7 isoseismal, and the most intense areas of landsliding are assumed to be within the MM8 isoseismal. Topographic effects appear to constrain the landslide distribution, e.g. the lack of slides on the south and west facing slopes of Mt Stewart, compared to Camp Spur immediately opposite. In the 1995 event, only modified slopes (road cuts and fills) were affected in the area enclosed by the inferred MM6 isoseismal, but topographic effects such as slope aspect relative to the epicentre mean that the failed slopes were probably subjected locally to at least MM7.

Because there are few buildings in the mountainous area that was most affected, and little building damage except in Arthur's Pass Township, the 1994 Arthur's Pass earthquake provided little opportunity to compare MM intensities assigned on environmental and criteria with those based on structural damage. It is also worth noting that no landslides were reported for the Cass earthquake of 24 November 1995 ($M_L$ 6.3), probably because it was located in a more isolated mountainous area about 20 km east of Arthur's Pass (Figure 17).

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>(1) Camp Spur</td>
<td>6.5 km, NNW</td>
<td>2</td>
<td>DR/F</td>
<td>41°/000°</td>
<td>Greywacke; s(WSW)</td>
</tr>
<tr>
<td>(2) Camp Spur</td>
<td>5.5 km, NNW</td>
<td>1</td>
<td>DR/F</td>
<td>47°/070°</td>
<td>Greywacke; s(W3W)</td>
</tr>
<tr>
<td>(3) Moraine Flat</td>
<td>5 km, SW</td>
<td>0.8</td>
<td>DR/AV</td>
<td>50°/240°</td>
<td>Greywacke; s(NW)</td>
</tr>
<tr>
<td>(4) Greenlaw Hut</td>
<td>2 km, NNW</td>
<td>0.45</td>
<td>DR/F</td>
<td>38°/020°</td>
<td>Greywacke; s(N)</td>
</tr>
<tr>
<td>(5) Mid Basin Creek</td>
<td>12.5 km, S</td>
<td>0.4</td>
<td>DR/SL</td>
<td>38°/050°</td>
<td>Greywacke; s(N)</td>
</tr>
<tr>
<td>(6) Easy Creek</td>
<td>4.5 km, S</td>
<td>0.36</td>
<td>DR/SL</td>
<td>34°/270°</td>
<td>Greywacke</td>
</tr>
<tr>
<td>(7) Avoca-Basin-Mid Basin</td>
<td>11 km, S</td>
<td>0.3</td>
<td>CR/SL</td>
<td>34°/090°</td>
<td>Greywacke</td>
</tr>
<tr>
<td>(8) The Redoubt</td>
<td>3 km, E</td>
<td>0.25</td>
<td>DS/SL</td>
<td>27°/270°</td>
<td>Greywacke</td>
</tr>
<tr>
<td>(9) Black Range</td>
<td>5 km, SSW</td>
<td>0.2</td>
<td>DR/SL</td>
<td>36°/160°</td>
<td>Greywacke; s(vert?)</td>
</tr>
<tr>
<td>(10) Tobacco Range</td>
<td>5.5 km, SSW</td>
<td>0.2</td>
<td>DR/SL</td>
<td>34°/355°</td>
<td>Greywacke; s(NW)</td>
</tr>
<tr>
<td>(11) Basin Creek</td>
<td>9.5 km, SSE</td>
<td>0.2</td>
<td>DS/SL</td>
<td>41°/200°</td>
<td>Greywacke; s(N)</td>
</tr>
<tr>
<td>(12) Greenlaw Creek</td>
<td>2 km, NW</td>
<td>0.18</td>
<td>DR/F</td>
<td>51°/320°</td>
<td>Greywacke</td>
</tr>
<tr>
<td>(13) Basin Creek</td>
<td>10 km, S</td>
<td>0.18</td>
<td>DR/F</td>
<td>45°/000°</td>
<td>Greywacke; s(N); Idl</td>
</tr>
<tr>
<td>(14) Black Range</td>
<td>5 km, SSW</td>
<td>0.13</td>
<td>DS/SL</td>
<td>22°/200°</td>
<td>Greywacke</td>
</tr>
<tr>
<td>(15) Harper Creek</td>
<td>3 km, NW</td>
<td>0.125</td>
<td>DR/SL</td>
<td>37°/050°</td>
<td>Greywacke; s(E)</td>
</tr>
<tr>
<td>(16) Tobacco Range</td>
<td>6 km, S</td>
<td>0.12</td>
<td>DR/SL</td>
<td>29°/080°</td>
<td>Greywacke; s(NW)</td>
</tr>
<tr>
<td>(17) Moraine Flat</td>
<td>6 km, SW</td>
<td>0.09</td>
<td>DR/F</td>
<td>45°/070°</td>
<td>Greywacke; s(NW)</td>
</tr>
<tr>
<td>(18) Basin Creek</td>
<td>9.5 km, S</td>
<td>0.09</td>
<td>DR/SL</td>
<td>42°/000°</td>
<td>Greywacke; s(NW); Idl</td>
</tr>
<tr>
<td>(19) Mt Ida</td>
<td>2.5 km, SE</td>
<td>0.09</td>
<td>DS/SL</td>
<td>34°/340°</td>
<td>Greywacke; s(SW?)</td>
</tr>
<tr>
<td>(20) Camp Spur/Carrington</td>
<td>6 km, NNW</td>
<td>0.08</td>
<td>DR/F</td>
<td>45°/075°</td>
<td>Greywacke; s(W3W)</td>
</tr>
</tbody>
</table>

NOTES:
[1] Name and number of landslide (as shown map of landslides caused by 1994/95 earthquakes, see Figure 17).
[2] Failure type classification (e.g., slides, falls, avalanches, and flows of rock, debris, or soil) based on Varnes, 1978.; and Keefer 1981.
[3] Abbreviations: DR = disrupted rock; S = soft; H = hard; CR = coherent rock; F = fall; SL = slide; AV = avalanche; Flt = rotational slide.
[4] Estimated slope angle prior to failure, and direction of landslide movement (which generally equates to slope aspect).
[5] Main lithology of landslide material: e.g. granite; greywacke (pewka); Tertiary sandstone (Tart sand); mudstone (ms); limestone (let); conglomerate (cong).
[6] Relationship of slope to geology: dip slope (dip); scarp slope (st); escarpment/toll (toll).
[7] Dip and direction of bedding: gentle (g, 0-10°); moderate (m, 11-30°); steep (s, >30°); north (N), east (E), south (S), west (W) etc.
[8] Effect on drainage: Landslide-dammed lake (dld); infiltrated, drained landslide dammed lake (dldi).

Table 8. Main landslides caused by the 18 June 1994 Arthur’s Pass earthquake.
Figure 17.1: Typical disrupted rock debris falls and slides (1-2 x 10^6 m^3) formed on Camp Spur during the June 1994 Arthur's Pass earthquake (M_L 6.6), about 4 km north of the epicentre and 12 km southwest of Arthur's Pass. Both failures originated on very steep 40°-50° rock bluffs at the bushline and descended 300-400 m to the valley floor. GNS Photo by Lloyd Homer: CN 380356

Figure 17.2: Aerial view of the “Zig-Zag” rock avalanche area on the Arthur's Pass highway (SH 73), with the debris scree slope and very steep headscarp bluffs rising about 400-500 m above the road. During the 1994 Arthur’s Pass earthquake, the highway was damaged by a number of small-moderate rock falls (F) on the Otira side of Arthur’s Pass (AP), one blocking the road and damming the Otira River for several days (LD). Photo by G T Hancox: 3/99 - 24/2/96

Institute of Geological & Nuclear Sciences Limited

Earthquake-induced landsliding in NZ & implications for MM intensity and hazards
<table>
<thead>
<tr>
<th>Earthquake 7</th>
<th>Intensity MM 6 2</th>
<th>Intensity MM 7</th>
<th>Intensity MM 8</th>
<th>Intensity MM 9 and greater</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) Waikato, 16 Oct 1856 (Mw 8.2)</td>
<td>None recorded. Liquefaction noted in Hawkes Bay.</td>
<td>None recorded.</td>
<td>Small to moderate landslides widespread, many rock falls of steep slopes. Also significant areas of minor landsliding recorded in Marlborough. Liquefaction widespread.</td>
<td>Widespread landsliding. Many small to very large failures, mainly rock avalanches, disrupted rock and soil slides. MM10 shaking is indicated in a zone along the southern rimutaka Range and evidence of widespread liquefaction on the Waikato river plains.</td>
</tr>
<tr>
<td>(3) Nth Canterbury, 1 Sep 1888 (Mw 7.7-7.3)</td>
<td>No significant landslides. Small disrupted soil slides in places.</td>
<td>General areas of minor landsliding, southern MM 8 area only. Some liquefaction in the canterbury basin.</td>
<td>General areas of minor landsliding, southern MM 8 area only. Some liquefaction in the canterbury basin.</td>
<td>General area of minor to moderate landsliding (rockfalls and disrupted soil slides).</td>
</tr>
<tr>
<td>(4) Cheviot, 16 Nov 1901 (Mw 6.9)</td>
<td>None recorded.</td>
<td>Small areas of minor landsliding, mainly gorges and coastal cliffs affected.</td>
<td>General areas of minor landsliding, and some moderate landslides recorded. Some large coastal landslides.</td>
<td>General area of minor landsliding, some moderate landslides recorded. Some large coastal landslides.</td>
</tr>
<tr>
<td>(5) Cape Turnagain, 9 Aug 1904 (Mw 6.8)</td>
<td>None recorded.</td>
<td>Small areas of minor landsliding, river bank and coastal rockfalls. One area of liquefaction.</td>
<td>Moderately large areas affected by minor rock and soil falls, disrupted soil slides. Many failures of road cuts. Liquefaction common.</td>
<td>Not applicable</td>
</tr>
<tr>
<td>(7) Arthur's Pass, 9 Mar 1929 (Mw 7.1)</td>
<td>None recorded.</td>
<td>None recorded.</td>
<td>Widespread areas of general, minor to moderate landsliding (rock and soil falls, disrupted rock slides, especially along Arthur's Pass highway, and scree reactivations), and large to very large rock slides and avalanches. Minor liquefaction at Lake Sumner.</td>
<td>It is likely that the main zone of landsliding along the Kaikoura Fault was caused by MM 9 shaking. Several very large landslides occur in this zone, including the Thompson, Ellis Stream, Hurunui, and the extremely large Falling mountain landslide.</td>
</tr>
<tr>
<td>(8) Murchison, 16 June 1929 (Mw 7.6)</td>
<td>None recorded.</td>
<td>A few small to moderate landslides recorded. Sand boils at Greymouth.</td>
<td>Numerous small landslides, some moderate landslides in mountainous areas, rockfills in granite and limestone common. Some very large rockslides and avalanches in north (may be MM 9). Liquefaction in many places, including lateral spread at Westport.</td>
<td>Many large to very large landslides, including low angle bedded plane slides in Tertiary rocks. Liquefaction and lateral spreads are common near Murchison. MM 10 shaking is indicated in the area of main landsliding north of the epicentre along the White Creek Fault.</td>
</tr>
<tr>
<td>(9) Hawkes Bay, 3 Feb 1931 (Mw 7.0)</td>
<td>None recorded.</td>
<td>None recorded.</td>
<td>A few small to moderate landslides. Some liquefaction in places.</td>
<td>Many landslides, up to very large, particularly coastal cliffs and gorges. Liquefaction and lateral spread very common and widespread.</td>
</tr>
<tr>
<td>(10) Waikato, 16 Sep 1932 (Mw 6.9)</td>
<td>None recorded.</td>
<td>None recorded.</td>
<td>General minor landsliding in gorges. Liquefaction noted in places.</td>
<td>Extensive areas of general, minor landsliding, with a few moderate to very large landslides.</td>
</tr>
</tbody>
</table>

Notes: 1. See Table 2 for full list of earthquakes studied, only the most significant in terms of landsliding included here. 2. See Appendix 1 for MM Scale. MM 9 and greater includes MM 10, of which there are only a few confirmed cases.

Table 9. Summary of landsliding and ground damage in intensity zones MM 6 - MM9 during significant historical earthquakes. [Page 1 of 2]
<table>
<thead>
<tr>
<th>EARTHQUAKE</th>
<th>Intensity MM 6</th>
<th>Intensity MM 7</th>
<th>Intensity MM 8</th>
<th>Intensity MM 9 and greater</th>
</tr>
</thead>
<tbody>
<tr>
<td>(11) Pahiatua, 5 Mar 1934 (Mg 7.6)</td>
<td>General areas of minor landsliding along some major rivers. Some liquefaction recorded near the Manawatu River mouth.</td>
<td>Large areas of minor landsliding in Tertiary rocks, especially near Cape Turnagain. Small rock and soil slides reported in greywacke terrain.</td>
<td>Very extensive areas of minor landsliding.</td>
<td>Extensive areas affected by small to moderate landslides.</td>
</tr>
<tr>
<td>(12) Masterton, 24 June 1942 (Mg 7.2)</td>
<td>Moderate rock slide on modified coastal slope at Gost Point blocked road and railway.</td>
<td>General, minor to moderate failures of road cuts, especially Rimutaka Hill, area of minor landsliding near Martinborough.</td>
<td>Moderate to large landslides and general areas of minor landsliding recorded in epicentral area. Liquefaction recorded near Gladstone.</td>
<td>Not applicable.</td>
</tr>
<tr>
<td>(13) Lake Coleridge, 27 June 1946 (Mg 6.4)</td>
<td>Extensive area of minor landsliding near Lake Heron only.</td>
<td>Discontinuous areas of minor landsliding (reactivation of scree, disrupted soil slides).</td>
<td>Area of landsliding at north end of Lake Coleridge may indicate MM 8.</td>
<td>Not applicable.</td>
</tr>
<tr>
<td>(15) Inangahua, 24 May 1968 (Mg 7.4)</td>
<td>None recorded.</td>
<td>A few small to moderate landslides recorded.</td>
<td>Many small to moderate, some large to very large landslides. Liquefaction recorded at Westport.</td>
<td>Many small to large and a few very large avalanches, rockfalls and rockslides, including a low angle bedding plane slide. Liquefaction and lateral spreads in places.</td>
</tr>
<tr>
<td>(17) Edgecumbe, 2 Mar 1967 (Mg 6.6)</td>
<td>None recorded.</td>
<td>Small rock/sand falls in weak materials on coastal cliffs and settlements in soft ground at Ohope.</td>
<td>Many small to moderate disrupted soil slides and rockfalls. Liquefaction in places, lateral spread along river banks.</td>
<td>Extensive areas of small to moderate landslides. Liquefaction (sand boils) very widespread, and some lateral spreads.</td>
</tr>
<tr>
<td>(18) Waver, 13 May 1990 (Mg 6.4)</td>
<td>A few small landslides recorded (close to MM 7 isoseismal)</td>
<td>A few minor reactivations and road cut failures.</td>
<td>Many small to moderate rock and soil falls, disrupted rock and soil slides. Widespread failure of road cuts and settlement of road fills.</td>
<td>Not applicable.</td>
</tr>
<tr>
<td>(19) Ormond, 10 Aug 1993 (Mg 6.2)</td>
<td>Minor reactivations (acceleration of earth flows). Liquefaction reported in one place (sand boil).</td>
<td>A few small rock and soil falls and disrupted soil slides. Liquefaction (sand boils) widespread around Te Karaka-Waipaoa area.</td>
<td>Not applicable.</td>
<td>Not applicable.</td>
</tr>
<tr>
<td>(21) Arthur's Pass, 18 Jun 1994 (Mg 6.8)</td>
<td>None recorded.</td>
<td>Widespread road cut failures, several small to moderate landslides (regolith failures, rock falls in gully heads).</td>
<td>Many small to moderate landslides (rockfalls, avalanches, rock slides), and three large to very large rock falls and avalanches.</td>
<td>Not applicable.</td>
</tr>
</tbody>
</table>

**NOTES:**
1. See Table 2 for full list of earthquakes studied. Only the most significant in terms of landsliding are included here. 2. See Appendix 1 for MM Scale. MM 9 and greater includes MM 10, of which there are only a few confirmed cases.

