

RISK OF CASUALTIES IN NEW ZEALAND EARTHQUAKES

David J. Dowrick^{1,2} and David A. Rhoades^{1,3}

ABSTRACT

This paper reports on a study of all earthquakes that have caused (or could have caused) casualties in New Zealand in the period 1840 – 2003 inclusive. The intensity which has been the effective threshold for injuries is Modified Mercalli intensity VII (MM7). In the period of interest at least 73 earthquakes of magnitude $M_w \geq 5$ have caused MM7 or greater in populated areas, and of these events 16 have caused direct casualties, 297 deaths and 640 hospitalized injured. The causes of the casualties are tabulated and discussed, and the potential to reduce casualties in the future is assessed, in particular in a large earthquake on the Wellington fault. Death rates have been determined empirically as functions of four types of structure and MM intensity.

1.0 INTRODUCTION

Since the beginning of earthquake engineering in New Zealand in the 1920s, its primary aim has rightly been to minimize casualties in future earthquakes. This has been done mainly through attempting to prevent the collapse of structures. Curiously, no systematic study has previously been made of the historical incidence of earthquake casualties in New Zealand, their causes, and probabilities of occurrence. The brief beginnings of such a study was carried out fairly recently (Dowrick, 1998a), and the present paper is the result of expanding that work into a more substantive study of the risk of casualties in New Zealand earthquakes.

2.0 HISTORICAL INCIDENCE OF EARTHQUAKE CASUALTIES IN NEW ZEALAND

In gathering data of casualties we start at the usual time of 1840, with the advent of European- style construction and colonial administration in New Zealand. The first known earthquake casualties are two men who died in a landslide in the 1843 Wanganui earthquake (Eiby, 1968a) which had a magnitude of about 7.5, and the most recent casualty was the injury (broken arm) of a paper mill worker in the magnitude M_w 6.5 Edgecumbe earthquake of 1987. Our data gathering has been restricted to deaths, and injuries requiring admission to hospital.

A summary of the known deaths and hospitalized injured people is presented in Table 1. It is seen that such casualties have occurred in 16 earthquakes, which is at an average rate of one casualty-causing earthquake per decade. The

estimated total numbers of direct deaths and hospitalized direct injured in Table 1 are 297 and 640 respectively. These numbers should be considered as best estimates, particularly because there are considerable uncertainties in the numbers of casualties in the 1931 Hawke's Bay earthquake which gave rise to over 90 percent of the total casualties.

From Table 1 it is seen that casualties have occurred in earthquakes of a wide range of magnitude (5.6-8.2) and from Modified Mercalli intensity MM7 to MM10. Thus intensity MM7, which is the effective threshold of structural damage for New Zealand construction, is correspondingly the threshold for casualties. It follows that the search for historical data on casualties has been concentrated on (but not limited to) earthquakes which have caused intensities of MM7 or greater in populated areas. In all, 73 such earthquakes were identified as having occurred, with magnitudes in the range 4.9 to 8.2, as listed in Appendix A. The maximum intensity was MM10, MM9, MM8 and MM7 in 4, 10, 18 and 39 events respectively. The key reference to each of a number of the earthquakes is given in the right hand column, in addition to newspapers and the Atlas of isoseismal maps (Downes, 1995). References to the 1931 Hawke's Bay earthquake are given in the following section which is dedicated to that dominant event.

The geographical distribution of casualties (deaths + injured) across the whole country is shown in Figure 1. It is seen that of the total 924 casualties, 97 percent have occurred in the North Island. This distribution is a direct consequence of the dominance of the majority of casualties to date having occurred in the 1931 Hawke's Bay earthquake.

¹ *Institute of Geological & Nuclear Sciences, Lower Hutt*

² *Fellow*

³ *Member*

Table 1: Numbers of deaths and hospitalized injured as a function of Modified Mercalli intensity in New Zealand earthquakes, 1840-2003 inclusive (indirect casualties are excluded).

Local date and time			M_w	MM7		MM8		MM9		MM10	
				Dth	Inj	Dth	Inj	Dth	Inj	Dth	Inj
1843	Jul 8	1645	7.5	-	-	2	-	-	-		
1848	Oct 17	1540	6?	3	-						
1855	Jan 23	2102	8.2	-	1	2	-	6 ⁽³⁾	4?		
1882	⁽¹⁾ Day	Day	5 to 6	-	-	3 ⁽²⁾					
1897	Dec 8	0240	6.5	-	1						
1901	Nov 16	0745	6.8	-	-	-	-	1	-		
1913	Apr 12	1912	5.6	1	0						
1914	Oct 7	0646	6.6	-	-	1	-				
1922	Dec 25	1503	6.4	-	-	-	1				
1929	Jun 17	1017	7.7	-	-	3	1	12	-		
1931	Feb 3	1047	7.8	-	-	2	18	5	8	254 ⁽⁴⁾	594 ⁽⁴⁾
1932	Sep 16	0125	6.8	-	-	-	3	-	-		
1934	Mar 5	2346	7.4	-	1	-	-	-	-		
1942	Jun 24	2316	7.1	-	-	-	2				
1968	May 24	0524	7.2	-	-	-	-	-	-	2 ⁽⁵⁾	1 ⁽⁵⁾
1987	Mar 2	1342	6.5	-	-	-	-	-	1		
Totals				4	3	13	28	24	13	256 ⁽⁶⁾	596 ⁽⁶⁾

Notes: ⁽¹⁾ Date and hour not known; ⁽²⁾ Most likely to have been MM8; ⁽³⁾ 5 to 7 deaths; ⁽⁴⁾ Deaths and injuries both include 27 injured who died; ⁽⁵⁾ Includes one injured who died; ⁽⁶⁾ Includes 28 injured who died.

Also shown in Figure 1 are the seismic zone factor contours prepared by G. McVerry for the New Zealand loadings standard (NZS, 2004). They show that the highest hazard part of the country, which is in the South Island, has not contributed to the casualties count, and it cannot contribute much in the foreseeable future because it is only lightly populated. Indeed, the biggest future contribution will be in the southern North Island when the Wellington fault ruptures (Section 6).

3.0 CASUALTIES IN THE 1931 HAWKE'S BAY EARTHQUAKE

In the M_w 7.8 Hawke's Bay earthquake of 1931 there were hundreds of casualties. For many days after the main shock newspapers carried lists of names of people reported to have died, to have been injured, or to be missing. Estimates of the total numbers of deaths and injured, appeared in the press and in various other publications. Callaghan (1933) states that approximately 260 were killed. In his book on the earthquake, Conly (1980) states that 258 people were killed,

and that 454 injured people were admitted to emergency hospitals in Napier and Hastings. Conly lists 230 dead people (one duplicated) who were apparently identified and notes that 28 unidentified people also died. He recounts many of the incidents in which people were killed or injured.

3.1 Deaths in 1931

The most complete list of names of people thought to have died that has been prepared is that of the NZ Society of Genealogists (NZSG, 1983). Their extensive research resulted in a list of 291 names, not all of whom have been verified as real unique entities. This uncertain outcome is the result of the inaccuracy or vagueness of some of the information, arising from the chaotic situation which prevailed in and around Napier and Hastings after the main shock.