Table 9. Summary of landsliding and ground damage in intensity zones MM6-MM9 during significant historical earthquakes. [Page 2 of 2]
3. Relationships of landsliding to seismic and environmental factors

3.1 Introduction

Several measures were used in this study to relate earthquake-induced landslide distribution to seismic parameters (as done by Keefer, 1984) and also environmental factors. The measures used are: the relation between landsliding and earthquake magnitude and MM intensity; the relation between magnitude and the area affected by landsliding; the relations between magnitude, MM intensity, and the maximum distance of landslides from the epicentre; and the relationships of landslides to slope angle, failure direction relative to the epicentre, rock and soil type, and slope type. The latter include dip and scarp slopes, which are controlled by geological structure, and topographic features such as cliffs and escarpments. Several other factors influencing landsliding during earthquakes are also briefly discussed, including distance to surface fault rupture, earthquake mechanism and seismic focussing, shaking amplification due to topography and ground conditions, and climate.

The data used to assess and compare the measures listed above are presented in the landslide maps (Figures 2-17) and Tables 3 to 9. Relationships between these measures and landsliding are illustrated in Figures 18-22 and discussed below. Figure 23 shows the locations of all historical earthquake-induced landslides in New Zealand (in the GNS database), and provides a basis for subsequent discussion of the geographic areas most likely to be affected by landslides during future earthquakes and implications for hazard and risk (Section 5).

3.2 Earthquake magnitude and MM intensity

Using data presented in Section 2 and Figures 2 to 17 it has been possible to assess the magnitudes of historical earthquakes causing significant landsliding in New Zealand and determine the most common and range of MM intensities at which landslides occurred. This information is presented in Figure 18. Other relationships of landsliding to MM intensity and distance from the epicentre are shown in Figures 20b and 21. A summary of landsliding in intensity zones MM6 - 9 during significant historical earthquakes is presented in Table 9.

The data shown in Figures 18 and 20b indicate that the minimum magnitude for obvious (minor) landsliding in New Zealand is M 4.6 to 5.5 (or about M 5), as shown during several more recent earthquakes, such as 1983 Waipatiki, 1963 Peria, and 1995 Arthur's Pass, at intensities of MM6 and MM7 (lower half of MM7 zone). However, the historical data show that significant landsliding generally only occurs in New Zealand during earthquakes of magnitude 6 or greater, depending on their depth and position on land, at minimum shaking intensities of MM6. Figure 18 shows that most historical earthquake-induced landsliding in N Z has been caused by shallow earthquakes of magnitude 6.2 to 7.8, at intensities of MM7 to MM9 and 10. Earthquakes of magnitude 4.6 to 8.2 have caused landslides at MM6 and MM7 at distances of 5 km to almost 300 km, whereas landsliding caused by shaking of MM8 and MM9 or greater has been associated with earthquakes of M 6.2 or greater at distances of up to 120 km (Figure 20b).
Figure 18. Range of MM intensities for initiation of landslides during historical New Zealand earthquakes of different magnitude. The bars and triangles show the range and most common intensities at which landsliding occurred for earthquakes listed in Table 2. Isoseismal lines and intensity zones are as shown on isoseismal maps. Note that in this figure, and also figures 19, 20.1 and 20.2, earthquakes numbered 13, 16, 18, 19, 20, and 21 have been plotted using magnitudes (mostly $M_L$) that were formerly assigned to them (Table 2), but this has no significant effect on the relationships that are shown on these figures.
Figure 19. Area affected by landslides during historical New Zealand earthquakes of different magnitude. Dots show the total areas affected, and circles show the main area of landsliding for some earthquakes (where significantly different from the total area affected). The solid line is the approximate upper bound for about 90% of New Zealand data, and dashed lines show the limits of Keefer’s (1984) worldwide data. The mean regression lines and expressions for New Zealand data and Keefer’s data are also shown.
Figure 20.1 Maximum distances from epicentre to landslides of various sizes during historical New Zealand earthquakes of different magnitude. Roman numerals indicate the intensity at which the landslide occurred. The solid line shows the approximate upper bound of New Zealand data, and dashed lines show the upper and lower limits of Keefer's (1981) overseas data. Circled numbers show the earthquake magnitudes and epicentral distances associated with the largest and most significant N Z earthquake-induced landslides, which plot in an envelope with a lower magnitude bound of M 7 and distance limit of almost 100 km.
Figure 20.2 This figure also shows the maximum distances of landslides from the epicentre of historical earthquakes, but highlighting the shaking intensity required for landsliding. Coloured envelopes show the MM intensities (MM 6 to MM 9 or greater) at which landslides have occurred in relation to earthquake magnitude and distance. The other data shown are described in Figure 20.1.
Figure 20.3 Distances from epicentre to liquefaction phenomena (sand boils and lateral spreads) during historical New Zealand earthquakes of different magnitude (dotted lines). The numbers indicate the intensity at which liquefaction occurred, and the dashed lines show the MM intensity zones (MM 7 to MM 10) for liquefaction phenomena in relation to earthquake magnitude and distance. The minimum shaking threshold for the occurrence of sand boils is generally MM 7, and for lateral spreads MM 8. Liquefaction occurrences at lower intensities are probably microzone effects in highly susceptible materials.
Figure 21. Distance/intensity zones for earthquake-induced landsliding in New Zealand. These zones (defined by different line patterns) show the relationship of landslide occurrence to distance from epicentre and MM intensity during nine historical earthquakes causing the most extensive or (in some cases) the best documented evidence of landsliding. The zones are based on landslide data presented in Figures 2 to 17 and Tables 3 to 8. Black triangles show the largest and most significant earthquake-induced landslides which plot in an envelope with a lower intensity bound of MM 8 and distance limit of about 100 km.
Figure 21 shows that larger earthquakes (≥ M = 6.7) cause landsliding at a greater range of intensities and epicentral distances (MM6-10 at 2 km to 200 km) than do smaller earthquakes (MM6-8 at 1 km to about 30 km). All of the very large and more significant earthquake-induced landslides occur during earthquakes of magnitude 6.9 or greater at intensities of MM8 or higher, at distances of up to almost 100 km from the epicentre.

The earthquake magnitude threshold for significant earthquake-induced landsliding in New Zealand (all rock types and all types of slides) is therefore considered to be about M 5, and the minimum shaking intensity threshold for landsliding is MM6. The higher (MM7) threshold determined for earthquake-induced landsliding in the Wellington Region (Hancox et al., 1994) reflects the better performance of greywacke slopes under earthquake conditions, as indicated by this study (see 1929 and 1994 Arthur’s Pass earthquakes).

The most common levels of shaking associated with historical earthquake-induced landsliding in New Zealand are MM8 and MM7, and the predominant minimum intensity for landsliding was MM6 and MM7 (Figure 18). Although landsliding associated with high intensity MM9 and 10 shaking was more widespread and damaging (as it was during the 1929 Murchison and 1968 Inangahua earthquakes) it has occurred less frequently. Most of the landslides that occurred at MM6 and 7 (or higher intensities) were disrupted slides or falls (Tables 3 to 9).

Data presented in Figures 2-17c and summarised in Figure 20c show that the minimum threshold for liquefaction phenomena (see Appendix 2) during historical earthquakes was commonly MM7 for sand boils, and MM8 for lateral spreading. However, such effects may also occur at one intensity level lower in areas of highly susceptible materials or abnormally high groundwater levels, as shown by the Edgcumbe 1987, and Ormond 1993 earthquakes. Ground damage due to liquefaction is most common at intensities MM8 to 10 at epicentral distances of 10 to 100 km, and that the minimum magnitude for features such as sand boils and lateral spreads in New Zealand is about M 6. The absence of liquefaction effects from earthquakes smaller than M 6 indicates that soil liquefaction is most likely to occur during longer-duration shaking associated with moderate and large earthquakes. Relationships of liquefaction phenomena to magnitude and distance are discussed further in Section 3.4 below.

The above relationships of landsliding to magnitude and intensity in New Zealand are generally consistent with Keefer’s (1984) study of worldwide and United States earthquakes, who found that the predominant minimum intensities for landsliding were MM6 and MM7, with the minimum intensity required for disrupted falls and slides being MM6, and for coherent slides and lateral spreads MM7. However, Keefer (1984) also found that the threshold (minimum) earthquake magnitude for landsliding was M 4, and the minimum threshold intensity for landsliding was MM4/5, which is 1-2 levels lower than indicated in this study of New Zealand data. This difference is probably due to the influence of the United States earthquakes in Keefer’s (1984) data, many of which occurred in arid areas, where landslides tend to occur at lower shaking levels than in temperate areas. In arid areas, loose slope debris derived from thermal weathering can be mobilized by relatively low intensity shaking, whereas in wetter areas rainfall regularly removes much of the less stable slope debris, and therefore stronger shaking is required for landsliding during earthquakes. Nikonov (1988), found that small landslides occur at MSK intensities VI-VII and occasionally at V, large landslides at intensity VIII-IX, and "large landslides in basement rocks at intensities IX or greater. This is similar to New Zealand (see Section 4.4 for a comparison of the MSK and MM intensity scales)
3.3 Earthquake magnitude and area affected by landsliding

For the historical earthquakes listed in Table 2 it was possible to assess the areas affected by landslides by drawing a boundary around reported landslide localities on the landslide maps (Figures 2-17, and draft maps not included in the report) and measuring the size of the enclosed area. Such areas are those where earthquake shaking was strong enough to trigger landslides on susceptible slopes, although not all slopes within those areas produced landslides. Figure 19 shows areas affected by landsliding during historical earthquakes in New Zealand plotted against magnitude. These areas are generally irregular in shape and asymmetric with respect to instrumentally-determined epicentres, which are probably only accurate to within \pm 5-10 km, and may occur at sea or under alluvial plains where there are few landslide susceptible slopes (see Figures 2-17). Nevertheless, areas of earthquake-induced landsliding show a strong correlation with magnitude, as shown by Keefer (1984) for worldwide data.

Correlations between magnitude and landslide distribution during New Zealand earthquakes show that the maximum area likely to be affected by landsliding ranges from zero at M 4, about 100 km² at M 5, 500 km² at M 6, 2000-3000 km² at M 7, 8000 km² at M 7.8, and up to 20,000 km² at M 8.2. Although these areas are somewhat lower than Keefer’s (1984) upper bound for worldwide data, most New Zealand earthquakes plot within or just below the limits of the overseas data (Figure 19).

The approximate upper bound of about 90% of the NZ data shows the greatest area likely to be affected by an earthquakes of a given magnitude. In general the NZ data show that larger the earthquake the greater the area affected by landsliding, and the most notable historical earthquakes were Wairarapa 1855, Murchison 1929, Pahiatua 1934, Hawke’s Bay 1931, Cape Turnagain 1904, and Inangahua 1968. The magnitudes of these earthquakes ranged from M 7.4 to 8.2, and all affected areas of more than 2000 km², with a maximum of about 20,000 km² for the M 8.2 Wairarapa earthquake. Linear regression of the semi-log plot of total areas affected by landsliding against earthquake magnitude yielded the following expression for the mean regression line shown on Figure 19:

\[ \log_{10} A = 0.96 (\pm 0.16) M - 3.7 (\pm 1.1) \]

where M is earthquake magnitude, and A is area in km². (Error limits of \pm 1 standard error, the standard error of the estimate of \log_{10} A is \pm 0.43. The coefficient of determination is 68%.) Data points for the lowest magnitude earthquakes were not used in the regression because their areas affected and magnitudes are not well determined. The above relationship also allows earthquake magnitude to be estimated from the total area affected by landsliding, the equation for which is: \( M = 1.04 \log_{10} A + 3.85 \)

Figure 19 also shows the regression line for the average area likely to be affected by landslides during earthquakes from Keefer’s (1984) overseas data, the equation for which is:

\[ \log A = M_S - 3.46 \]

where A is the area affected by landslides in km² and M_S is earthquake surface wave magnitude (Keefer and Wilson, 1989; Jibson, 1996).
As with the overseas data (Keefer, 1984) there is considerable scatter in the NZ data, and in many cases the area of landsliding depends on the earthquake location and the terrain affected, as well as magnitude. For example, offshore earthquakes or those under alluvial plains generally affect smaller areas than those in hilly or mountainous areas as they contain fewer landslide-susceptible slopes. Likewise, some rock types, such as greywacke, tend to be less susceptible to landsliding than weaker Tertiary mudstone, sandstone, and limestone. Other factors causing scatter in the areas of landsliding may include uncertainties in the area affected, earthquake magnitude and depth, the nature of ground motions. Climate may also influence the area affected by landsliding, with wetter slopes (in higher rainfall areas or during winter) likely to be more susceptible to slope failure during earthquakes.

Note that the NZ and overseas regression lines shown in Figure 19 are similar, but the line for Keefer’s data consistently indicates larger affected areas than the New Zealand data, as do the upper bound lines. However, the regression line expression based on NZ data is considered more appropriate for estimating the area likely to be affected by earthquakes of different magnitude and seismic hazard assessments in New Zealand.

For any given earthquake, magnitude is probably the most important factor influencing the size of area affected by landsliding. However, Figure 23 shows that the geographic location of that area is strongly influenced by natural seismicity and terrain. Areas affected by landslides during New Zealand earthquakes are more likely to be located in the central part of the country, coincident with the main seismic area (Figure 23 inset). The regions most likely to be affected are northwest Nelson, central Southern Alps, Marlborough, Wellington, Wairarapa, and Hawke's Bay. Historically, this is the area where most of the shallow earthquakes of magnitude 5 and 6 or greater have been located. Of the four main centres, Wellington has been most affected by historical earthquake-induced landsliding, and this will probably be true in the future. The inset map Figure 23 shows that few earthquakes of M 5-6 or greater are known to have occurred in the central North Island, Auckland, Canterbury and Central Otago and Southland areas, where the hazard from earthquake-induced landsliding is regarded as low.
3.4 Earthquake magnitude and distance from epicentre

For the earthquakes listed in Table 2, data collected during this study has enabled the relationship between earthquake magnitude and the maximum distance from the epicentre at which an earthquake causes landslides to be assessed for New Zealand conditions. To explore this relationship the maximum epicentral distances to landslides and liquefaction-induced ground damage were determined (from Figures 2-17 and Tables 3-8 mainly) and plotted in Figure 20.1, 20.2, and 20.3. Keefer (1984) examined similar relationships for landslides of different type such as disrupted and coherent falls and slides of rock and soil, lateral spreads and flows (Table 1). However, there have been few coherent earthquake-induced slope failures in New Zealand, with most landslides during earthquakes being disrupted rock and soil falls, slides, and avalanches of varying size. For this reason the magnitude/distance relationship of landslides of different sizes was determined for each earthquake in Table 2 where locations and data was sufficiently reliable and plotted in Figure 20.3.

It should be noted, however, that it would have been better to plot the distance of landslides from the earthquake source, but this was not done as it is not possible to define the geometry of the fault rupture surface for many of the events considered (see Section 3.7).