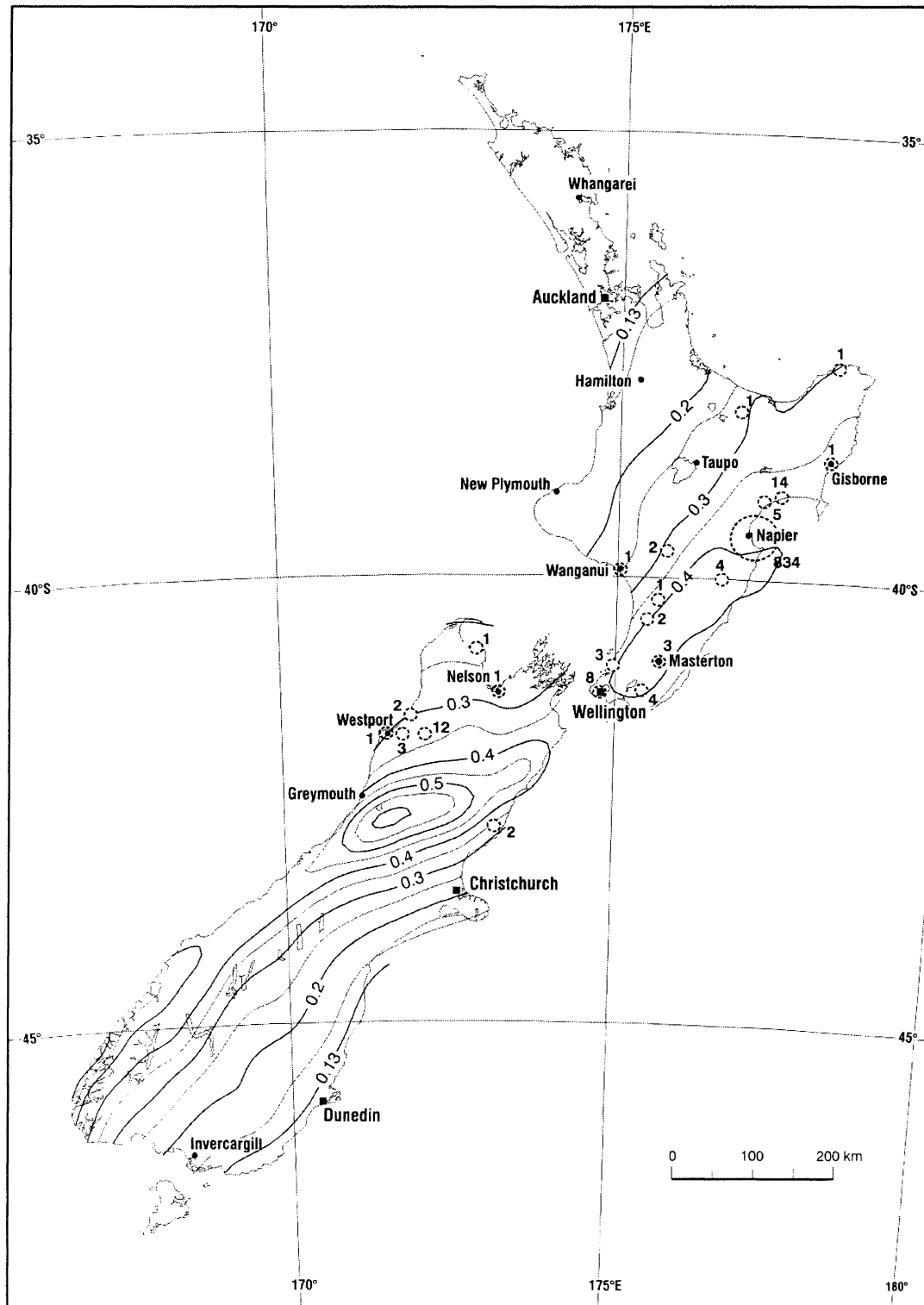


Figure 1: Geographical distribution of earthquake casualties in New Zealand in the period 1840-2001 inclusive. The numbers are the sums of deaths + hospitalized injured within the adjacent circles. Also shown are the seismic zone factor contours for the 500 year return period from NZS (2004) (see text).

In the present study it was found that four people not listed by NZSG died of injuries in hospitals, as included in the lists prepared by the Department of Health (1931a; 1931b). In all, 39 injured people had died in hospital by 4th March, i.e. within 29 days of the main shock. It is possible that a few more of the seriously injured died after 4th March 1931, as 28 of the 58 seriously injured still in hospital at that date were reported as not improving, and from four to seven died in the week preceding that date. The Department of Health's list of hospitalized people is incomplete, at least to the extent that it does not include 12 people in the NZSG death's list in Hastings (Racecourse, Royston and Memorial Hospitals). Six of these 12 people died on the day of the earthquake and three more on the following day, so did not get listed by the hospital staff who were so badly overstretched at that time.

Considering the people who died as a result of the earthquake, we have a maximum number of potential deaths of $291 + 4 = 295$, as noted above. Of the 291 potential deaths in the NZSG list, 26 may be eliminated immediately with reasonable certainty, as they were either duplicates or people who did not die. The remaining total of $(265 + 4) = 269$ potential deaths have been classified as 253 certain deaths and 16 possible deaths. The names and other information of the *possible deaths* are listed in Appendix B, together with one example of the *certain deaths*. None of the possible names occur in the national Deaths Register, Stones 1930 Directory, or the 1928 Electoral Rolls (of Napier, Hawke's Bay and Waipawa), and all but two cases (Gannaway and Heeney) rely on only one source, the Official Police List (OPL) or the newspaper lists which mostly were derived from the OPL. Note that the OPL is far from infallible, and the absence of a name from the other lists does

not prove the non-existence of a person. For example, not all deaths were registered.

From the above analysis it is concluded that the number of deaths in the 1931 Hawke's Bay earthquake most probably lies in the range 253-269. This is similar to, but much better supported than, the range of 256-266 suggested by Callaghan. If a single value best estimate of deaths is required the mean value of 261 is appropriate.

A further three deaths occurred as an indirect result of the earthquake. Conly (1980, p.123) recounts that three men in an aeroplane delivering telegrams crashed at Wairoa on Sunday, February 8. As this aeroplane flight was only made because of the earthquake, these deaths should be added to the totals given in the previous paragraph, bringing the range of deaths to 257-273.

The geographical locations of casualties are important for risk modelling purposes. Considering all the available information, the best assessments of the locations at the time of the earthquake of the people who died are as follows: Napier Hospital (22), Napier Technical School (6), others in Napier (130), Greenmeadows + Seminary (15), Taradale (4), Park Island Home (16), Roach's shop, Hastings (17), others in Hastings (85), Eskdale (1), Pakipaki (4), Mohaka viaduct construction (1), Wairoa (2). These data are mapped on Figure 2, where it is seen that all but the two deaths in Wairoa lie within the MM9 isoseismal and nearly all were in the Napier/Hastings area and were associated with an intensity of MM10. Hastings experienced a local intensity of MM10, although it lies outside of the MM10 isoseismal (Dowrick, 1998b).

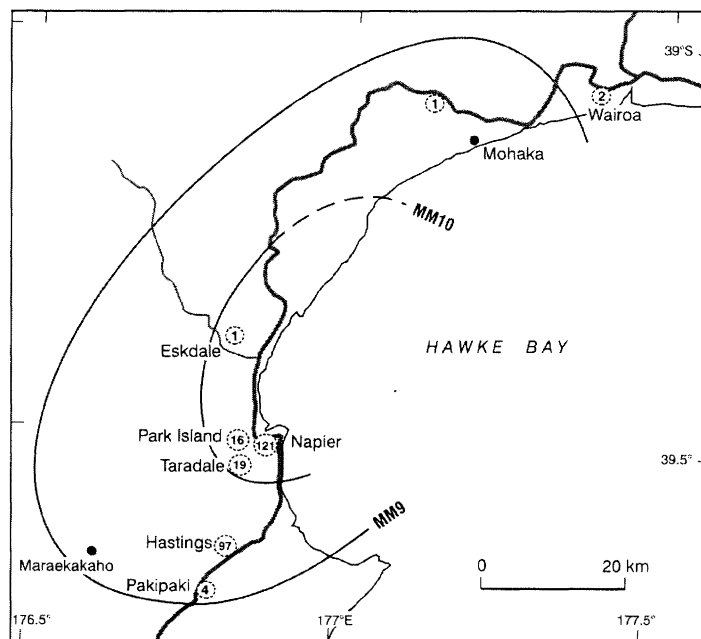


Figure 2: Geographical distribution of deaths caused by the 1931 Hawke's Bay earthquake, in relation to the intensity. Only two deaths occurred outside of the MM9 isoseismal.

Most of the deaths were caused by falling brickwork, as summarised in Table 2. Apart from the Nurses Home in Napier, which was made of defective reinforced concrete, the early reinforced concrete buildings performed very well (Dowrick, 1998*b*; Van de Vorstenbosch *et al.*, 2002), thus causing few casualties. According to Callaghan (1933), “No record was kept as to where the greatest proportion of fatalities occurred, but one may conjecture that over 60 percent lost their lives on the footpaths where they were overwhelmed by falling masonry, or were entrapped while attempting to escape from collapsing buildings”. This statistic is consistent with the fact that a study of photographs of the Napier commercial district shows that about 60 percent of masonry buildings lost their parapets or gables, as well as the buildings where the whole front facade fell.

Table 2: Statistics of causes of death in the 1931 Hawke’s Bay earthquake.

Cause of death	Number of deaths
Falling URM buildings or parts thereof ⁽¹⁾	236-252
Collapse of weak-storey r.c. building ⁽²⁾	8
Falling domestic brick chimneys	~6
Scalded by boiling beer	1
Falling domestic water tank ⁽³⁾	1
Collapsing excavation ⁽⁴⁾	1
Total	253-269

Notes: ⁽¹⁾ Some people trapped by rubble were killed by fire;
⁽²⁾ Napier Nurses Home;
⁽³⁾ Wairoa;
⁽⁴⁾ Near Mohaka.

3.2 Injured in 1931

According to the Wellington surgeon Begg (1931), writing of his experiences helping with casualties in Napier: “The injured were in small proportion to the dead. By this is meant only the serious cot cases, some 300 against 150 or more killed. Of course many hundred had slight cuts and abrasions. Burns were not common.”

The best source of data on injured people needing hospital care comprises the two Department of Health lists (NZDH, 1931*a* and 1931*b*). These lists, comprising 646 people, were made 20 days and 29 days respectively after the main shock. A sample of the type of information contained in the lists taken from the beginning of the later list, is given in Table 3. Some of the people on the lists were not injured by the earthquakes, but were in hospital in Napier or Hastings for some other condition at the time of the earthquakes. In the column headed “Injuries” some of the entries state “Hospital transfer”. The inference in many cases is that this indicates that the patient was uninjured. In the present study 19 further

injured people have been added to the NZDH lists, as found in other sources, e.g. Conly (1980) and newspaper lists.

The NZDH lists of injured include 27 people who died as a result of their injuries, four of whom were not in the Genealogist’s list (NZSG, 1983) discussed above.

In the NZDH lists the information in the columns headed “Injuries” and “Present Condition” (Table 3) allows the severity of the injury in the majority of cases to be approximately classified as *serious* or *moderate*. Serious injuries were taken as those which were (i) life threatening, (ii) required lengthy hospital care, or (iii) caused permanent disability. Some examples of these are:

- Internal (abdominal) injuries
- Severe head injuries (cerebral haemorrhage)
- Compound pelvis fractures
- Multiple injuries
- Fractured spine
- Loss of limbs

Moderate injuries included the following:

- Fractured leg
- Fractured leg and arms
- Septic leg wounds
- Scalp wounds
- Bruising, contusions, abrasions

The numbers of patients in the various classes were as listed in Table 4. The breakdown in Table 4 shows that the numbers and degree of seriousness are uncertain. About 90 people were seriously injured and about 400 people were moderately injured. Disregarding the causes of their medical conditions, the medical services had to deal with about 660 patients. Most of the injured or ill came from in or near Napier or Hastings where the total population was about 30,000. As the main local hospital (Napier) was wrecked, injuries had to be treated, including emergency surgery, at a variety of places scattered about the southern half of the North Island as shown on Figure 3. The 26 hospitals and other institutions concerned are listed in Appendix C.

The geographic locations of injured people are broadly similar to those of the deaths given in Figure 2, but there are more uncertainties. In addition, a few injuries occurred outside of the region of deaths, with two in Waipawa (32 km SSW of the southernmost death) and possibly three at Puketitiri (28 km WNW of the one at Eskdale). Waipawa and Puketitiri were both in the intensity MM8 zone. The other localities outside of the Napier/Hastings area where up to 30 people were injured are Clive, Havelock North, Kotemaori, Mohaka, Onga Onga, Opapa, Otare, Pakipaki, Pakowhai, Puketapu, Pukehou, Waipawa and Wairoa. The numbers of people injured as a function of MM intensity are listed in Table 5. Because of the uncertainties in the location and hence intensity where some of the injuries occurred, the numbers assigned to the three intensity zones add up to more than the totals.

Table 3: Progress report on patients from earthquake area as recorded by Department of Health on 4 March 1931 (sample from NZDH, 1931b) .