As shown by Keefer (1984), the distances at which earthquake-induced landslides occur in New Zealand show a strong correlation with magnitude and also intensity. Figures 20a and 20b show that very small to small (≤ 10³ - 10⁴ m³) landslides, excluding single rock falls and slides of only a few tens of cubic metres, occur at maximum epicentral distances of about 10 km for M 5 (MM6), 30 km for M 6 (MM7), 100 km for M 7 (MM7), and almost 300 km for M 8.2 (at MM6). Moderate to large landslides (10⁴-10⁶ m³) generally only occur at magnitudes greater than 6 to 6.5 at epicentral distances of about 5 km (MM8) to 70 km (MM7). Very large (>1-50 × 10⁴ m³) and extremely large (>50 × 10⁶ m³) landslides only occur at magnitudes greater than about M 6.9 and 7.1 respectively, at distances of 10 km at MM9 (or MM10) to almost 100 km at intensity MM8-9. The largest and most significant historical landslides have all occurred during earthquakes of magnitude M 6.9 to M 8.2 at distances of almost 100 km and intensities MM8 and 9 or greater.

The MM intensity zones shown in Figure 20.2 highlight the shaking intensities associated with landslides of various size at different epicentral distances. As expected, the intensity zones and landslides within them are magnitude and distance dependant, with the smaller slides occurring at lower intensities at a greater range of magnitudes and distances. The overlap between intensity zones is not unexpected, and reflects both variations in the factors causing landsliding, and the scatter and accuracy of the intensity data and earthquake locations.

It is notable that the maximum distances to landslides during New Zealand earthquakes are usually less than those associated with overseas earthquakes, falling mainly between the median and lower bounds of Keefer’s (1984) worldwide data (Figure 20.1). This difference is probably due to a combination of factors including geographic setting, seismic attenuation, geology, and climate, but their relative importance and interaction are currently unknown.
However, compared to other parts of the world, the lesser distances at which landslides occur, and the smaller areas affected during earthquakes in New Zealand (see Section 3.3), are somewhat beneficial from a hazard and risk perspective.

Figure 20.3 shows the relationship of liquefaction phenomena to magnitude, epicentral distance, and intensity for New Zealand earthquakes. This shows a similar magnitude threshold and upper bound magnitude/distance relationship to that determined by Kuribayashi and Tatsuoka (1975) for liquefaction during earthquakes in Japan. Kuribayashi and Tatsuoka (1975) also found that the minimum intensities for liquefaction in Japan was JMA grade V, which equates to MM7 and MM8 in the Modified Mercalli scale, as indicated by New Zealand data.

The general agreement between the New Zealand and Japanese liquefaction data and about 90% of Keefer’s (1984) data for lateral spreads and flows (Figure 22c) suggest that the maximum distances of liquefaction from the epicentre in New Zealand may be predicted by the formula of Kuribayashi and Tatsuoka, 1975:

\[
\log_{10} R_{\text{max}} = 0.77 M - 3.6 \quad \text{(for earthquakes} \geq M 6) \\
\text{where:} \quad R = \text{maximum distance from the site to the epicentre (km);} \quad M = \text{magnitude}
\]

From this study the main implications from the magnitude/distance/intensity relationships in NZ are that smaller landslides are caused by lower magnitude earthquakes (M 5 - M 6), moderate shaking intensities (MM6 and MM7), and at a great range of distances (5 km to almost 300 km). Larger landslides and liquefaction phenomena such as sand boils and lateral spreading require earthquakes of at least M 6 and higher intensities of MM7 to MM8. Extremely large landslides (50 million m$^3$ or greater) are formed only during large earthquakes of M 7 or more, at intensities of at least MM9 and epicentral distances of up to 50 km.
3.5 Slope angle and failure direction

Relationships of earthquake-induced landslides to slope angle, failure direction relative to the epicentre, and also the main rock and slope types were assessed for some of the larger earthquakes in which the landslides were well documented and accurately located. Relevant data on the main landslides attributed to the Wairarapa 1855, Arthur’s Pass 1929, Murchison 1929, Hawke’s Bay 1931, Inangahua 1868, and Arthur’s Pass 1994 earthquakes (Tables 3-8) were plotted in Figure 22.1.

Figure 22.1 shows landslides in relation to slope angle and failure direction relative to the epicentre. In order to represent failure direction, slope movements towards the epicentre plot as zero, and those away from the epicentre as 180°. Movements obliquely towards or away from the epicentre plot from 0-90° or 90°-180° respectively. The number of landslides in various directional segments relative to the epicentre are shown by the histogram at the bottom of Figure 22.1. Figure 22.2 shows the main rock and slope types in which these landslides have occurred, as well as slope angle and failure direction.

Data from some of the more important historical earthquakes show that earthquake-induced landslides occur on slopes of varying steepness, with most failures occurring on slopes of 20° to 50°, and mainly obliquely or directly away from the epicentre (along a line back to that point, see for example, Figure 7.1), with notably fewer landslides moving towards the epicentre (Figure 22.1). This probably reflects the dominant directions and effects of the initial shorter period (higher acceleration) earthquake shaking which triggers landsliding.

Figure 22.2 shows that there have also been many slope failures normal to a line back to the epicentre. However these failures are dominantly rock and soil falls on very steep (>35°) cliffs and escarpments, or are on less steep structurally-controlled dip slopes, which have been influenced more by topographic and geological factors than the nature of the shaking. However, in addition to the intensity and duration of strong shaking, landslide size seems to be most strongly influenced by slope angle and slope type, with the largest and most significant earthquake-induced landslides occurring on slopes steeper than 30°, cliffs and escarpments. Although some very large landslides have occurred on gentle to moderate slopes (10°-20°) these are mainly bedding-controlled dip slope failures in Tertiary rocks (see 3.6), as shown by the Matakitaki Landslide during the 1929 Murchison earthquake (Figure 7.2).

It would probably have been better to plot landslide movement directions in relation to the earthquake source, but (as in the case of epicentral distance) this was not done as it is not possible to define the geometry of the fault rupture surface for many of the events considered (see Section 3.7 also).
Figure 22.1 Relationships of earthquake-induced landslides caused by important historical earthquakes in New Zealand to slope angle and failure direction relative to the epicentre. Failures towards the epicentre plot as zero, and failures away from the epicentre as 180°. Movements obliquely towards or away from the epicentre plot from 0-90° or 90°-180° respectively. The number of landslides in various directional segments relative to the epicentre are shown by the histogram at the bottom. The circled numbers indicate the slope angles and relative failure directions of the largest and most significant historical earthquake-induced landslides (see Figure 20.1 for details of these).
Figure 22.2 Relationships of earthquake-induced landslides caused by important historical earthquakes in New Zealand to slope angle and failure direction relative to the epicentre, and the main rock and slope types. Failures towards the epicentre plot as zero, and failures away from the epicentre as 180°. Movements obliquely towards or away from the epicentre plot from 0-90° or 90°-180° respectively (as in Figure 22.1). Circled numbers indicate the largest and most significant historical earthquake-induced landslides.
FIGURE 23 – Inset
Historical earthquakes in New Zealand of magnitude 5 and greater since 1840

EARTHQUAKES SHOWN ON MAP
1. Murchison 16 Oct 1848 (M 7.5)
2. Waihi 29 Jan 1960 (M 8.2)
3. Waihi 29 Jan 1960 (M 8.2)
4. Christchurch 16 June 1931 (M 8.5)
5. Napier 26 Aug 1931 (M 7.4)
6. Napier 26 Aug 1931 (M 7.4)
7. Napier 26 Aug 1931 (M 7.4)
8. Napier 26 Aug 1931 (M 7.4)
9. Napier 26 Aug 1931 (M 7.4)
10. Motueka 19 Feb 1993 (M 6.0)
11. Motueka 19 Feb 1993 (M 6.0)
12. Motueka 19 Feb 1993 (M 6.0)
13. Motueka 19 Feb 1993 (M 6.0)
14. Motueka 19 Feb 1993 (M 6.0)
15. Motueka 19 Feb 1993 (M 6.0)
16. Motueka 19 Feb 1993 (M 6.0)
17. Motueka 19 Feb 1993 (M 6.0)
18. Motueka 19 Feb 1993 (M 6.0)
19. Motueka 19 Feb 1993 (M 6.0)
20. Motueka 19 Feb 1993 (M 6.0)
21. Motueka 19 Feb 1993 (M 6.0)
22. Motueka 19 Feb 1993 (M 6.0)

LEGEND
- Locations of known landslides
- Area of landslides (location unknown)
- Historical earthquake causing landsliding (see Table 2)
- Turquoise squares
- Total area of landsliding caused by earthquakes

FIGURE 23
Main landslides caused by historical earthquakes in New Zealand
3.6 Rock type and slope type

Figure 22.2 also indicates that the relations of landslides to slope angle show a strong correlation with rock type, but slope failure direction is largely independent of rock type. Failures in strongly jointed rock types such as greywacke and granite occur mainly on 25° to 45° slopes, with more failures away from the epicentre than towards. Failures in Tertiary sandstone and mudstone occur on gentle to steep (10° - 40°) dip slopes, whereas limestone failures mainly occur on steeper cliffs and escarpments (Figures 8.2 and 8.3). Such landslides are apparently independent of the direction of seismic shaking as indicated by the epicentre location, but not the intensity and duration of strong shaking. New Zealand data indicate that the larger slides and rock fall avalanches are more likely to be triggered by longer-duration shaking associated with larger earthquakes (> M 6.5), mostly on slopes steeper than 25°-30°. Such failures invariably occur on natural slopes more than 100-200 m high, with smaller failures occurring on mainly steep coastal or inland cliffs, road and rail cuttings, and quarry faces. A similar relationship was found by Keefer (1984) for worldwide earthquakes.

The rock types affected by earthquake-induced landsliding in New Zealand are strongly dependant on earthquake location. Figure 23 shows that earthquakes likely to trigger landslides occur in central New Zealand, in northwest Nelson, central Southern Alps, Marlborough, Fiordland, Wellington, Wairarapa, Hawkes Bay, and East Cape. The most commonly affected rock types (Tables 3-8) are therefore older greywacke, granite, schist and conglomerate; Tertiary sandstone, mudstone, limestone, and in some cases Quaternary volcanics and tephra. Closely jointed and weathered rock masses (granite and greywacke) and overlying colluvial slope deposits tend to be more affected, especially in higher rainfall areas of northwest Nelson and the Southern Alps, and Wellington regions as indicated by the large 1929 Murchison (Figures 7.4 to 7.6) and Arthur’s Pass earthquakes (Figures 6.1, 17.1, and 17.2), and the great 1855 Wairarapa earthquake (see Figure 2.1).

Moderate to large earthquakes in Wairarapa and Hawke’s Bay have resulted in significant failures in relatively weak Tertiary rocks, particularly from sandstone conglomerates in steep coastal cliffs, and limestone escarpments and narrow gorges. However, earthquake-induced landslides in Tertiary rocks have probably been most extensive and spectacular in the Buller and northwest Nelson areas during the 1929 Murchison and 1968 Inangahua earthquakes. Failures at low intensities (MM6) in weakly cemented upper Tertiary sandstones and shelly limestone have also been common in the Wanganui River area during several earthquakes.

The 1987 Edgecumbe earthquake demonstrated the vulnerability of closely jointed volcanic rocks and weakly compacted tephra deposits to earthquakes, with numerous failures on natural slopes and road cuts, and liquefaction-induced sand boils and lateral spreads widespread over pumiceous alluvial plains (see Figures 14.1, 14.2, and 14.3). The 1983 Waiotapu earthquake produced similar landslides on a very minor scale, but no liquefaction effects as the earthquake was too small. Volcanic rocks appear to be vulnerable to widespread landsliding only during M 6.0 earthquakes or greater (≥ MM7), but historically few earthquakes of this size have occurred in the central volcanic areas of the North Island, and none have occurred in the Auckland area (Downes, 1995).
3.7 Relationships to other factors

In this section the affects of other factors that may have influenced landsliding during earthquakes are briefly discussed. These include: distance to the zone of fault rupture; earthquake focal plane mechanism; focussing of seismic shaking; local amplification of shaking due to topography and ground conditions, and climate.

(a) Zone of fault rupture

During an earthquake seismic energy is thought to be released throughout a zone of fault rupture, rather than at a single point, the hypocentre or focus, which is the location at which an earthquake originates (represented on maps as the epicentre, the point immediately above the hypocentre on the ground surface). Keefer (1984) therefore suggested that the maximum distance of landslides from a fault-rupture zone may be a better relation than maximum epicentral distance. For a given earthquake, part of the fault rupture zone may be represented by a ground surface fault trace, or the sub-surface extent and orientation of the fault plane may be instrumentally defined by the distribution of aftershock hypocentres. The latter is potentially more useful to relate to landslide distribution as it can show more accurately the full extent of the fault rupture. Ground surface faulting is often very difficult to locate in bush-covered mountainous country, and only defines the parts of the fault rupture zone reaching the earth's surface.

In New Zealand a variety of fault rupture data are available. Except for the 1929 Murchison earthquake, only surface faulting data are available for older events (pre 1960), with aftershock data determined only for some more recent earthquakes. Of the earthquakes in Table 2 surface faulting occurred during 8 earthquakes (numbers 2, 3, 8, 9, 10, 12, 15 and 17) and aftershock data are available for 6 earthquakes (8, 15, 17, 18, 19, and 21). Both types of data are available for only three events (8, 15, and 17). Landsliding centred along the Kapo Fault (Figure 6) suggests that the rupture zone for the 1929 Arthur’s Pass earthquake was on that fault, although surface faulting was not reported. Accordingly, there are adequate data on 12 historical New Zealand earthquakes to allow relationships between landslide distribution and the probable fault rupture zone to be determined.