Name	Last Address	Injuries	Present Condition	Hospital
Abbott, Mr Harry	704 Karamu Rd, Hastings	Hosp. trans.	Discharged	Hawera
Alexander, Kathleen	Bolling St, Greenmeadows	Injury to shoulder	Discharged	Wgton
Allen, Mrs D	65 Harding Rd, Napier	Medical	Discharged	Palm N
Allen, Muriel Miss (42)	Napier Hosp.	Hosp. trans.	Discharged	Wanganui
Amner, Kathleen Mary (Miss)	Napier Hosp.	Lacerated hand.	Discharged	Napier
Anderson, Albert (35)	34 Munro St., Napier	T.B.		Dannevk
Anderson, Miss Annie	Park Is Home, Napier	Fr.leg, Shock.	Satisfac	Palm Nth
Anderson, Wm	Bay View, Napier	Head injury	Discharged	Wgton
Andrew, John B (52)	14 Nelson Cres., Np	Shock	Satisfac	Waipuk
Andrew, Samuel				Wanganui
Ansell, Mrs Florence (53)	Napier		Satisfac	Hawera
Anstis, Mrs Isabel (44)	Marine Parade, Wairoa	Abrasions & int. injuries	Satisfac	Wairoa
Aplin, Anna Maud (14)	Charles St, Westshore	Alvelor abscess	Discharged	Wanganui
Apperley, Mrs Isa (38)	2 Cameron Rd, Np	Fr. radius	Readmitted Satisfact	Waipuk
Arnold, Mrs Jennie	Napier	Shock	Satisfac	Palm Nth
Arrowsmith, Mrs Margaret (56)	Napier	Cerebral haemorrhage Lac. head.	Died	Waipuk

Table 4: Statistics of hospital patients from the area affected by the 1931 Hawke's Bay earthquake.

Condition of Patient	Number
• Injured who died	27
• Serious injuries	51
• Probably serious	12
• Moderate injuries	284
• Probably moderate	97
• Shock	53
• Hospital transfers	
Uninjured	55
Probably injured	58
• Condition unknown	22
Total No. of patients	659
Maximum No. of injured*	605

Note: *Including 27 injured who died in hospital.

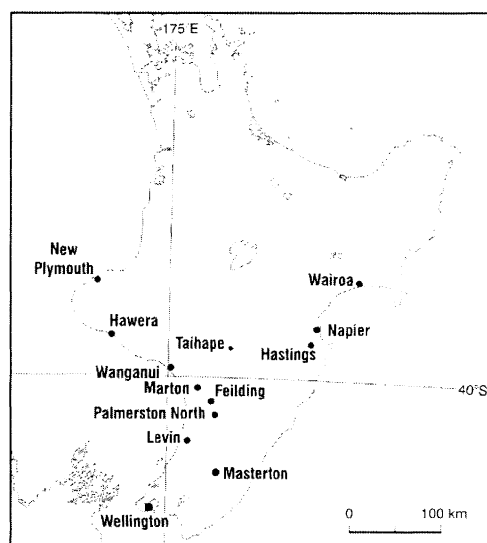


Figure 3: Locations of hospitals to which injured people from Napier and Hastings had to be transferred, as a result of the 1931 Hawke's Bay earthquake.

As given in Table 5, the number of injured in the Hawke's Bay earthquake is likely to lie in the range 583 to 605. If a single value best estimate is required, the mean value of 594 is appropriate.

Further background information on the organisation of emergency medical services in Hawke's Bay has been documented by the Medical Superintendent of Napier Hospital (Biggs, 1931).

Table 5: Estimates of numbers of people injured as a function of MM intensity in the 1931 Hawke's Bay earthquake.

Intensity	Number Injured		
	Max	Min	Mean
MM10	584	549	567
MM9	11	5	8
MM8	23	16	18
Total	605	583	594

3.3 Casualties if the 1931 earthquake happened in 2003

How much has the risk of casualties in New Zealand urban areas reduced since 1931? One measure of this would be to estimate the likely number of deaths in a repeat of the 1931 earthquake assuming that the Hawke's Bay numbers of people and buildings is as it was in 1931, and that the buildings are as they are today (say 2003) but without any URM buildings or chimneys. This may be estimated approximately in proportion to population from the numbers

of deaths associated with non-URM low-rise buildings in the Wellington region, as found in a study a magnitude 7.5 earthquake on the Wellington fault (Spence *et al.*, 1998).

Such calculations result in an estimate of about 21 deaths. This represents more than an order of magnitude reduction from the 260 or so deaths that occurred in 1931.

4.0 CAUSES OF EARTHQUAKE CASUALTIES

Casualties in New Zealand earthquakes have been principally due to damage to buildings, with a minority caused by ground damage, and a few to other causes. These causes are discussed below.

4.1 Casualties from ground damage

Casualties caused by ground damage have occurred in seven of the 16 casualty-causing New Zealand earthquakes, and comprise 28 (i.e. 3 percent) of the total number (924) of casualties. Table 6 lists these earthquakes together with the numbers of deaths and injured people at each intensity. Three of the deaths at the lowest intensity (MM8) occurred in a railway tunnel being constructed near Paekakariki, in an ill-defined earthquake in 1882; the most likely intensity is MM8. The other types of ground damage causing the casualties in Table 6 are landslides, rockfalls in mines, ground fissures, and collapse of a caisson for the construction of a bridge pier near Mohaka. Note that ground damage casualties have mostly been fatal.

Note that in Tables 6-8 and 11-12 *Night-time* (N) is defined as times outside of normal working hours when most people are likely to be home, while D_n is daytime or holidays.

Table 6: Numbers of deaths and injured (hospitalized due to ground damage) as a function of Modified Mercalli intensity in New Zealand earthquakes.

Date (LT)	Day or Night	M_w	MM7 Zone		MM8 Zone		MM9 Zone		MM10 Zone	
			Deaths	Injured	Deaths	Injured	Deaths	Injured	Deaths	Injured
1843 Jul 8	D	7.5			2 L	0				
1855 Jan 23	N	8.2			2 GF?	0				
1882 sometime	D	5-6			3 T	0				
1914 Oct 7	N	6.6			1 L	0				
1929 Jun 17	D	7.7			2 M	0	12 L	0		
					1 L					
1931 Feb 3	D	7.8					1 C	0		
1968 May 24	N	7.2							2 L ⁽¹⁾	2 L ⁽¹⁾
Totals			0	0	11	0	13	0	2 ⁽¹⁾	2 ⁽¹⁾

Notes: C = Caisson; D = Daytime; GF = Ground fissures; L = Landslides; M = Mine; N = Night time (see text); T = Tunnel;

⁽¹⁾ Includes one injured who died in hospital.

Table 7: Numbers of deaths and total population at risk due to building damage as a function of Modified Mercalli intensity in New Zealand earthquakes.

Date (LT)	Day or Night	M_w	MM7 Zone		MM8 Zone		MM9 Zone		MM10 Zone	
			Bldg Deaths	Total Popn.	Bldg Deaths	Total Popn.	Bldg Deaths	Total Popn.	Bldg Deaths	Total Popn.
1848	Oct 17	D	c.6	3 B						
1855	Jan 23	N	8.2				4-6 Cob			
1901	Nov 16	D _h	6.8				1 BC	5000		
1913	Apr 12	N	5.6	1 P	9300		1 Cob	200		
1931	Feb 3	D	7.8			1 B 1 WT			6 BC 240 B 8 NH	30000
Totals				3 B		1 B 1 WT	5-7 Cob 1 BC		6 BC 240 B 8 NH	

Notes: B = URM; BC = Brittle chimney; Cob = Cob house; D_h = Daytime but people at home; NH = Nurses Home; P = Ornamental plaster; WT = Domestic water tank.