Relationships between landslide distribution and the rupture zone are summarised in Table 10. This shows that except for the 1888 North Canterbury earthquake (Figure 3) there is no obvious correlation of landslide distribution with ground surface faulting. This is probably because much of the surface faulting was of limited extent, as in the Murchison earthquake, or was secondary in nature, as occurred during the Hawke’s Bay, Wairoa, and Inangahua earthquakes. However, there is generally very good correlation of landslide distribution with the fault rupture zone indicated by aftershocks. This relationship is best demonstrated by the 1929 Murchison earthquake (Figure 7), 1968 Inangahua earthquake (Figure 13), 1990 Weber earthquake (Figure 15), and the 1994 Arthur’s Pass earthquake (Figure 17). This close relationship suggests that landslide distribution can provide an indication of the probable epicentre location and extent of the fault rupture zone for a given earthquake, although allowance must be made for topographic features, such as cliffs and escarpments where there are many landslide-susceptible slopes, or alluvial plains where there are few.
<table>
<thead>
<tr>
<th>EARTHQUAKE</th>
<th>RELATIONSHIPS OF LANDSLIDING TO FAULT RUPTURE ZONE</th>
<th>REPORT FIGURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2) Wairarapa, 18 Oct 1855 (Mw 8.2) [Depth 20 km]</td>
<td>Extensive surficial fault rupture along West Wairarapa Fault for about 90 km from coast. The landslide distribution shows no obvious relation to the fault trace, except at the southern end where there are numerous landslides on steep slopes of the Rimutaka Range within 5-7 km west and north of the epicentre.</td>
<td>2</td>
</tr>
<tr>
<td>(3) Nth Canterbury, 1 Sep 1888 (Mw 7.7-7.3) [Depth 10 km]</td>
<td>Well defined 30-35 km long surface trace on the Hope Fault. The greatest concentration of landsliding and ground damage was reported to be in the vicinity and south of the fault rupture zone, with other areas 15-20 km to the south. Landslide distribution shows clear link to the fault rupture zone.</td>
<td>3</td>
</tr>
<tr>
<td>(7) Arthur's Pass, 9 Mar 1929 (Mg 7.1) [Depth &lt; 15 km]</td>
<td>Main zone of landsliding and ground damage centred along the Kapapo Fault. Although no evidence of surface fault rupture was found, landslide distribution suggests that the earthquake was probably caused by near-surface rupture on the Kapapo Fault.</td>
<td>6</td>
</tr>
<tr>
<td>(8) Murchison, 16 June 1929 (Mg 7.8) [Depth 10 km]</td>
<td>Prominent 8 km long surface fault rupture on the White Creek Fault centred about the Buller River shows no obvious relation to landsliding. However, the probable full fault rupture zone indicated by relocated aftershocks extends about 75 km north and 25 km south of the epicentre close to the Buller River, very closely matching the main area of landsliding that has been identified.</td>
<td>7</td>
</tr>
<tr>
<td>(9) Hawke's Bay 3 Feb 1931 (Mg 7.6) [Depth 17 km]</td>
<td>Small (secondary) surface fault ruptures 40 km southwest of epicentre show no obvious link to landsliding, with strong topographic control of failures on steep coastal cliffs, and escarpments and gorges inland. The main fault rupture zone probably extended to within 5 km of the surface and centred mainly in the MM19 &amp; 10 zones of the epicentral area (Dowrick, in prep), where most landslides were located.</td>
<td>8</td>
</tr>
<tr>
<td>(10) Wairau, 18 Sep 1932 (Mg 6.9) [Depth 20 km]</td>
<td>A small (1 km) surface fault trace 12 km southwest of epicentre is centred in a significant area of landslides. That area and the other main area of landsliding near the epicentre are probably both within 5-10 km of a near-surface fault zone related to the earthquake.</td>
<td>9</td>
</tr>
<tr>
<td>(12) Masterton, 24 June 1942 (Mg 7.2) [Depth 15 km]</td>
<td>Two landslides close to a 2 km surface fault trace 8 km southwest of the epicentre, and a landslide area 2-5 km southwest, indicates a probable landslide-fault rupture zone association, but not strongly.</td>
<td>11</td>
</tr>
<tr>
<td>(15) Inangahua, 24 May 1968 (Mg 7.4) [Depth 10 km]</td>
<td>Two areas of surface fault rupture 12-22 km southwest of the epicentre show little association with landsliding. However the main aftershock zone coincides closely with the main area of landsliding.</td>
<td>13</td>
</tr>
<tr>
<td>(17) Edgecumbe, 2 Mar 1987 (Mg 6.6) [Depth 8 km]</td>
<td>Four well defined surface fault traces lie within or are very close to the aftershock (fault rupture) zone, 5 km SW of the epicentre. Most landslides and liquefaction effects were within 5-10 km of this zone.</td>
<td>14</td>
</tr>
<tr>
<td>(18) Weber, 13 May 1990 (Mg 6.4) [Depth 11 km]</td>
<td>No ground surface faulting was reported. However, the fault rupture zone indicated by aftershocks coincides closely with the main landslide areas, being mostly inside or within 4-5 km of it.</td>
<td>15</td>
</tr>
<tr>
<td>(19) Ormond, 10 Aug 1993 (Ms 6.2) [Depth 39 km]</td>
<td>No surface faulting reported. The main area of landsliding is mainly at the northern end or up to 5 km northwest of the aftershock zone, otherwise good correlation of fault rupture zone and landsliding.</td>
<td>16</td>
</tr>
<tr>
<td>(21) Arthur's Pass, 18 Jun 1994 (Mw 6.8) [Depth 4 km]</td>
<td>No ground surface faulting reported. However, there is very close agreement between landslide distribution and the fault rupture zone, as most of the landslides are within the area of aftershocks.</td>
<td>17</td>
</tr>
</tbody>
</table>

Table 10. Relationships of landsliding to fault rupture zone during NZ earthquakes.
(b) **Focal plane mechanism and seismic focussing**

In this study there has been little opportunity to look closely for a possible relationship between the focal plane mechanism (fault rupture type) of earthquakes causing significant landsliding, mainly because it has not been feasible to study any single earthquake in sufficient detail. It is likely, however, that a relationship does exist. For example, as ground accelerations are generally higher during reverse fault earthquakes than those with normal and transcurrent movements (Campbell, 1981; Joyner and Boore, 1988) more extensive landsliding might be expected during such events.

This is apparently true in the case of the 1929 Murchison earthquake, but as that was a very large magnitude ($M_s$ 7.8) earthquake in mountainous terrain, other factors such as steep, landslide susceptible slopes, combined with strong, long duration shaking were probably more important in triggering the widespread landsliding, including the many very large rock avalanches and Tertiary dip slope failures up to 90 km from the epicentre.

Tectonic focussing of seismic shaking, up or along the fault rupture plane, may also occur during certain types of earthquakes, leading to more intense (ground) damage effects in some areas adjacent to or along the fault rupture zone than in others. This may explain the apparent close association between landslide distribution and the fault ruptures zone, and is best demonstrated by the 1929 Murchison earthquake, and the 1888 North Canterbury earthquake, both of which were accompanied by extensive surface faulting, and also the 1994 Arthur's Pass earthquake, where landsliding was mostly within the aftershock (fault rupture) zone.

The results of this study have so far failed to demonstrate certain links between landslide distribution and focal plane mechanism, fault type, and seismic focussing during earthquakes. However, further detailed studies of landsliding during some specific large earthquakes (for example, 1929 Murchison, 1931 Hawke's Bay, 1932 Wairoa, and possibly the 1994 Arthur's Pass) may provide convincing evidence of such a relationship, and also a better understanding of the shaking effects and damage likely during future earthquakes.
(c) Topography and ground conditions

Whether a particular slope fails during an earthquake depends on many inter-related factors, including rock and soil type, material strength, and slope configuration. As already discussed, slope angle is clearly important in landslide susceptibility during earthquakes (Section 3.5), as is (to a lesser extent) slope aspect or direction relative to the epicentre. Rock falls generally originate on slopes steeper than 40°, such as cliffs, escarpments, and man-made excavations (road and rail cuts, quarry faces). Rock avalanches mainly originate on natural slopes steeper than 25°-30° and more than 100-200 m high, while rock and soil slides can form on slopes as gentle as 10° to more than 40°.

Landsliding during historical N Z earthquakes (Section 2) suggests that while cliffs, gorges, escarpments, and man-made cuts are particularly prone to earthquake induced landsliding, so too are narrow spurs and ridge crests, as illustrated by the large rock avalanches that formed on high ridges during the 1929 Murchison earthquake (e. g., Lindsay Landslide, Figure 7.1), the Big Buller slip during the 1968 Inangahua earthquake (Figures 13.2 and 13.3), and the many failures that occurred on Camp Spur during the 1994 Arthur’s Pass earthquake (see Figure 17.1). This suggests that earthquake shaking is amplified on high narrow ridges, making them particularly prone to rapid, large-scale landsliding, with steep slopes facing away from the epicentre being somewhat more vulnerable to failure.

Such topographic amplification of earthquake shaking on ridge crests is a common effect during earthquakes, and can result in ground damage ranging from very large rock avalanches (Dowrick, 1994) to ridge-top cracking (Franks et al., 1987) and also ridge rents if the cracking is more developed. Landslides due to amplification of earthquake shaking (as well as rock defects and weathering) commonly occur on steep coastal cliffs (Figures 7.7, 8.3, and 8.4), escarpments (Figures 7.6, 8.2, and 13.6), and river gorge slopes (Figure 13.5) as well as ridges (Figure 7.1, 7.4, and 7.5). If landslides or ground damage are isolated occurrences, they can probably be regarded as local strong shaking effects, but if they are numerous and widespread they are probably evidence of general strong shaking of at least intensity MM8-9 or MM10.

There are numerous examples of large and extensive landslides from steep ridges and rock faces during historical New Zealand earthquakes discussed in Section 2, as illustrated, for example by Figures 7, 8, and 15. Therefore, slope configuration and steepness are key factors, which together with lithology and geological structure, combine to control the distribution of rock fall, slides and avalanches during earthquakes. These relationships are well known (Keefer, 1984; Hansen and Franks, 1991; Brabaharan et al., 1994) and they enable areas below steep natural and man-made slopes to be zoned as highly hazardous and susceptible to the effects of earthquake-induced landsliding. In New Zealand, this hazard was tragically demonstrated during the 1929 Murchison earthquake, when fourteen people lost their lives due to rock falls and slides (Table 5), and the 1968 Inangahua earthquake when one person was killed by a rock fall from a steep limestone bluff (Table 7, Figure 13.6).
Earthquake shaking amplification also occurs on soft wet ground, in areas of high groundwater levels on alluvial plains and particularly around estuaries and along the banks of streams, rivers, and man-made canals. Slumping of banks, subsidence, and liquefaction phenomena such as sand boils and lateral spreads commonly occur in these areas during moderate and large earthquakes, mainly at MM7 - 8 or greater at maximum distances of 100 to 200 km from the epicentre (Figure 20.3). Such ground damage occurring at long distances is probably due to amplification of long-period, low frequency earthquake shaking associated with larger earthquakes of about M 6.3 or greater, as a result of susceptible ground conditions. It may also result from resonance effects in topographic basins filled with saturated cohesionless sediments near or at some distance from the epicentre.

Some earthquakes discussed in Section 2 show that thick deposits of colluvium and weathered bedrock (regolith) on steep slopes (30° or greater) are highly susceptible to landsliding during earthquakes. For example, many colluvial slides and slope debris avalanches occurred in the Buller Gorge during the 1929 Murchison and 1968 Inangahua earthquakes (Figures 7 and 15). These failures resulted from the oversteepening effects of high ground accelerations during earthquakes, which tend to be greater on slopes and ridge crests than in valley bottoms.
(d) Effects of climate

Climatic factors affecting landslide distribution during earthquakes are mainly water-related, including groundwater level, slope drainage, heavy and antecedent rainfall, and also slope direction or aspect (shady versus sunny) which affects soil moisture levels. However, as already mentioned, aridity also affects landslide distribution during earthquakes, with landslides often occurring at lower shaking intensities in arid areas than in temperate areas. Because rainfall regularly removes much of the less stable slope debris, stronger shaking seems to be required in temperate areas for earthquake-induced landsliding to occur. As no historical earthquakes in arid parts of New Zealand (such as Central Otago) have caused any significant landsliding, these effects have so far not been demonstrated in this country.

During strong earthquake shaking, groundwater in weak slope materials makes them more prone to failure by temporarily raising pore-water pressures and reducing soil strength. In some loose cohesionless slope materials liquefaction-induced flow movements may occur, and although this process has not been conclusively demonstrated during New Zealand earthquakes, it may have occurred within slide debris during some long-runout rock slide avalanches, such as the Matakitaki Landslide during the 1929 Murchison earthquake.

In general, climatic effects have not obviously influenced landsliding caused by New Zealand earthquakes, with magnitude, depth, and location close to susceptible slopes being the most important factors. Of the earthquakes discussed in this study (Table 2) 10 occurred during winter, 5 during spring, and 7 during summer. Only the 1929 Murchison earthquake was apparently affected by weather, with the landslides described as being particularly widespread because the winter of 1929 was very wet (Henderson, 1937). However, although this is probably true to some extent for that earthquake, and possibly in a minor way for some others that occurred during winter, other factors such as earthquake magnitude and depth, fault rupture zone, slope angle, topography, and geology are probably much more important in controlling landslide distribution during earthquakes than are climatic factors. Nevertheless, if other factors are about equal, earthquake-induced landsliding in New Zealand is likely to be somewhat more severe and widespread during winter than it is in summer.

For a given earthquake climatic influences in slope aspect do not appear to be a significant factor in controlling landsliding distribution. Rainfall-induced landslides are more likely to occur on “shady” slopes than on “sunny” slopes because of the higher and more prolonged antecedent moisture (the amount of moisture present in a soil mass at the beginning of a seasonal runoff period or storm event) experienced by “shady” or south-facing (100°-220°) slopes (Crozier, 1986). However, no such relationship can be demonstrated for earthquake-induced landslides in New Zealand (see Tables 3 to 8).
4. LANDSLIDING AND MM INTENSITY

4.1 Introduction

As discussed in Section 1, landslides and ground damage effects are poorly defined in the MM scale, partly because of their variability, and also because there are few comprehensive studies correlating landsliding with MM intensities or other seismicity parameters. The 1991 revision of the MM intensity scale (Study Group of the NZNSEE, 1992) made changes to the 1965 version (Eiby, 1966). However, these changes were primarily aimed at making the MM scale appropriate for modern earthquake resistant construction, and did little to redefine or clarify environmental criteria (landslides, subsidence, sand boils, lateral spreads) within it. A more recent revision to the intensity scale (Dowrick 1996) made improvements to the structural damage criteria for MM6 - MM8, included structural criteria for MM10 - MM12, and clarified and expanded the environmental criteria, reintroducing them for MM10. This version of the intensity scale is the most complete currently available for use in New Zealand.

In an earlier study of the 1929 Murchison earthquake, Dowrick (1994) was unable to assign MM10 from building damage, but suggested that shaking probably reached MM10 in the "heavy" landslide zone close to the fault rupture where there were no buildings, but was unable to assign that intensity because the environmental criteria were vague. Dowrick (1994) therefore suggested that criteria for assigning intensity based on landslides need to be described in more detail in order to be reliable at MM8 to MM10, and that a range of categories of landslide vulnerability similar to those used for buildings would be appropriate.

After comparing isoseismal maps with landslide distribution and noting discrepancies of one to five MM levels, Keefer (1984) also suggested that a revision of landslide-related criteria in the MM scale was needed. From his study of worldwide and USA earthquakes, Keefer’s suggested revisions are: (1) that shallow disrupted slides from steep slopes are common at MM6, (2) that rapid soil flows, lateral spreads, and coherent deep-seated slides from gentler slopes are common at MM7, and (3) that landslides of all types occasionally occur at one or two MM levels lower than the levels at which they are common (see Table 1).

From this study of historical earthquakes it has been possible to determine the minimum and most common magnitudes and MM intensities at which earthquake-induced landsliding has occurred in New Zealand. As discussed in Section 3.2, the minimum magnitude for minor landsliding is M 4.6 to 5.5, but significant landsliding generally only occurs during events of magnitude 6 or greater, at minimum shaking intensities of MM6. Most widespread landsliding has been caused by shallow earthquakes (about 30 km or less) of magnitude 6.2 to 7.8, at intensities of MM7 to MM10 at distances of up to 120 km. In general, larger earthquakes (M 6.7 or greater) cause landslides at a wider range of intensities and epicentral distances (MM6-10 at 2-200 km) than do smaller earthquakes (MM6-8 at about 1-30 km).
The magnitude threshold for significant earthquake-induced landsliding in New Zealand is thought to be about M 5, and the minimum intensity threshold for landsliding is MM6. The most common levels of shaking for landsliding (all types of slides) are MM7 and MM8, with the predominant minimum intensity being MM7. Most of the landslides that occurred at MM6 and 7 (or higher intensities) were small disrupted slides or falls. Landsliding caused by MM9 and 10 shaking has been more widespread and damaging, causing most of the known very large landslides. The minimum threshold for liquefaction phenomena during earthquakes was commonly MM7 for sand boils, and MM8 for lateral spreading. Such effects may also occur at one intensity level lower in areas of highly susceptible materials or abnormally high groundwater levels. In New Zealand, ground damage due to liquefaction is most common at intensities MM8 to 10 at epicentral distances of 10 to 100 km, with the minimum magnitude for sand boils and lateral spreads being about M 6.

4.2 Landslide criteria for assigning MM intensity

The summary of landsliding and ground damage in intensity zones MM6-9 during historical New Zealand earthquakes (Table 9) illustrates many of the points summarised above, and provides the basis for a suggested revision of environmental criteria in the MM scale by expanding and describing landslide and ground damage effects in more detail. The proposed amendments to the wording of the criteria relating to landsliding and ground damage responses of the environment at intensities MM6 - MM10 of the MM scale are presented in Table 11. For ease of comparison, the text of the environmental criteria included in the NZ 1996 Modified Mercalli Intensity Scale (Dowrick, 1996) is also included. The significance of these criteria in relation to causative earthquakes and areas likely to be affected are discussed below.

Landsliding and ground damage may occur during some but not all earthquakes causing MM6 shaking. Minor landsliding and liquefaction effects likely in near field (say < 20 km) for MM6 shaking caused by moderate earthquakes (about M 6-6.7). In the MM6 zones associated with larger earthquakes (> M 7) little landsliding has been reported in New Zealand, probably because of the greater epicentral distances at which MM6 intensity shaking occurs, where longer duration and lower frequency shaking may cause slight building damage and sand boils, but few slope failures, except on steep cuts or cliffs in very weak materials. Of the 16 earthquakes for which good data are available, minor landsliding occurred at MM6 only during 7 events. No landsliding was recorded at MM6 for 9 earthquakes.

Minor to significant landsliding is very likely to occur at intensity MM7 during moderate to large earthquakes (say M 6.2 - M 7.4) in New Zealand. Small to moderate-sized landslides and occasional cases of non-damaging liquefaction (sand boils, water ejections) have occurred during most earthquakes causing MM7 shaking. However, except on highly susceptible very steep cliffs, few or no landslides have occurred in the MM7 zones of some large and damaging earthquakes, such as 1855 Wairarapa, 1929 Arthur’s Pass, Murchison, 1931 Hawke’s Bay, and 1932 Wairoa. As for MM6, this is probably because of the greater epicentral distances at which MM7 intensity shaking occurred for those larger earthquakes. Landsliding at intensity MM7 has been notably more extensive during moderate to large earthquakes at epicentral distances of about 15 to 120 km (see Figure 20.2).
<table>
<thead>
<tr>
<th>MODIFIED MERCALLI INTENSITY SCALE - N Z 1996 (Dowrick, 1996)</th>
<th>REVISED MODIFIED MERCALLI INTENSITY SCALE - N Z 1997 (this report)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Existing Environmental Criteria</strong></td>
<td><strong>Suggested New Environmental Criteria</strong></td>
</tr>
<tr>
<td><strong>MM6</strong> Trees and bushes shake, or are heard to rustle.</td>
<td><strong>MM6</strong> Trees and bushes shake, or are heard to rustle.</td>
</tr>
<tr>
<td>Loose material may be dislodged from sloping ground. e.g.</td>
<td>Loose material dislodged on some slopes, e.g. existing</td>
</tr>
<tr>
<td>existing slides, talus slope, shingle slides.</td>
<td>slides, talus and scree slope.</td>
</tr>
<tr>
<td></td>
<td>A few very small (≤ 10³ m³) soil and regolith slides and</td>
</tr>
<tr>
<td></td>
<td>rock falls from steep banks and cuts.</td>
</tr>
<tr>
<td></td>
<td>A few minor cases of liquefaction (sand boil) in highly</td>
</tr>
<tr>
<td></td>
<td>susceptible alluvial and estuarine materials.</td>
</tr>
<tr>
<td><strong>MM7</strong> Water made turbid by stirred up mud.</td>
<td><strong>MM7</strong> Water made turbid by stirred up mud.</td>
</tr>
<tr>
<td>Small slides such as falls of sand and gravel banks, and</td>
<td>Very small (≤ 10³ m³) disrupted soil slides and falls of</td>
</tr>
<tr>
<td>small rock falls from steep slopes and cuttings.</td>
<td>sand and gravel banks, and small rock falls from steep</td>
</tr>
<tr>
<td>Instances of settlement of unconsolidated or wet or weak</td>
<td>slopes and cuttings are common.</td>
</tr>
<tr>
<td>soils.</td>
<td>Fine cracking on some slopes and ridge crests.</td>
</tr>
<tr>
<td>Some⁡ fine cracks appear in sloping ground.</td>
<td>A few small to moderate landslides (10²-10⁶ m³), mainly</td>
</tr>
<tr>
<td>A few⁡ instances of liquefaction (e.g. small water and</td>
<td>rock falls on steeper slopes (&gt;30°) such as gorges,</td>
</tr>
<tr>
<td>sand ejections).</td>
<td>coastal cliffs, road cuts and excavations.</td>
</tr>
<tr>
<td></td>
<td>Small discontinuous areas of minor shallow sliding and</td>
</tr>
<tr>
<td></td>
<td>mobilisation of scree slopes in places.</td>
</tr>
<tr>
<td></td>
<td>Minor to widespread small failures in road cuts in more</td>
</tr>
<tr>
<td></td>
<td>susceptible materials.</td>
</tr>
<tr>
<td></td>
<td>A few instances of non-damaging liquefaction (small water</td>
</tr>
<tr>
<td></td>
<td>and sand ejections) in alluvium.</td>
</tr>
<tr>
<td><strong>MM8</strong> Cracks appear on steep slopes and in wet ground.</td>
<td><strong>MM8</strong> Cracks appear on steep slopes and in wet ground.</td>
</tr>
<tr>
<td>Small to moderate slides in roadside cuttings and</td>
<td>Significant landsliding likely in susceptible areas.</td>
</tr>
<tr>
<td>unsupported excavations.</td>
<td>Small to moderate (10⁰-10⁴ m³) slides widespread; many</td>
</tr>
<tr>
<td>Small water and sand ejections, and localised</td>
<td>rock and disrupted soil falls on steeper slopes (steep</td>
</tr>
<tr>
<td>lateral spreading adjacent to streams, canals, and lakes</td>
<td>banks, terrace edges, gorges, cliffs, cuts etc). Significant</td>
</tr>
<tr>
<td>etc.</td>
<td>areas of shallow regolith landsliding, and some reactivation of</td>
</tr>
<tr>
<td></td>
<td>scree slopes.</td>
</tr>
<tr>
<td></td>
<td>A few large (10⁵-10⁶ m³) landslides from coastal cliffs,</td>
</tr>
<tr>
<td></td>
<td>and possibly large to very large (&gt;10⁶ m³) rock slides and</td>
</tr>
<tr>
<td></td>
<td>avalanches from steep mountain slopes.</td>
</tr>
<tr>
<td></td>
<td>Small temporary landslide-dammed lakes may be formed by</td>
</tr>
<tr>
<td></td>
<td>larger landslides in narrow valleys.</td>
</tr>
<tr>
<td></td>
<td>Roads damaged and blocked by small to moderate failures of</td>
</tr>
<tr>
<td></td>
<td>cuts and slumping of road-edge fills.</td>
</tr>
<tr>
<td></td>
<td>Evidence of liquefaction common, with small sand boxes and</td>
</tr>
<tr>
<td></td>
<td>water ejections in alluvium, and localised lateral</td>
</tr>
<tr>
<td></td>
<td>spreading (fissuring, sand ejections) and settlements along</td>
</tr>
<tr>
<td></td>
<td>banks of rivers, lakes, canals etc.</td>
</tr>
</tbody>
</table>

**NOTES:**
1. Early results from the present study contributed to the environmental criteria of Dowrick (1996) shown above.
2. "Some" or a few indicates that the threshold for a particular effect or response has just been reached at that intensity.
3. Intensity is principally a measure of damage. Environmental damage (response criteria) occur mainly on susceptible slopes and 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.

Table 11. Proposed environmental criteria for the NZ Modified Mercalli Intensity Scale.
<table>
<thead>
<tr>
<th>MODIFIED MERCALLI INTENSITY SCALE - N Z 1996 (Dowrick, 1996)</th>
<th>REVISED MODIFIED MERCALLI INTENSITY SCALE - N Z 1997 (this report)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Existing Environmental Criteria</strong></td>
<td><strong>Suggested New Environmental Criteria</strong></td>
</tr>
<tr>
<td><strong>MM9</strong> 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.</td>
<td><strong>MM9</strong> 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 rockfalls 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 (10^2-10^6 m^3) failures of regolith and bedrock, and some very large landslides (10^6 m^3 or greater) on steep susceptible slopes. Very large failures on coastal cliffs and low-angle bedding plane slides likely in Tertiary rocks. Large rock &amp; debris avalanches formed on steeper mountain slopes in well jointed greywacke and granitic rocks. Landslide-dammed lakes may be 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 likely, and extensive, potentially damaging lateral spreading (fissuring and sand ejections) along banks of rivers, lakes, canals etc. Spreading and settlements of river stop banks and other embankments likely.</td>
</tr>
<tr>
<td><strong>MM10</strong> 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.</td>
<td><strong>MM10</strong> Landsliding very widespread in susceptible terrain. Similar effects to MM9, but more intensive and severe, with very large rock masses displaced on steep mountain slopes and coastal cliffs. Large landslide-dammed lakes may be formed. Many moderate to large failures of 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 are 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.</td>
</tr>
</tbody>
</table>

**NOTES:**
1. Early results from the present study contributed to the environmental criteria of Dowrick (1996) shown above.
2. "Some" or "a few" indicates that the threshold for a particular effect or response has just been reached at that Intensity.
3. Intensity is principally a measure of damage. Environmental damage (response criteria) occur mainly on susceptible slopes and 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.
4. 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 12 are similar to the new criteria proposed for MM9 and 10 above, but are possibly more severe.

Table 11. Proposed environmental criteria for the N Z Modified Mercalli Intensity Scale.  
(page 2 of 2)
Landsliding caused by intensity MM8 shaking in New Zealand has occurred in the epicentral areas of moderate to large earthquakes (M 6.2 - 7.4) at epicentral distances of about 5-50 km, and at greater distances (c.50-120 km) during larger earthquakes (M 7.8 - M 8.2, Figure 20.2).

Landsliding caused by intensity MM9 shaking in New Zealand has occurred mainly in the epicentral areas of large earthquakes (M 7.1 - M 8.2) at epicentral distances of 10 km or less to about 90 km (Figure 20.2). However, some moderate earthquakes (M 6.6 - 6.9, such as Cheviot 1901, Wairoa 1932, and Edgecumbe 1987) have also caused landsliding and liquefaction-induced ground damage at MM9, but generally at epicentral distances of less than 20 km. Intensity MM9 appears to be the threshold for widespread and damaging landsliding. All of the largest and most significant earthquake-induced landslides in New Zealand have at occurred at intensity MM9 or greater, as have all the known extremely large landslides (those with volumes of 50 million m³ or greater), regardless of cause.

Although there are few confirmed cases of MM10 shaking in New Zealand, all have caused widespread landsliding and ground damage effects in the epicentral area similar to, and not obviously greater those described for MM9. In some cases this is because the earthquake was located in less susceptible terrain (e.g. alluvial plains). In other cases it is due to the poor MM data that are available from the epicentral areas of large earthquakes, many of which occurred in mountainous terrain where there are few buildings. For example, in his study of the 1929 Murchison earthquake, Dowrick (1994) was unable to assign MM10 from building damage, but considered that shaking probably reached MM10 in the “heavy” landslide zone close to the fault rupture where there were no buildings.

Therefore, during some large earthquakes, landslides in some areas previously zoned as MM9 (or MM8) on the basis building damage alone, may in fact have been caused by intensity MM10 (or MM9) shaking. It is likely that this is the case for some large landslides on high ridge crests, where topographic amplification has caused higher intensity shaking locally. Although isolated occurrences of such landslides can probably be attributed to local site effects, numerous failures of that nature probably represent high intensity shaking over the entire affected area. Therefore, extensive and very large landslides have been used in this study to re-define zones of MM9 and MM10 shaking for the 1929 Murchison and 1855 Wairarapa earthquakes, and establish a MM9 zone for the 1929 Arthur’s Pass earthquake.

Although construction response criteria in the MM intensity scale have been developed for MM11 and MM12 (see Appendix 1b), shaking at these levels has not been reported in New Zealand. The proposed criteria are therefore speculative, and the probability of shaking greater than MM10 occurring in a New Zealand urban area is considered to be low (Dowrick, 1996). For these reasons, no attempt was made to propose environmental criteria for MM11 and 12 in this study. However, earlier versions of the intensity scale (Appendix 1a) refer to “large rock masses displaced” at MM12. Accordingly, the effects of the 1929 Murchison earthquake, New Zealand’s most damaging historical earthquake in terms of landsliding, probably illustrate the type of environmental responses that can be expected at MM9 and greater. The shaking intensity on high ridges where very large landslides formed during the Murchison earthquake probably reached at least MM10 locally, and possibly MM11-12.
4.3 Ground type classes and MM Intensity

Dowrick (1994, 1996) suggested that it would be helpful if environmental responses could be developed in relation to different classes of ground (similar to the classification used in the MM scale for structures) that could be used for assigning more consistent and reliable earthquake intensities in areas where there were few buildings. For particular earthquakes, such an approach would relate the landslide susceptibility of the terrain to factors such as slope angle, rock type, stratigraphy, and groundwater conditions etc. Relationships to these and other factors have been addressed in this study (Section 3) but it has not been possible to reach firm conclusions on ground type classes. However, based on landslide effects distinguished during this study a preliminary classification of ground type classes for identifying landslide susceptibility and effects within the MM intensity scale (mainly in the near field) is as follows:

**Ground Type I:**
(a) Bedrock - massive hard to firm rocks, relatively unbedded and both widely jointed, and well jointed indurated greywacke and granitic rocks, moderately weathered to fresh, with thin (<1-2 m) surficial colluvial materials, on gentle to moderate slopes (5°-30°). Also, firm older alluvial deposits (gravel) forming high terraces (not terrace edges).
(b) Supported cut slopes in bedrock; engineered fills on firm ground.

*Susceptibility to earthquake-induced landsliding or failure:* Low - very low
*Average change in MM intensity levels:* 0

**Ground Type II:**
Bedrock - well bedded, slightly to moderately weathered Tertiary sandstone, mudstone, and limestone dipping down slope on gentle to moderate slopes (15°-30°, dip slopes), with thin regolith and thin surficial materials. Also firm-stiff soils.

*Susceptibility to earthquake-induced landsliding or failure:* Moderate-high
*Average change in MM intensity from Type I:* + 0.5 - 1

**Ground Type III:**
Bedrock - well jointed indurated greywacke and granitic rocks, moderately to highly weathered, with thick (>5 m) regolith and colluvium on high, steep to very steep (say 35°-50°) slopes, and on high narrow ridges (near and far field). Also low gravel banks and terrace edges, scree, and slopes and cuts formed in loose unconsolidated deposits.

*Susceptibility to earthquake-induced landsliding or failure:* High
*Average change in MM intensity from Type I:* + 1 - 1.5

**Ground Type IV:**
(a) Areas of very steep (>45°) natural slopes in hard, well jointed rocks and also weaker Tertiary rocks (such as coastal cliffs, escarpments, gully heads, and gorges).
(b) Unsupported high (>3-6 m), steep to very steep (say >60°) cuts and excavations in harder bedrock and soft rocks, especially those cuts capped with 1-3 m of soils and regolith deposits, and not designed to withstand the effects of seismic shaking.

*Susceptibility to earthquake-induced landsliding or failure:* High-very high
*Average change in MM intensity from Type I:* + 1 - 2

**Ground Type V:**
Loose, saturated, unconsolidated, fine-grained (fine sand and silt), alluvial, estuarine and marine deposits, and other soft sediments, and non-engineered fills and reclamations on flat, low-lying terrain and gentle slopes (<10°).