Table 8: Numbers of injured (hospitalized) and total populations at risk due to building damage as a function of Modified Mercalli intensity in New Zealand earthquakes

Date (LT)	Day or Night	M_w	MM7 Zone		MM8 Zone		MM9 Zone		MM10 Zone		
			Bldg Injured	Total Popn.	Bldg Injured	Total Popn.	Bldg Injured	Total Popn.	Bldg Injured	Total Popn.	
1855	Jan 23	N	8.2	1 B	2500			1 Wh 2 B 1 BC	4000		
1897	Dec 8	D	6.5	1 BC	11000						
1922	Dec 25	D _h	6.4			1 BC	2300				
1929	Jun 17	D	7.7			1 BC	43000				
1931	Feb 3	D	7.8			18 B	28000	8 B	9000	580 B 6 BC 8 NH	30000
1932	Sep 16	N	6.8			2 UB 1 B	25900				
1934	Mar 5	N	7.4	1 BC	6000						
1942	Jun 24	N	7.1			2 E	24000				
1987	Mar 2	D	6.5					1 NS	11000		
Totals				3	-	26	-	13	-	594	-

Notes: B = Bricks; BC = Brittle chimneys; NH = Nurses Home; E = Equipment; NS = Non-structure; UB = Unknown but probably brick; Wh = Whare (Maori house); see also Notes to Table 7

4.2 Casualties from damage to buildings

The data on deaths and injuries arising from damage to buildings are summarized by intensity in Tables 7 and 8. The types of construction causing deaths are Unreinforced Masonry (URM) buildings (251), URM chimneys (7), a

domestic watertank (1) and the Nurses Home in Napier (8) which was of defective reinforced concrete. There were no casualties in the other 90 or so reinforced concrete buildings in Napier and Hastings which performed remarkably well at intensity MM10 (van de Vorstenbosch, 2002).

4.3 Indirect Casualties

In addition to the above direct earthquake casualties, a modest number of deaths and injuries have occurred which are known to have been indirect results of earthquakes shaking. Twelve such deaths have occurred in five earthquakes, for the following reasons:

- 1888 Aug 31: A woman died of heart failure due to shock at intensity MM5.
- 1929 June 16: A diabetic woman from Murchison lost access to her medication.
- 1931 Feb 2: Three men in a plane delivering telegrams were killed in a crash at Wairoa.
- 1934 March 5: Two people with existing health problems died of heart failure due to shock, one at intensity MM7 and one at MM8.
- 1942 June 24: A man in Wellington died in his sleep due to coal gas leaking from a broken pipe (MM7)
- 1968 May 23: Three men in a helicopter on repair work were killed in a crash near Inangahua. A man racing to check the safety of his family, died as a result of crashing into an exposed bridge abutment near Runanga.

As well as the above deaths, three people are known to have been injured indirectly in three earthquakes, as follows:

- 1931 Feb 2: A workman at the Whakatu meatworks jumped a 5 m height from a building and broke a leg (MM9).
- 1942 June 24: A woman jumped out of a hotel window in Otaki and broke a leg (MM7).
- 1990 May 13: A girl broke a leg by being thrown from her frightened horse near Hastings (MM5).

Considering earthquake related deaths, we note that in the period 1840-2003 in New Zealand there have been 11 known indirect deaths and 298 direct deaths, with almost all of the latter being due to brittle building materials. Thus 3.5 percent of the deaths have been indirect. It is of interest to observe the difference of these New Zealand historical statistics from those for the 1994 Northridge earthquake in California. According to Durkin (1996), in the Northridge

event 43 (60%) of the 72 deaths were attributed to causes other than damage, as follows:

• Falls	5
• Automobile accidents	3
• Fire	1
• Suicide	1
• Exposure	2
• Heart attacks	30

Much of the difference between the proportion of indirect deaths in the 1994 earthquake and that of the New Zealand earthquakes arises from the much lower incidence of structure-related deaths in the Northridge earthquake. This is a reflection of the dominance of failures of brittle structures at intensity MM10 in the 1931 Hawke's Bay earthquake, and the absence of such high casualty rates in the Northridge event. As noted in Section 3.3, structure related deaths in 1931 would be reduced by an order of magnitude if the URM buildings were replaced by a present-day mix of New Zealand construction.

5.0 RISK OF CASUALTIES

We now consider the risk of occurrence of earthquake casualties as derived from the 1840-2003 historical data discussed above. Considering the populated regions in all 21 events subject to intensities \geq MM8 (Table 9), the numbers were counted of deaths and the total populations exposed that were associated with four types of structure:

- Houses (non-URM)
- Non-domestic buildings (ND)
- Unreinforced masonry buildings (URM)
- Brittle chimneys (Ch)

From these data, given in Tables 10-12, the following two statistics were calculated:

- Death rate per head of population (by intensity zone)
- Death rate per structure (by intensity zone)

Intensity zones are defined such that the MM7 zone (say) is the area between the MM7 and MM8 isoseismals of a given earthquake.

Table 9: Minimum numbers of New Zealand earthquakes affecting different classes of structure at intensities MM7-MM10 from 1840-2003 inclusive.

Class of structure	Number of earthquakes			
	MM7	MM8	MM9	MM10
URM Buildings	34	11	4	1
Buildings with URM chimneys	58	21	11	2
Domestic ⁽¹⁾ non-URM buildings	71	21	12	2
Non-domestic non-URM buildings	19	19	7	2

Note: ⁽¹⁾ Domestic = Houses + farm buildings

The calculated historical death rates together with their 95 percent confidence intervals are summarized in Table 13 and are presented graphically in Figure 4.

First consider the death rates per head of population (Figure 4A). The highest risk of death (unsurprisingly) exists for people in or near URM buildings subjected to intensity MM10, for whom the death rate is 0.054. At MM10 the death rate drops by nearly two orders of magnitude to 0.0011 for people in or near non-URM non-domestic buildings (mostly pre-code, as the MM10 statistics are dominated by the 1931 earthquake, see Table 1). The death rate for non-URM houses at MM10 is zero, as no deaths have been caused by them.

Brittle chimneys, curiously, have not been nearly as lethal as might be expected, considering that about 90,000 of them have fallen at intensity MM8 or greater; at MM10 the death rate per head of population due to chimneys is 0.0004.

Figure 4B gives a general idea of the death rate associated with the four types of structure. In interpreting this figure it should be noted that none of the non-domestic buildings were large (the tallest being four storeys), and that the number of people in all the building types varied depending on the time of occurrence of the earthquake across the intensities MM8 to MM10. The number of occupants per house averaged 2 to 3; for non-domestic buildings the numbers were 4 for MM8, 12 for MM9 and 10 for MM10; for URM buildings the numbers were 4 for MM8, and 10 for MM9 and MM10; while for chimneys the associated numbers of people were 1.6 per chimney for MM8 and MM9 and 1.0 for MM10.