*Susceptibility to earthquake-induced failure or liquefaction:* High - very high
*Average change in MM intensity from Type I - Near field:* + 0.5 - 1
*Low frequency shaking - Far field* (M 7.2 earthquakes): + 1 - 3

---

1 The extent (radius) of the Near Field and maximum epicentral MM intensity varies with earthquake magnitude, approximately as follows: M 5.0 - MM5, 5 km; M 5.5 - MM7, 15 km; M 6.0 - MM8, 25 km; M 6.5 - MM9, 35 km; M 7.0 - MM10, 40 km; M 7.5 - MM11, 45 km (Kalinitsky and Chang, 1977).
The concept of the *Near Field and Far Field* was developed by Krinitzsky and Chang (1977) to improve the predictability of intensity-based ground motions. The extent (radius) of the *Near Field* and maximum epicentral MM intensity varies with earthquake magnitude, and as defined by Krinitzsky and Chang (1977) are approximately as follows:

<table>
<thead>
<tr>
<th>Magnitude</th>
<th>Intensity</th>
<th>Radius of near field (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M 5.0</td>
<td>MM6</td>
<td>5</td>
</tr>
<tr>
<td>M 5.5</td>
<td>MM7</td>
<td>15</td>
</tr>
<tr>
<td>M 6.0</td>
<td>MM8</td>
<td>25</td>
</tr>
<tr>
<td>M 6.5</td>
<td>MM9</td>
<td>35</td>
</tr>
<tr>
<td>M 7.0</td>
<td>MM10</td>
<td>40</td>
</tr>
<tr>
<td>M 7.5</td>
<td>MM11</td>
<td>45</td>
</tr>
</tbody>
</table>

The above ground type classes are provisional, based on subjective landslide data used in this study. However, the classes proposed here are broadly consistent with Van Dissen et al. (1992) in their earthquake and ground shaking hazard assessment in Wellington.

For example, on soft and or loose, saturated ground (*proposed Ground Type V*), Van Dissen et al. (1992) suggested MM shaking intensity increases (compared to greywacke bedrock) of plus 1-2 for near field and plus 2-3 for far field effects. These increases probably result from frequency-dependent ground motion amplification (resonance effects), and also increased duration of strong shaking duration, which on soft ground during large earthquakes may be more than 2-3 times greater in the near and far field respectively (Van Dissen et al., 1992).

More detailed studies of landsliding during selected specific earthquakes (such as Murchison, 1968 Inangahua) are required and recommended to refine and establish more definitive ground type classes, and their inter-relationships, and to clarify their use within the MM intensity scale and application in seismic hazard assessments.
4.4 Other earthquake intensity scales

There are several other types of earthquake intensity scales for describing earthquake effects. Below is a comparison of some of these scales (after Krinitzsky and Chang, 1988).

Of the intensity scales commonly used today (right), only the Japanese (JMA) scale differs greatly from the MM scale. The JMA scale has few environmental criteria, referring to "numerous landslides, embankment failures, and fissures on flat ground" at only JMA VI (= MM9). The Rossi-Forel scale does not distinguish between separate levels of severe damage to structures or the environment, and has fallen from use. The Chinese scale is almost identical to the MM scale, while the Medvedev, Sponheuer and Karnik (MSK) version is a slight modification of the MM scale. In 1992 the MSK scale was renamed the European Macroseismic Scale (EMS), but it remains broadly similar level-for-level (Dowrick, 1996).

Environmental criteria are also quite well defined within the MSK scale. The following is a summary of the environmental responses that are highlighted:

**MSK VI** - Narrow cracks (up to 10 cm) in wet ground, occasional landslides in mountains.

**MSK VII** - Isolated falls from sandy and gravelly banks.

**MSK VIII** - Small landslips in hollows and embankments; cracks several cm in ground.

**MSK IX** - On flat land overflow of water, sand, and mud is often observed (liquefaction effects); ground cracks to widths of up to 10 cm; falls of rock, many landslides & earth flows.

**MSK X** - In ground, cracks up to widths of several decimeters, sometimes up to 1 m. Broad fissures occur parallel to water courses. Loose ground slides from steep slopes. Considerable landslides are possible from river banks and steep coasts. In coastal areas, displacements of sand and mud; new (landslide-dammed) lakes formed.

**MSK XI+** - Ground fractured considerably by broad cracks and fissures, slumps and spreads; numerous landslides and falls of rock. Other effects similar to MMX, but more severe.

Environmental criteria in the MSK scale are similar to new criteria proposed above (Table 11), which are considered somewhat more detailed and appropriate for use in New Zealand.
5. IMPLICATIONS FOR HAZARD AND RISK ASSESSMENT

Relationships between earthquake magnitude, zone of fault rupture, shaking intensity, and the distribution of landslides discussed in preceding sections of this report, suggest that it should be possible predict the area likely to be affected by landsliding and its severity during future earthquakes of given magnitude and location. If this information is combined with rock type, topographic, and other data it will be feasible to assess earthquake-induced landslide hazards, and hence the damage potential and risk, during different earthquake scenarios. Following a review of historical earthquake-induced slope failures in Wellington (Hancox et al., 1994), this type of approach was used by Brabbaharan et al. (1994) to assess the future earthquake-induced slope failure hazard potential in the entire Wellington Region.

The present study of earthquake-induced landsliding in New Zealand has allowed national relationships to be developed for landslide distribution with which it is possible to assess earthquake-induced landslide susceptibility for different parts of the country. Although this could be done at a simple level with the results of the present study that are currently available and already described, it is unfortunately beyond the scope of this report. However, these results have significant implications for futures studies of earthquake-induced landslide hazard and risk in New Zealand and these are discussed briefly below.

Possible future studies planned by GNS involve development of a preliminary National Landslide Hazard Model for New Zealand using existing geology and the GNS Large Landslide Database using GIS, and incorporating the New Zealand database of earthquake-induced landslides created during the present study, plus new data on landslide damage and effects to be sought from Regional and District Councils, Transit NZ, and EQC and others. This would be preceded and aided by preparation of an overview report on the occurrence, nature and causes of both large and small landslides in NZ, their relationships to geology, topography and climate, and development of a methodology for integrating this information into a National Landslide Hazard Model. This model would incorporate methods used for recent New Zealand landslide zonation studies such as those in Wellington (Brabbaharan et al., 1994), Dunedin (Hancox, 1994; Glassey et al., 1994), Nelson (Johnston et al., 1993), and Auckland (Beca Carter, 1997).

The National Landslide Model and GIS application of it would be refined and tested by finishing a landslide susceptibility zonation study in the Dunedin area (partly completed, Glassey et al., 1994). This would involve inclusion of aspects of the National landslide model and additional factor layers (for surficial materials, ground-water, and slope modification). The model would then be applied and tested using GIS in areas with different rock types, terrain, climate, seismicity, and stability problems (e.g. Auckland, Whangarei, Wanganui, Nelson, Gisborne). Local information and new data from this study and GNS landslide databases would also be incorporated. The model would be adjusted as appropriate to predict landslide susceptibility in different regions of the country by refining the number and weighting of key causal factors (rock and soil types, slope angle and height, groundwater etc). Landslide potential in these regions could then be assessed by modelling the combined factors for major triggering events such as rainstorms and moderate to large earthquakes. The results of the present study will contribute significantly to the latter, as would future detailed studies of some large earthquakes (such as 1929 Murchison and 1932 Wairoa, see Section 6).
6. **RECOMMENDATIONS**

Understanding of the landsliding and ground damage that occurs during earthquakes in New Zealand has been advanced significantly by this study. Threshold levels for landslides and liquefaction phenomena have been established for earthquake magnitude and MM shaking intensity, along with relationships to the likely areas affected, the epicentre and zone of fault rupture. Revised environmental response criteria have been developed for use in the MM intensity scale have been developed, and preliminary ground type classes are proposed for identifying landslide susceptibility and differences in relative shaking intensity. However, the suggested ground classes and relationships of landsliding and ground failure to MM intensities are somewhat tentative, and further research is needed better define these important issues.

The following future studies are recommended to further improve our understanding of earthquake-induced landsliding and site effects in New Zealand:

1. **Detailed studies of the 1929 Murchison, 1968 Inangahua, and 1855 Wairarapa earthquake** to: (a) better define the areas of greatest landslide damage, and relationships to assigned epicentres and possible fault rupture zones, geology, slope types, and assigned MM intensities; and (b) compare their mechanisms and effects, and examine future seismotectonic hazard potential in the northwest Nelson and Wellington areas.

2. **Further refinement of ground type Classes established in this study** to better define the rock and soil types, slope conditions, landslide susceptibility, and relative differences in MM intensity in both the near and far field for each class. This would allow landslides and ground damage in different ground types to be used to assign with greater confidence MM intensities in areas where there are no buildings or structural damage.

3. **Incorporation of the main results of this study, particularly the earthquake-induced landslide database, and relationships that have been established between landslide distribution and earthquake magnitude, MM intensity, rock and soil types, and slope configuration into a GIS-based National Landslide Hazard Model.**

4. **Paleoseismic studies rely on evidence of the seismic origin of the landslides by a single earthquake, as shown by absolute or comparative (vegetation, geomorphic) dating. Landslide distribution can then be used to show the area affected by the earthquake, from which an indication of the earthquake epicentre, fault rupture zone, and magnitude can be determined. Such relationships developed during this study can be used with some confidence in future paleoseismic studies.**

It is therefore recommended that a pilot study be carried out to explore paleoseismic applications of earthquake/landslide relationships developed in this study. Possible key areas for such a study are the known “seismic gaps” on major active faults, such as the central and southern (Fiordland) sections of the Alpine Fault, and the southern end of the White Creek Fault.

5. **Continued reconnaissance studies of landsliding and other ground damage resulting from future moderate and large (M 6-7 and greater) earthquakes in New Zealand, and also some important large earthquakes overseas, to further improve our understanding of the effects and hazards associated with earthquake-induced landsliding.**
7. CONCLUSIONS

This study of landsliding and ground damage caused by 22 historical earthquakes in New Zealand has enabled relationships between landslide distribution and earthquake magnitude, epicentre, and the fault rupture zone to be defined, and revised environmental response criteria and ground classes to be proposed for assigning MM intensities in New Zealand. Potential applications of these relationships and criteria in future seismic hazard assessments, and possible further studies have also been discussed. The main conclusions resulting from the study are as follows:

(1) The minimum magnitude for minor earthquake-induced landsliding in New Zealand is about M 5. Significant landsliding occurs only at M 6 or greater. Most widespread landsliding has been caused by shallow earthquakes (< 45 km) of M 6.2- 8.2, at epicentral distances of up to about 150 km. The minimum MM intensity threshold for landsliding during earthquakes in New Zealand is MM6, while the most common intensities for significant landsliding are MM7 and 8. Small landslides at MM6 and distances of up about 300 km have caused little damage. Widespread and damaging large landslides occur mainly at MM9 and 10. Landslides at all intensities were mostly disrupted slides or falls or rock and soil.

(2) Relationships of landsliding to earthquake magnitude and intensity in New Zealand are generally consistent with overseas data. Although the magnitude threshold for landsliding worldwide is M 4 and the intensity threshold is MM4 - MM5, the predominant minimum intensities are MM6 and 7. Landslides during overseas earthquakes appear to be influenced by data from arid areas, where slopes can fail at weaker shaking levels than in temperate areas, possibly because there is less rainfall to remove loose rock and soil debris on slopes.

(3) The intensity threshold for liquefaction during N Z earthquakes was found to be MM7 for sand boils, and MM8 for lateral spreading, although such effects may also occur at one intensity level lower in highly susceptible materials. Ground failure due to soil liquefaction is most common at intensities MM8-10, at distances of 10-100 km. The minimum magnitude for liquefaction is about M 6, but is more likely during longer-duration moderate and large earthquakes (>M 6.2- M 7). Maximum distances of liquefaction from epicentres of New Zealand earthquakes may be predicted by the Kuribayashi and Tatsuoka (1975) equation, which is as follows: Log10 R_max (distance, km) = 0.77 M (magnitude) -3.6.

(4) Correlations between magnitude and landsliding for N Z earthquakes show the maximum area affected by landslides ranges from about 100 km² at M 5 to 20,000 km² at M 8.2. The expression: Log10 A (area km²) = 0.96 M (magnitude) - 3.7 was developed to estimate the area affected by landslides during earthquakes in N Z. Conversely, earthquake magnitude can be estimated from landslide areas by the expression: M = 1.04 Log10 A + 3.85.

(5) Landslide size in New Zealand also shows a strong correlation with magnitude, intensity, and epicentral distance. Very small to small (< 10²-10⁴ m³) landslides occur at maximum distances of almost 300 km for M 8.2 (at MM6). Moderate to large landslides (10⁴-10⁶ m³) generally occur at greater than M 6- 6.5, and distances of about 5-70 km (MM8-MM7). Very large and extremely large (10⁷-10⁹ m³) landslides only occur at magnitudes greater than about M 6.9 and 7.1, at distances of about 10 to 100 km (MM10 to MM8). Extensive and very large landslides are used in this study to re-define MM9 and 10 zones for the 1929 Murchison and 1855 Wairarapa earthquakes, and establish a MM9 zone for the 1929 Arthur's Pass earthquake.

(6) Landslides occur at greater distances, and the areas in which they occur are generally larger during overseas earthquakes than New Zealand earthquakes because of poorly understood combinations and interactions of topographic, geologic, climatic, and seismic factors.
(7) Earthquake-induced landslides occur mostly on moderate to very steep slopes (20°-50°), and mainly fail obliquely or directly away from the epicentre. However, many rock falls and slides are independent of epicentre location on very steep (35°-70°) cliffs and escarpments, which are more susceptible to rapid failure because of rock defects, poor strength, and topographic amplification of shaking. Failures in well jointed rocks (e.g. greywacke, granite) occur mainly on moderate to steep (25°-45°) slopes. Landslides of Tertiary sandstone and mudstone often occur on gentle to steep (10°-40°) dip slopes, whereas limestone failures mainly occur on steep cliffs and escarpments. Larger rock slides and rock avalanches are more likely caused by larger earthquakes (> M 6.5) on slopes steeper than 25°-30° and more than 100-200 m high on strongly shaken high narrow ridges. The most common earthquake-induced landslides are small to moderate disrupted rock and soil falls and slides from steep gravel banks, cliffs, gorges, and high unsupported man-made cuts at MM8 shaking or greater. Areas below high steep natural and man-made slopes are therefore highly hazardous during earthquakes.

(8) There is seldom an obvious correlation of landslide distribution with ground surface faulting focal mechanism (fault type), and seismic focussing during earthquakes. However, a good correlation has been demonstrated between landsliding and the fault rupture zone indicated by aftershocks. Accordingly, for a particular earthquake, landslide distribution may provide an indication of the probable epicentre location and extent of the fault rupture zone, although allowance must be made for topographic effects on cliffs and very steep slopes. Although climatic factors have not greatly affected the severity of earthquake-induced landsliding in New Zealand, if other factors are about equal, landslide damage is likely to be somewhat more severe and widespread during winter than it is in summer.

(9) Earthquakes that trigger landslides are more likely in northwest Nelson, the central Southern Alps, Fiordland, Marlborough, Wellington, Wairarapa, Hawke’s Bay, and East Cape areas. Historically, this is the area where most of the shallow earthquakes of magnitude 5 and 6 or greater have been located. The most commonly affected rock types are greywacke, granite, schist and conglomerate, Tertiary sandstone, mudstone, limestone, and Quaternary volcanics and tephra. Few earthquakes of M 5-6 or greater are known to have occurred in the central North Island, Auckland, Canterbury and Central Otago and Southland areas, where the hazard from earthquake-induced landsliding is regarded as low.