A notable feature of Figure 4 is how it illustrates the rapid rate at which the death rates decrease with decreasing intensity, such that the contribution to casualty counts at intensity MM8 are very small compared to those at MM10.

6.0 WELLINGTON FAULT EARTHQUAKE CASUALTIES

We now consider a future earthquake with the highest risk of casualties for New Zealand, i.e. a large earthquake on the

southern segment of the Wellington fault. This is a worst case scenario for casualties in New Zealand as it involves the most highly active fault in New Zealand located in a highly populated region. The fault runs through the centre of Wellington and Hutt Cities and generates earthquakes of about M_w 7.5 at average intervals of about 600 years.

Considering the case of a magnitude 7.5 earthquake on the Wellington fault, (Spence *et al.*, 1998) estimated the casualties from a work day (11 am) and a night time (2 am) event for the Accident Compensation Commission in New Zealand for reinsurance purposes. The (subsequently slightly) revised overall results of this partly probabilistic study are given in Table 14, where is seen that the best estimate (mean of the model) for deaths at 11am (746) are over five times as great as those for the 2 am event (134). This large difference in numbers of deaths is caused mainly by the fact that at night far more people in the Wellington region are in their mostly timber-framed houses compared to the work day, when more people are in non-domestic buildings which suffer much more volume loss in strong shaking than do timber-framed New Zealand houses. The need to assume specific times of occurrence of the scenario events is further illustrated in Section 7.0.

Of the casualties caused by building collapse (part or complete), it was found that the majority occurred in a relatively small number of buildings designed prior to the introduction in the 1970's of "capacity design" and detailing for ductility of structures.

As well as listing casualties due to ground shaking, Table 14 also gives the casualties estimated from other causes, including those associated with buildings straddling the causative fault, mostly (but not all!) built before the fault was identified. A field survey found that 74 houses and 70 other buildings had been built across this strike-slip fault, which is expected to have shear displacements of about 5 m horizontally and up to about a metre vertically.

Table 10: Deaths and exposures related to structures at intensity MM8 in New Zealand earthquakes, 1840-2003

Event No	Date (LT)	Total popn.	Exposures – Structures				Exposures – People in/near				Deaths in or near				
			Houses	ND	URM	Ch	Houses	ND	URM	Ch	Houses	ND	URM	Ch	
2	1848 Oct 15	N 2000	300	10	89	100E	1600	100	300	100	0	0	0	0	
4	1853 Jan 1	N 1000	250	30	30	100	1000	u	u	200	0	0	0	0	
5	1855 Jan 23	N 1000	300	10	30	100	960	10	30	200	0	0	0	0	
21	1888 Aug 31	N 100E	20	2	*	44	100	u	*	90	0	u	0	0	
23	1895 Aug 18	N 100	30	3	*	60	95	5	*	100	0	0	0	0	
25	1901 Nov 15	D _h 300	80	5	10	200	240	u	30	200	0	u	0	0	
26	1904 Aug 8	D 500	120	*	*	200	300	*	*	200	0	0	0	0	
28	1914 Oct 7	N 800	200	10	*	100	790	10	*	200	0	0	0	0	
34	1922 Dec 25	D _h 2300	600	2	10	600	1500	u	10	600	0	u	0	0	
36	1929 Mar 9	D 65	15	5	*	30	45	20	*	60	0	0	0	0	
38	1929 Jun 17	D 45000	8360	500	170	18000	20500	5000	1700	18000	0	0	0	0	
43	1931 Feb 3	D 27900	4910	120	80	10200	12000	1200	800	10200	0	0	1	0	
47	1932 Sep 16	N 23000	4470	190	160	11700	22500	190	160	21000	0	0	0	0	
48	1934 Mar 5	N 21000	4770	100	117	10000	20900	50	50	20000	0	0	0	0	
51	1942 Jun 24	N 24000	6020	204	120	12700	23900	50	50	23500	0	0	0	0	
55	1948 May 22	N 400	100	10	*	200	380	20	*	400	0	0	0	0	
59	1968 May 24	N 1000	3144	450	25	6700	9500	450	50	9500	0	0	0	0	
67	1987 Mar 2	D 8300	2500	100	*	500	5000	400	*	500	0	0	0	0	
69	1990 May 13	D 300	75	2	*	15	225	6	*	15	0	0	0	0	
70	1994 Jun 18	D 30	10	3	*	10	20	10	*	10	0	0	0	0	
71	1995 Nov 24	N 20	5	*	*	5	20	*	*	5	0	0	0	0	
Totals			159465	36159	1755	841	61034	121575	7521	3180	105080	0	0	1	0

Notes: E = guesstimate; Structures are defined in the text; u = unoccupied at night; *Few if any such structures.

Table 11: Deaths and exposures related to structures at intensity MM9 in New Zealand earthquakes, 1840-2003.

Event No	Date (LT)	Total popn.	Exposures – Structures				Exposures – People in/near				Deaths in or near			
			Houses	ND	URM	Ch	Houses	ND	URM	Ch	Houses	ND	URM	Ch
1	1843 Jul 8 D	NE	50	*	*	*	100	*	*	*	0	0	0	0
2	1848 Oct 15 N	100 E	5	*	20	0	25	*	400	400	0	0	0	0
5	1855 Jan 23 N	5000	1000	50	50	1000	4500	100	150	2000	0	0	5	1
21	1888 Aug 31 N	60	12	*	*	20	60	*	*	40	0	0	0	0
25	1901 Nov 16 D _h	200?	50?	2?	5	100?	150	u	15	100	0	u	1	0
38	1929 Jun 17 D	600	150	7	*	300	300	u	*	300	0	u	0	0
43	1931 Feb 3 D	8700	1660	20?	25	3350	3320	3000	500	3350	0	0	0	0
47	1932 Sep 16 N	2000	360	*	*	700	2000	*	*	1900	0	0	0	0
48	1934 Mar 5 N	3100	665	*	*	1330	3100	*	*	3100	0	0	0	0
59	1968 May 24 N	2040	545	130	*	1200	1900	130	*	2000	0	0	0	0
67	1987 Mar 2 D	10900	2800	440	*	600	5600	900	*	600	0	0	0	0
70	1994 Jun 18 D	80	20	9	*	10	40	40	*	10	0	0	0	0
Totals		32700	6697	598	100	8600	21070	7270	1065	13600	0	0	6	1

Notes: NE = Not estimated; See also notes to Table 10.

Table 12: Deaths and exposures related to structures at intensity MM10 in New Zealand earthquakes, 1840-2003.