(10) More detailed and expanded environmental response criteria (landslides, subsidence, sand boils, lateral spreads) in the MM intensity scale have been proposed, along with provisional group type classes of varying landslide susceptibility (similar to those used for buildings). The latter are based on landslide effects in different terrain, rock, and soil types, and it is hoped that when refined they can ultimately be used for assigning more consistent and reliable earthquake intensities in areas where there were few buildings.

(11) Relationships developed in this study between landslide distribution and environmental and seismic parameters can be used to assess earthquake-induced landslide susceptibility hazard and risk in New Zealand. Further studies are recommended to incorporate results from this study into a GIS-based National Landslide Hazard Model, which could be used to predict or zone landslide hazard in different parts of New Zealand for triggering events such as moderate to large earthquakes and rainstorms. Other research that is also recommended includes detailed studies of some earthquakes (e.g. 1929 Murchison, 1855 Wairarapa) to refine the ground type classes, palaeoseismic studies in known “seismic gaps” on major active faults, and continued earthquake reconnaissance studies in New Zealand and overseas.
8. References


Institute of Geological & Nuclear Sciences Limited

Earthquake-induced landsliding in NZ & implications for MM intensity and hazards


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APPENDIX 1a

MODIFIED MERCALLI EARTHQUAKE INTENSITY SCALE - NZ 1965 AND NZ 1991 PROPOSED VERSIONS

[Source: Bulletin of the N Z National Society for Earthquake Engineering, 25(4):345-357]
MODIFIED MERCALLI INTENSITY SCALE - NZ 1991

NZ 1965

MM1 Not felt by humans, except in especially favourable circumstances, but birds and animals may be disturbed. Reported mainly from the upper floors of buildings more than 10 storeys high. Dizziness or nausea may be experienced.

Branches of trees, chandeliers, doors, and other suspended systems of long natural period may be seen to move slowly.

Water in ponds, lakes, reservoirs, etc., may be set into seiche oscillation.

MM2 Felt by a few persons at rest indoors, especially by those on upper floors or otherwise favourably placed.

The long-period effects listed under MM1 may be more noticeable.

MM3 Felt indoors, but not identified as an earthquake by everyone. Vibration may be likened to the passing of light traffic.

It may be possible to estimate the duration, but not the direction. Hanging objects may swing slightly. Standing motorcars may rock slightly.

NZ 1991 Proposed

MM1 People

Not felt except by a very few people under exceptionally favourable circumstances.

MM2 People

Felt by persons at rest, on upper floors or favourably placed.

MM3 People

Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake.

COMMENTS

MM1. (1) "Reported mainly from ..." defines one favourable circumstance.

(2) "Birds and animals disturbed" and "systems of long natural period may ... move slowly". These phenomena may be observed at any intensity and are thus not definitive of any particular intensity.

MM2. The reference to an increase in long-period effects is tautological: it will be true of all intensities.

MM3. (1) The use of "trucks" rather than "traffic" is considered clearer.

(2) The NZ 1965 qualification "but not direction" is redundant - see MM 5.

(3) The reference to motorcars rocking slightly, but with the suggestion that their occupants could be unaware of the motion is considered doubtful (cf MM 4).
NZ 1965

MM4 Generally noticed indoors, but not outside.
Very light sleepers may be wakened.
Vibration may be likened to the passing
of heavy traffic, or to the jolt of a heavy
object falling or striking the building.
Walls and frame of buildings are heard
to creak.
Doors and windows rattle.
Glassware and crockery rattle.
Liquids in open vessels may be slightly
disturbed.

Standing motorcars may rock, and the
shock can be felt by their occupants.

NZ 1991 Proposed

MM4 People

Generally noticed indoors but not outside.
Light sleepers may be awakened.
Vibration may be likened to the passing
of heavy traffic or to the jolt of a heavy
object falling or striking the building.

Fittings

Doors and windows rattle. Glassware
and crockery rattle. Liquids in open
vessels may be slightly disturbed.
Standing motorcars may rock.

Structures

Walls and frame of buildings, and
partitions and suspended ceilings in
commercial buildings, may be heard to
creak.

COMMENTS

MM4. (1) "Very" qualification for light sleepers superfluous.

(2) If standing motorcars rock, their occupants are likely to feel the movement.

(3) Creaking of walls is not general at this level.
NZ 1965

MM5 Generally felt outside, and by almost everyone indoors.
Most sleepers awakened.
A few people frightened.

Direction of motion can be estimated.
Small unstable objects are displaced or upset.
Some glassware and crockery may be broken.
Some windows cracked.
A few earthenware toilet fixtures cracked.
Hanging pictures move.
Doors and shutters may swing.
Pendulum clocks stop, start, or change rate.

NZ 1991 Proposed

MM5 People

Generally felt outside, and by almost everyone indoors.
Most sleepers awakened.
A few people alarmed.
Direction of motion can be estimated.

Fittings

Small unstable objects are displaced or upset. Some glassware and crockery may be broken.
Hanging pictures knock against the wall.
Open doors may swing.
Cupboard doors secured by magnetic catches may open.
Pendulum clocks stop, start, or change rate (H*).

Structures

Some Windows Type I* cracked.
A few earthenware toilet fixtures cracked (H).

COMMENTS

MM5. (1) "Alarmed" for "frightened". This is consistent with higher intensities, but there is some feeling that "fright" rather than "alarm" may generally be better.

(2) Pictures "knock" rather than swing at this intensity.

(3) Inclusion of "shutters" with doors is doubtful; few New Zealand houses have them, and most are secured.

* See Appendix.
NZ 1965

MM6  Felt by all.
People and animals alarmed.
Many run outside.
difficulty experienced in walking steadily.

Slight damage to Masonry D.
Some plaster cracks or falls.
Isolated cases of chimney damage.
Windows, Glassware, and Crockery broken.
Objects fall from shelves, and Pictures from walls.
Heavy furniture moved.
Unstable furniture overturned.
Small church and school bells ring.

Trees and bushes shake, or are heard to rustle.
Loose material may be dislodged from existing slips, talus slopes, or shingle slides.

NZ 1991 Proposed

MM6 People

Felt by all.
People and animals alarmed.
Mary run outside.
Difficulty experienced in walking steadily.

Fittings

Objects fall from shelves.
Pictures fall from walls (H*).
Some furniture moved on smooth floors.
Some unsecured free-standing fireplaces moved.
Glassware and crockery broken.
Unstable furniture overturned.
Small church and school bells ring (H).
Appliances move on bench or table tops.
Filing cabinets or "easy glide" drawers may open (or shut).

Structures

Slight damage to Buildings Type I*.
Some stucco or cement plaster falls.
Suspended ceilings damaged.
Windows Type I* broken.
A few cases of chimney damage.

Environment

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.

COMMENTS

MM6. (1) Pictures secured with modern pinned picture hooks unlikely to fall at this intensity.

(2) "Some" (rather than "Heavy") furniture moved on smooth floors. Furniture on carpet unlikely to move at this intensity.

(3) "Plaster" falls - ambiguous. "Stucco" rather than interior plaster is intended.

(4) Cracking to unreinforced chimneys is common.

* See Appendix
NZ 1965

MM7 General alarm.
Difficulty experienced in standing.
Noticed by drivers of motorcars.

Trees and bushes strongly shaken.
Large bells ring.
Masonry D cracked and damaged.
A few instances of damage to Masonry C.
Loose brickwork and tiles dislodged.
Unbraced parapets and architectural ornaments may fall.
Stone walls cracked.
Weak chimneys broken, usually at the roof-line.
Domestic water tanks burst.
Concrete irrigation ditches damaged.

Waves seen on ponds and lakes.
Water made turbid by stirred-up mud.
Small slips, and caving-in of sand and gravel banks.

NZ 1991 Proposed

MM7 People

General alarm.
Difficulty experienced in standing.
Noticed by motorcar drivers who may stop.

Fittings

Large bells ring.
Furniture moves on smooth floors, may move on carpeted floors.

Structures

Unreinforced stone and brick walls cracked.
Buildings Type I cracked and damaged.
A few instances of damage to Buildings Type II.
Unbraced parapets and architectural ornaments fall.
Roofing tiles, especially ridge tiles may be dislodged.
Many unreinforced domestic chimneys broken.
Water tanks Type I burst.
A few instances of damage to brick veneers and plaster or cement-based linings.
Unrestrained water cylinders (Water Tanks Type II*) may move and leak.
Some Windows Type II* cracked.

Environment

Water made turbid by stirred up mud.
Small slides such as falls of sand and gravel banks.
Instances of differential settlement on poor or wet or unconsolidated ground.
Some fine cracks appear in sloping ground.
A few instances of liquefaction.

COMMENTS

MM7.  (1) “Noticed by motorcar drivers who may stop.” Modern cars transmit the shaking to the occupants more effectively than old ones. This effect may commence at a lower intensity.

(2) “Trees and bushes strongly shaken” is too subjective to be of much use.

(3) Buildings types replace Masonry types.

(4) “Concrete irrigation ditches” doubtfully damaged at this intensity.

(5) Commencement of damage in a number of areas at this intensity in brick veneers, wall linings, ordinary windows, perhaps liquefaction under most favourable conditions.

(6) “Waves seen” not useful and omitted.

(7) “Slides” rather than “slips” is consistent with international use.

(8) Care must be taken to ensure that ground cracking was due to shaking and not shrinkage, etc.
NZ 1963

MM 8 Alarm may approach panic.
Steering of motorcars affected.
Masonry C damaged, with partial collapse.
Masonry B damaged in some cases.
Masonry A undamaged.

Chimneys, factory stacks, monuments, towers, and elevated tanks twisted or brought down.
Panel walls thrown out of frame structures.
Some brick veneers damaged.
Decayed wooden piles broken.
Frame houses not secured to the foundation may move.
Cracks appear on steep slopes and in wet ground.
Landslips in roadside cuttings and unsupported excavations.
Some tree branches may be broken off.
Changes in the flow or temperature of springs and wells may occur.
Small earthquake fountains.

NZ 1991 Proposed

MM 8 People
Alarm may approach panic.
Steering of motorcars greatly affected.

Structures
Buildings Type II damaged, some seriously.
Buildings Type III damaged in some cases.
Monuments and elevated tanks twisted or brought down.
Some pre-1965 infill masonry panels damaged.
A few post-1980 brick veneers damaged.
Weak piles damaged.
Houses not secured to foundations may move.

Environment
Cracks appear on steep slopes and in wet ground.
Slides in roadside cuttings and unsupported excavations.
Small earthquake fountains and other manifestations of liquefaction.

COMMENTS

MM 8
1. Steering of motorcars is likely to be so affected that drivers will have to stop.
2. Changes to building damage consistent with changes to Building types.
3. "Weak Piles" covers a wider range than "Decayed wooden piles".
4. "Tree branches broken off" is too likely to depend on the state (i.e. rottenness) of the branch.
5. "Manifestations of liquefaction" - these are likely to be general at this intensity in susceptible ground.
6. "Changes in the flow or temperature of springs and wells may occur" - no New Zealand data to support inclusion at this intensity. Springs and wells are affected by stress changes before and after a shock.
NZ 1965  
MM 9 General panic.
Masonry D destroyed.
Masonry C heavily damaged, sometimes collapsing completely.
Masonry B seriously damaged.
Frame structures racked and distorted.
Damage to foundations general.
Frame houses not secured to the foundations shifted off.
Brick veneers fall and expose frames.
Cracking of the ground conspicuous.
Minor damage to paths and roadways.
Sand and mud ejected in alluviated areas, with the formation of earthquake fountains and sand craters.
Underground pipes broken.
Serious damage to reservoirs.

NZ 1991 Proposed  
MM 9 Structures
Very poor quality unreinforced masonry destroyed. Buildings Type II heavily damaged, some collapsing.
Buildings Type III damaged, some seriously.
Damage or permanent distortion to some Buildings and Bridges Type IV.
Houses not secured to foundations shifted off.
Brick veneers fall and expose frames.

Environment
Cracking of ground conspicuous.
Landsliding general on steep slopes.
Liquefaction effects intensified, with large earthquake fountains and sand craters.

COMMENTS

MM9.  (1) "Sand and mud ejected" - an intensification of MM8 effects.
(2) "Serious damage to reservoirs" - not at this intensity without qualification about the construction of the reservoir.
(3) "Minor damage to paths" and "underground pipes broken" - very doubtfully by shaking at this intensity.
(4) "Landsliding general" - the area of widespread landslides has approximately corresponded to the MM 9 isoseismal in several historical events.
NZ 1965

MM 10 Most masonry structures destroyed, together with their foundations.
Some well built wooden buildings and bridges seriously damaged.
Dams, dykes, and embankments seriously damaged.
Railway lines slightly bent.
Cement and asphalt roads and pavements badly cracked or thrown into waves.
Large landslides on river banks and steep coasts.
Sand and mud on beaches and flat land moved horizontally.
Large and spectacular sand and mud fountains.
Water from rivers, lakes and canals thrown up on the banks.

NZ 1991 Proposed

MM 10 Structures

Most unreinforced masonry structures destroyed.
Many Buildings Type II destroyed.
Many Buildings Type III (and bridges of equivalent design) seriously damaged.
Many Buildings and Bridges Type IV have moderate damage or permanent distortion.

COMMENTS

MM 10. (1) Very few clear examples of MM 10 in the recent past.

(2) Damage that could arise from static compression or dilatations of the ground ("bent railway lines", "cracked pavements") is omitted.

(3) "Large landslides" occur at lower intensities under favourable (i.e. saturated) conditions.

(4) Liquefaction effects here represent a subjective intensification.

(5) "Water thrown up on banks" may occur at lower intensities.
MM 11 Wooden frame structures destroyed. Great damage to railway lines and underground pipes.

MM 12 Damage virtually total. Practically all works of construction destroyed or greatly damaged. Large rock masses displaced. Lines of sight and level distorted. Visible wave-motion of the ground surface reported. Objects thrown upwards into the air.

COMMENTS

MM 11. Great damage to underground pipes and railway lines not unambiguously caused by shaking observed at MM 9 at Edgecumbe.

"Wooden frame structures destroyed" did not appear in pre-1965 versions of the scale.

MM 12. "Large rock masses" have undoubtedly been displaced at lower intensities (e.g. 1929).

"Lines of sight and level distorted" and "visible wave motion reported" undoubtedly occur at lower intensities.

"Objects thrown upwards", when general, indicates a vertical acceleration of more than 1.0 g. Where this has been reported it has been in an area of generally lower intensity.
Appendix

NZ 1965
Categories of non-Wooden Construction

Masonry A
Structure designed to resist lateral forces of about 0.1 g, such as those satisfying the New Zealand Model Building Bylaw, 1955. Typical buildings of this kind are well reinforced by means of steel or ferro-concrete bands, or are wholly of ferro-concrete construction. All mortar is of good quality and the design and workmanship is good. Few buildings erected prior to 1935 can be regarded as in category A.

Masonry B
Reinforced buildings of good workmanship and with sound mortar, but not designed in detail to resist lateral forces.

Masonry C
Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate bonding of the corners, but neither designed nor reinforced to resist lateral forces.

Masonry D
Buildings with low standard of workmanship, poor mortar, or constructed of weak materials like mud brick and rammed earth. Weak horizontally.