Event No	Date (LT)	Total popn.	Exposures – Structures				Exposures – People in/near				Deaths in or near			
			Houses	ND	URM	Ch	Houses	ND	URM	Ch	Houses	ND	URM	Ch
43	1931 Feb 3 D	30000	7020	700	443	15000	14040	7000	4430	15000	0	8	240	6
59	1968 May 24 N	250	90	15	0	180	235	15	0	235	0	0	0	0
Totals		30250	7110	715	443	15180	14275	7015	4430	15235	0	8	240	6

Notes: See notes to Table 10.

Table 13: Death rates with their 95 percent confidence intervals associated with different types of structure in New Zealand, 1840-2003.

	Deaths per head of population in or near structure			Deaths per structure		
	Mean	95% confidence interval limits		Mean	95% confidence interval limits	
MM8						
Houses*	0	0	1.9×10^{-5}	0	0	4×10^{-5}
ND*	0	0	3.1×10^{-4}	0	0	0.0013
URM*	3×10^{-4}	1.5×10^{-5}	0.0016	0.0012	5.9×10^{-5}	0.0059
Ch*	0	0	2×10^{-5}	0	0	3.2×10^{-5}
MM9						
Houses	0	0	1.1×10^{-4}	0	0	2×10^{-4}
ND	0	0	5.5×10^{-4}	0	0	0.0035
URM	0.0056	0.0023	0.012	0.060	0.024	0.13
Ch	3×10^{-5}	3.8×10^{-6}	3.6×10^{-4}	2×10^{-4}	5.7×10^{-6}	5.7×10^{-4}
MM10						
Houses	0	0	1.6×10^{-4}	0	0	3.2×10^{-4}
ND	0.0011	5.3×10^{-4}	0.0022	0.011	0.0052	0.021
URM	0.054	0.047	0.061	0.54	0.47	0.61
Ch	3.9×10^{-4}	1.6×10^{-4}	8.2×10^{-4}	4.0×10^{-4}	1.6×10^{-4}	8.2×10^{-4}

* Abbreviations explained in text

The casualties attributed to “miscellaneous other causes” in Table 14 are given in more detail in Table 15, where it is seen that the largest contributor to miscellaneous causes of daytime casualties (350 deaths + injured), is that from contents of buildings. These arise mainly from very dangerously stored goods on high shelving in several large shops for food and hardware. The second largest contributing cause of daytime casualties (60 deaths + injured) is falling brick parapets and gables of older (pre-code) commercial buildings in shopping or business streets. Despite efforts of local government in a 25-year campaign to reduce this risk, not all of these dangerous brick parts had been secured at the time of the study (1997).

Of the 746 deaths in the 11 am event, 702 occur in the intensity MM10 zone, where the population exposed is 238,270. This gives a fatality rate of 1 in 339. It is of interest to compare this with the fatality rate for the MM10 zone of the 1931 Hawke’s Bay earthquake, which occurred at 10.47 am on a work day. In this case 254 deaths occurred in a population of 30,000, giving a fatality rate of 1 in 118. Thus the fatality rate is expected to have reduced by a factor

of almost three from Hawke’s Bay in 1931 to the modelled present day Wellington event. This improvement is due largely to the replacement (not yet complete) of URM with more ductile construction materials for non-domestic buildings.

7.0 HISTORICAL TRENDS

It is obvious that casualties increase with increasing earthquake magnitude, but the number of casualties is also dependent on the location of the source of the event in relation to the geographic distribution of people. This explains much of the large scatter in the plot of numbers of deaths against magnitude for New Zealand given in Figure 5. For the same reason there is a similarly large scatter in the plot of numbers of deaths in New Zealand as a function of time since 1840, as shown in Figure 6. The same randomness is seen when worldwide deaths are plotted against time for the 20th century, as given in Chapter 1 of Dowrick (2003b). This means that historical trends need to be examined on a location-by-location basis, using theoretical models, as discussed in Sections 3.3 and 8.0.

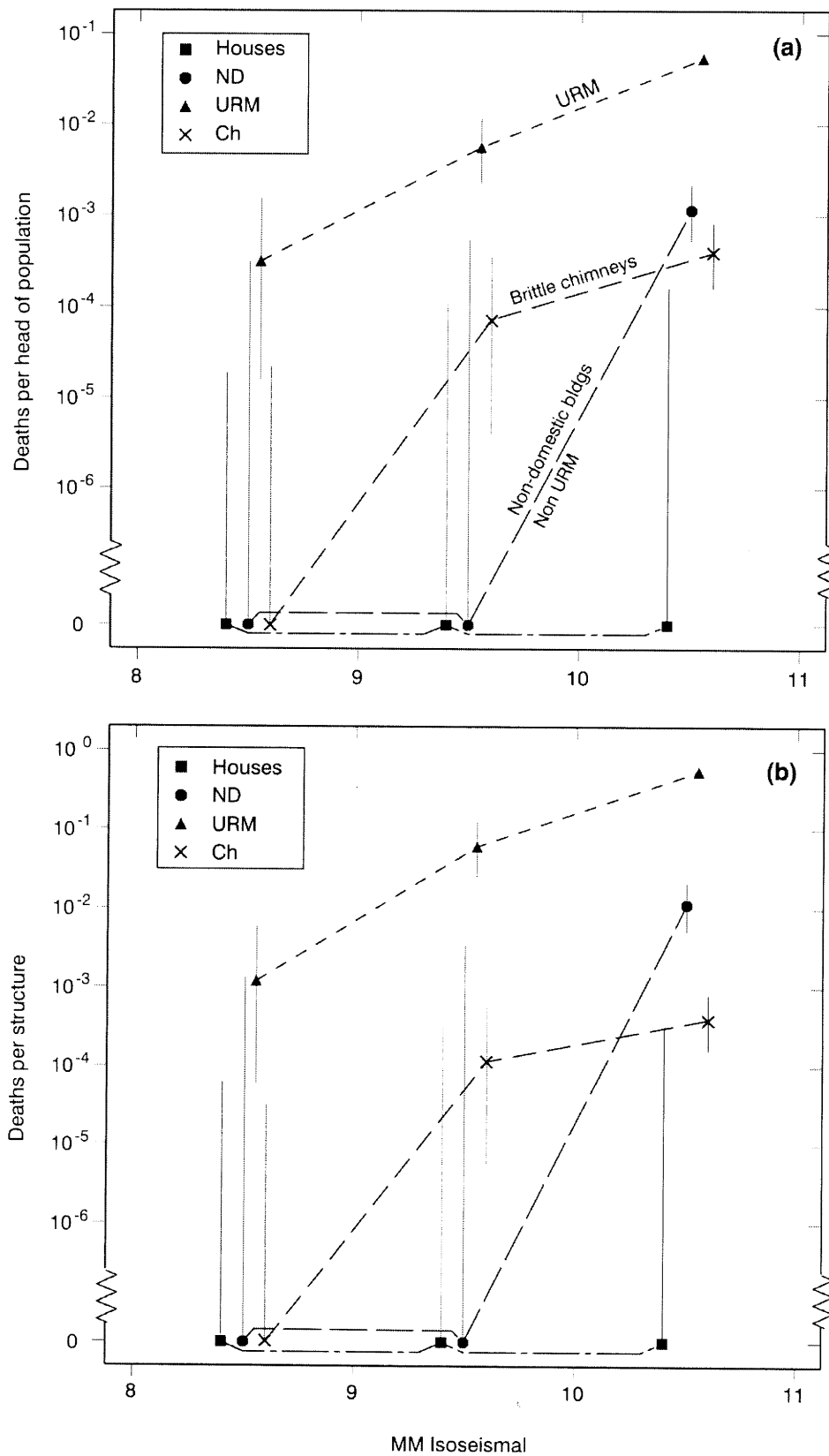


Figure 4: *Death rates in New Zealand earthquakes in the period 1840-2001: (A) based on the population in or near four types of structure (as defined in the text); (B) based on the number of structures.*

Table 14: Summary of deaths and hospitalized injured estimated for two M_w 7.5 scenario earthquakes on the Wellington fault (slightly revised by Dowrick from Spence *et al.*, 1998).