Windows
Window breakage depends greatly upon the nature of the frame and its orientation with respect to the earthquake source. Windows cracked at MM5 are usually either large display windows, or windows tightly fitted to metal frames.

Water Tanks
The "domestic water tanks" listed under MM7 are of the cylindrical corrugated-iron type common in New Zealand rural areas. If these are only partly full, movement of the water may burst soldered and riveted seams.

Hot-water cylinders constrained only by supply and delivery pipes may move sufficiently to break the pipes at about the same intensity.

NZ 1991 Proposed
Categories of Construction

Buildings
Type I:
Weak materials such as mud brick and rammed earth; poor mortar; low standards of workmanship (Masonry D in other MM scales).

Buildings
Type II:
Average to good workmanship and materials, some including reinforcement, but not designed to resist earthquakes (Masonry B and C in other MM scales).

Buildings
Type III:
Buildings designed and built to resist earthquakes to normal use standards, i.e. no special damage limiting measures taken (mid-1930's to c. 1970 for concrete and to c. 1980 for other materials).

Buildings and Bridges
Type IV:
Since c. 1970 for concrete and c. 1980 for other materials, the loadings and materials codes have combined to ensure fewer collapses and less damage than in earlier structures. This arises from features such as: (i) "capacity design" procedure, (ii) use of elements (such as improved bracing or structural walls) which reduce racking (i.e. drift), (iii) high ductility, (iv) higher strength.

Windows
Type I - Large display windows, especially shop windows.
Type II - Ordinary sash or casement windows.

Water Tanks
Type I - External, stand mounted, corrugated iron water tanks.
Type II - Domestic hot-water cylinders unrestrained except by supply and delivery pipes.

H - (Historical). Important for historical events. Current application only to older houses, etc.

General Comment
"Some" or "a few" indicates that the threshold of a particular effect has just been reached at that intensity.
APPENDIX 1b

MODIFIED MERCALLI EARTHQUAKE INTENSITY SCALE - NZ 1996 VERSION

Appendix 1b, page 1

MODIFIED MERCALLI INTENSITY SCALE - 1996 (after Dowrick, 1990**)

MM1 People
Not felt except by a very few people under exceptionally favourable circumstances.

MM2 People
Felt by persons at rest, on upper floors or favourably placed.

MM3 People
Felt indoors; hanging objects may swing, vibration similar to passing of light trucks, duration may be estimated, may not be recognised as an earthquake.

MM4 People
Generally noticed indoors but not outside. Light sleepers may be awakened. Vibration may be likened to the passing of heavy traffic, or to the jolt of a heavy object falling or striking the building.

Fittings
Doors and windows rattle. Glassware and crockery rattle. Liquids in open vessels may be slightly disturbed. Standing motorcars may rock.

Structures
Walls and frame of buildings, and partitions and suspended ceilings in commercial buildings, may be heard to creak.

MM5 People
Generally felt outside, and by almost everyone indoors. Most sleepers awakened. A few people alarmed.

Fittings
Small unstable objects are displaced or upset. Some glassware and crockery may be broken. Hanging pictures knock against the wall. Open doors may swing. Cupboard doors secured by magnetic catches may open. Pendulum clocks stop, start, or change rate (H*).

Structures
Some windows Type I* cracked. A few earthenware toilet fixtures cracked (H).

MM6 People
Felt by all. People and animals alarmed. Many run outside.* Difficult experienced in walking steadily.

Fittings
Objects fall from shelves. Pictures fall from walls (H*). Some furniture moved on smooth floors, some unsecured free-standing fireplaces moved. Glassware and crockery broken. Very unstable furniture overturned. Small church and school bells ring (H). Appliance move on bench or table tops. Filing cabinets or "easy glide" drawers may open (or shut).

Structures
Slight damage to Buildings Type I*. Some stucco or cement plaster falls. Windows Type I* broken. Damage to a few weak domestic chimneys, some may fall.

Environment
Trees and bushes shake, or are heard to rattle. Loose material may be dislodged from sloping ground, e.g. existing slides, talus slopes, shingle slides.

MM7 People

Fittings
Large bells ring. Furniture moves on smooth floors, may move on carpeted floors. Substantial damage to fragile contents of buildings.

Structures
Unreinforced stone and brick walls cracked. Buildings Type I cracked some with minor masonry falls. A few instances of damage to Buildings Type II. Unbraced parapets, unbraced brick gables, and architectural ornaments fall. Roofing tiles, especially ridge tiles may be dislodged. Many unreinforced domestic chimneys damaged, often falling from roof-line. Water tanks Type I* burst. A few instances of damage to brick veneers and plaster or cement-based linings. Unrestrained water cylinders (Water Tanks Type II*) may move and leak. Some windows Type II* cracked. Suspended ceilings damaged.

Environment
Water made turbid by stirred up mud. 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. Some fine cracks appear in sloping ground. A few instances of liquefaction (ie small water and sand ejections).

MM8 People
Alarm may approach panic. Steering of motorcars greatly affected.

Structures
Building Type I, heavily damaged, some collapse*.
Buildings Type II damaged, some with partial collapse*.

Buildings Type III damaged in some cases. A few instances of damage to Structures Type IV. Monuments and pre-1976 elevated tanks and factory stacks twisted or brought down. Some pre-1965 infill masonry panels damaged. A few post-1980 brick veneers damaged. Decayed timber piles of houses damaged. Houses not secured to foundations may move. Most unreinforced domestic chimneys damaged, some below roof-line, many brought down.

Environment
Cracks appear on steep slopes and in wet ground. Small to moderate slides in roadside cuttings and unsupported excavations. Small water and sand ejections and localised lateral spreading adjacent to streams, canals, lakes, etc.

* Items marked * in the scale are defined in the following note.
**Buildings Type II (Masonry C in the NZ 1966 MM scale)**

Buildings of ordinary workmanship, with mortar of average quality. No extreme weakness, such as inadequate boning of the corners, but neither designed nor reinforced to resist lateral forces. Such buildings not having heavy unreinforced masonry towers.

**Buildings Type III (Masonry B in the NZ 1966 MM scale)**

Reinforced masonry or concrete buildings of good workmanship and with sound mortar, but not formally designed to resist earthquake forces.

**Structures Type IV (Masonry A in the NZ 1966 MM scale)**

Buildings and bridges designed and built to resist earthquakes to normal use standards, i.e. no special collapse or damage limiting measures taken (mid-1930’s to c. 1970 for concrete and to c. 1980 for other materials).

**Structures Type V**

Buildings and bridges, designed and built to normal use standards, i.e. no special damage limiting measures taken, other than code requirements, dating from since c. 1970 for concrete and c. 1980 for other materials.

**Structures Type VI**

Structures, dating from c. 1980, with well-defined foundation behaviour, which have been specially designed for minimum damage, e.g. seismically isolated emergency facilities, some structures with dangerous or high contents, or new generation low damage structures.

**Windows**

Type I - Large display windows, especially shop windows.
Type II - Ordinary sash or casement windows.

**Water Tanks**

Type I - External, stand mounted, corrugated iron water tanks.
Type II - Domestic hot-water cylinders unrestrained except by supply and delivery pipes.

H - (Historical) More likely to be used for historical events.

**Other Comments**

"Some" or "a few" indicates that the threshold of a particular effect has just been reached at that intensity.
"Many run outside" (MM6) variable depending on mass behaviour, or conditioning by occurrence or absence of previous quakes, i.e. may occur at MM5 or not till MM7.
"Fragile Contents of Buildings". Fragile contents include weak, brittle, unstable, unrestrained objects in any kind of building. "Well-built timber buildings" have: wall openings not too large; robust piles or reinforced concrete strip foundations; superstructure tied to foundations.

v Buildings Type III - V at MM10 and greater intensities are more likely to exhibit the damage levels indicated for low-rise buildings on firm or stiff ground and for high-rise buildings on soft ground. By inference lesser damage to low-rise buildings on soft ground and high-rise buildings on firm or stiff ground may indicate the same intensity. These effects are due to attenuation of short period vibrations and amplification of longer period vibrations in soft soils.
APPENDIX 2

LIQUEFACTION - A SUMMARY AND DEFINITIONS
APPENDIX 2: LIQUEFACTION - A SUMMARY

1. Definition of liquefaction and related terms

Liquefaction of soils generally occurs at strong levels of earthquake ground shaking, during which weak saturated soils may "liquify" and flow or behave like a liquid. In the NZ 1965 version of the Modified Mercalli (MM) intensity scale liquefaction effects are first mentioned at MM 8 (Appendix 1a). However, in more recent versions of the MM scale (1991, 1996, Appendix 1a, 1b) liquefaction effects appear at MM 7 (small ejections of water and sand). Ambraseys (1988) notes that liquefaction can occur at distances of 100-150 km from the epicentre for earthquakes of magnitude 7-7.5, and up to 400 km from the epicentres of great (M 8-9) earthquakes. Commonly accepted definitions of terms related to soil liquefaction \(^1\) (ASCE Committee, 1978) are presented below.

1.1 Liquefaction - The act or process of transforming cohesionless soils from a solid state to a liquified state as a consequence of increased pore pressure and reduced effective stress.

Comments:
(a) Liquefaction is usually associated with and initiated by strong shaking during earthquakes, which causes certain soils (mainly cohesionless, uniformly-graded fine sands and coarse silts) to compact, increasing pore water pressure and decreasing shear strength. The term is strictly defined as a changing of state that is independent of the initiating disturbance that could be a static, vibratory, sea wave, or shock loading, or a change of ground water pressure. The definition is also independent of deformation or ground failure movements that might follow the transformation to a liquid state. The liquefaction process always produces a transient loss of shear resistance, but not always a longer-term loss of shear strength.

(b) Liquefaction is most likely to occur in saturated, relatively uniform, cohesionless, fine sands, silty sands, or coarse silts of low relative density (loose), generally at depths of up to 15 to 20 m below ground level, in areas where the water table is within 5 m of the ground surface. Such materials have relatively low permeability and dissipate increased pore-water pressures (drain) slowly. Although liquefaction effects are observed only in loose soils, dense sands and silts may show initial liquefaction (strain softening) effects, these are rapidly inhibited by the dilatancy characteristics of such soils.

1.2 Cyclic strain softening - this process is defined in relation to liquefaction as a stress-strain behaviour under cyclic loading conditions in which the ratio of strains to differential shear stresses increases with each stress or strain cycle. In saturated cohesionless soils cyclic strain softening is caused by increased pore-water pressure.

Comments:
Cyclic strain softening occurs in cohesionless loose soils as a part of the liquefaction processes. However, in cohesive soils (mud and clayey soils) cyclic strain softening effects (increased pore-pressures and decreased shear strength) can occur, resulting in some ground deformation or damage (collapse and settlement due to decreased bearing capacity), but complete liquefaction does not occur.

\(^1\) see also Whitman, 1987.
1.3 Ground failure - A term related to the field behaviour of soil and rock masses, and defined as a permanent differential ground movement capable of damaging or seriously endangering a structure. Related terms include:

(a) **Lateral spread** - distributed lateral extensional movements in a fractured soil or rock mass, in which extension of the ground results from liquefaction or plastic flow of the materials. Lateral spreading commonly develops along the banks of rivers and streams, and man-made water courses (canals). Sand and water ejections are often associated with lateral spread fissures.

(b) **Flow failure** - Flow failures (slides) are a form of slope movement involving the transport of earth materials in a fluid-like manner over relatively long distances, at least tens of metres.

(c) **Sand boil** - An ejection of sand and water from cracks or fissures, and caused by piping from a zone of excess pore pressure within a soil mass. Sand boils commonly form as a ground oscillation effect during or immediately after strong earthquakes, as pressures are relieved from liquefied zones, or zones of excess pore pressures in subsurface saturated cohesionless soils. Sand boils are the most common and unambiguous indicator that liquefaction due to ground oscillation has occurred (see also Whitman, 1987).

2. References


Committee, 1978: Definition of terms related to liquefaction: Report submitted by the Committee on Soil Dynamics of the Geotechnical Engineering Division of the American Society of Civil Engineers (ASCE). *ASCE Journal of the Geotechnical Engineering Division, Vol 104, No GT9.*

Figure 2 – Landslides and ground damage attributed to the Wairarapa earthquake of 23 January 1855

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FIGURE 3
Landslides and ground damage attributed to the North Canterbury earthquake of 1 September 1888
FIGURE 4
Landslides and ground damage attributed to the Cheviot earthquake of 16 November 1901
Figure 5 – Landslides and ground damage attributed to the Wairarapa earthquake of 23 January 1855

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FIGURE 6
Landslides and ground damage attributed to the Arthur's Pass earthquake.

LEGEND

- MAIN LANDSLIDES: Known very large (10⁶ m³ or greater) to moderate (10⁴ - 10⁵ m³) size landslides (numbered). Landslide names and other relevant data given below and in the text (Section 2, Table 4).
- OTHER LANDSLIDES: Known smaller, less significant landslides, mainly moderate–small (10³ m³) to very small (up to 10⁴ m³). Generally poorly described.
- LANDSLIDE AREA: Area of reported landsliding. Slides generally small (10³ - 10⁴ m³), locations unknown.
- Main area of landsliding
- Area affected by landsliding
- LIQUEFACTION PHENOMENA:
  - sand boils
  - Kakapo Fault
- Isosismals (MMI intensity; Dowrick pers. comm., 1997 with NN9 assigned from this study)
- Epicentre (M 7.1)

Key References:
- Speight, 1933 (landsliding)
- Yang, 1992 (epicentre, landsliding)
- Dowrick pers. comm., 1997 (isoseismals)
- Dowrick and Smith, 1990 (magnitude)

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Figure 7 - Landslides and ground damage attributed to the Murchison earthquake of 17 June 1929

Figure 8 - Landslides and ground damage attributed to the Hawke’s Bay earthquake of 3 February 1931

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LEGEND

- LANDSLIDES: Known moderate (10⁹ m³) to very large (10¹³ m³ or greater) landslides.
- McCordie's landslide (c.20x10⁶ m³)
- Waihoa landslide (c.10x10⁶ m³)
- LANDSLIDE AREA: Area of reported generally moderate (10⁹ m³) to very small (10⁷ m³) superficial landsliding.
- Main area of landsliding
- Area affected by landsliding

LIQUEFACTION PHENOMENA:
- Sand boils
- Ground surface fault rupture

9 - Isoseismals (MV Intensity; Dowrick pers.comm. 1997)
7 - VM7 inferred

S - Epicentre (Ms 8.9)

Key References: - Ongley, 1937
- Dowrick pers. comm., 1997
- Dowrick and Smith, 1990 (magnitude)

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FIGURE 9
Landslides and ground damage attributed to
Figure 10 - Landslides and ground damage attributed to the Pahiatua earthquake of 5 March 1934

Figure 11 - Landslides and ground damage attributed to the Masterton earthquakes of 24 June and 2 August 1942

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FIGURE 12
Landslides and ground damage attributed to the Lake Coleridge earthquake of 27 June 1946
FIGURE 13
Landslides and ground damage attributed to the Inangahua earthquake of 24 May 1968

Key References:—— Adams et al, 1968
— Lensen and Suggate, 1968, 1969
— Dawrick and Smith, 1990
— Anderson et al, 1994
(epicentre position, aftershock zone)
FIGURE 14
Landslides and ground damage attributed to the Edgecumbe earthquake of 2 March 1987
FIGURE 15
Landslides and ground damage attributed to the Weber earthquake of 13 May 1990
FIGURE 16
Landslides and ground damage attributed to the Ormond earthquake of 10 August 1993
FIGURE 17
Landslides and ground damage attributed to the Arthur’s Pass earthquake of 18 June 1994 and 29 May 1995