		Workday 11 a.m. Event			Night-time 2 a.m. Event		
		Deaths	Seriously injured	Moderate injured	Deaths	Seriously injured	Moderate injured
	Building collapse (Volume Loss) due to ground shaking	463	76	176	67	17	64
	Buildings sheared by fault	101	53	57	27	65	67
	Misc. other causes	182	151	312	40	33	100
	Best Estimate	746	280	545	134	115	231
Totals	90 percentile	1425	623	1127	283	263	499
	10 percentile	313	90	228	44	41	91

Table 15: Summary of expected casualties in a Wellington fault earthquake that are not related to collapse (volume loss) of buildings (from Dowrick, 2003b).

Category	Cause	Workday 11 a.m. Event			Night 2 a.m. Event		
		Deaths	Injured		Deaths	Injured	
			Serious	Moderate		Serious	Moderate
Associated Phenomena	Fire	6	6	24	6	6	24
	Landslide	5	2	3	9	4	6
	Liquefaction	0	(2) few	(7)	0	(1) few	(2)
	Tsunami	0	0	0	0	0	0
Civil Engineering Structures	Bridges	c.12	4	11	few (6)	(2) few	(6)
	Elevated motorways ¹	4	1	2	few (2)	(0) few	(2)
	Tunnels	few (3)	(1) few	(2)	few (1)	(0) few	(1)
	Dams	unlikely	0		0	0	0
Building Related (non-collapse)	Glass glazing	few (5)	(7) some	(23)	unlikely		unlikely
	Brick parapets and gables	22	8	30	few (3)	(1) few	(3)
	Contents etc.	c.100	c.100	c.150	few (3)	(7)	(18)
Other Causes (non-building)	Fault rupture	13	3	7	unlikely		unlikely
	Severe shaking	few (7)	(10) some	(30)	few (5)	(5) some	(15)
	Panic reaction	few (5)	(7) some	(23)	few (5)	(7) some	(23)
Totals		182	151	312	40	33	100

Notes: Few = Less than 10
Some = 10 to 50
¹Retrofitted

() = Numbers in brackets are "guesstimates"

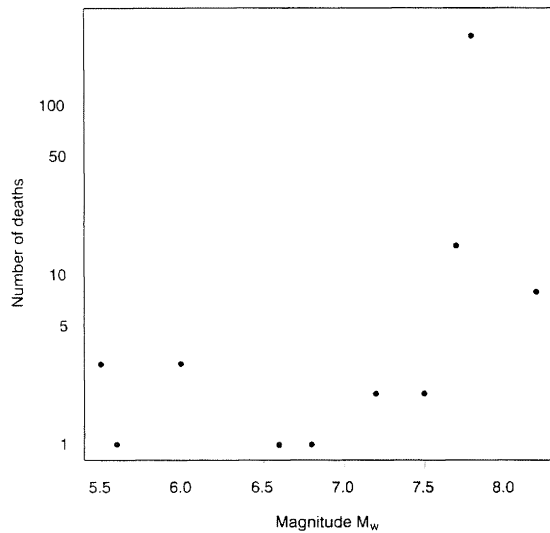


Figure 5: *Numbers of deaths as a function of earthquake magnitude in New Zealand in the period 1840-2003.*

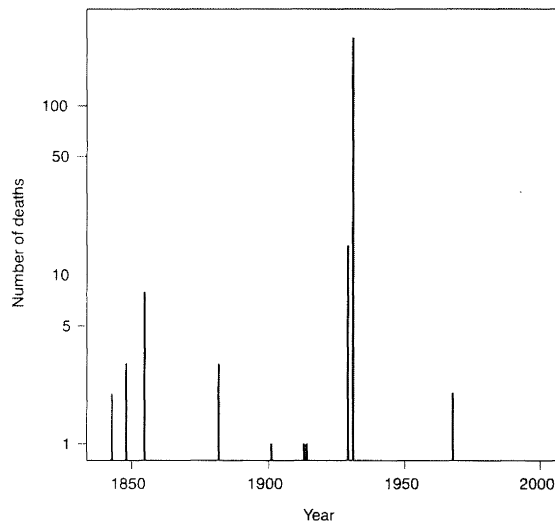


Figure 6: *Numbers of deaths as a function of time in New Zealand earthquakes in the period 1840-2003.*

The number and location of casualties is dependent on the precise time of the earthquake, as well as its location. For instance the 1931 Hawke's Bay earthquake occurred during school playtime. If it had occurred a few minutes earlier or later the children would have been in their classrooms, many in URM buildings. The resulting casualty toll would have been much greater, i.e. two or three times as great as actually happened. Another illustration of this time dependency comes from the 1987 Edgecumbe earthquake in which only one casualty occurred because the main shock occurred shortly (seven minutes) after the foreshock which had caused many people to have vacated dangerous work places (e.g. storage spaces).

8.0 REDUCING FUTURE CASUALTIES

The numbers of casualties in future New Zealand earthquakes could be reduced to substantially better than the improvements that have already been made since 1931. This could be done by systematically following the actions such as those suggested for reducing earthquake risk by Dowrick (2003a). The three most beneficial such actions would be: (1) retrofitting the more dangerous brittle buildings, (2) reducing risk from dangerously stored goods, and (3) permanently vacating buildings straddling the Wellington fault.

9.0 CONCLUSIONS

In the period 1840-2003, earthquakes in New Zealand have caused 297 direct deaths and 640 hospitalized direct injured. Over 90 percent of the casualties occurred in one event, i.e. in 1931.

The casualties have occurred in 16 earthquakes, on average once every 10 years.

Most of the casualties (97 percent) have been caused by damage to buildings and their equipment or contents, the remaining three percent have been caused by ground damage.

Death rates range from 0.054 per head of population for people in or near URM buildings subjected to intensity MM10, decreasing rapidly for other types of structure and for lower intensities.

The future earthquake having the highest risk of casualties in New Zealand is a rupture of the Wellington fault (M_w 7.5, mean recurrence interval 600 years). Such an event in a work day (11 am) is expected to cause about 750 deaths and somewhat more hospitalized injured.

Steps could be taken to substantially reduce the likely casualties in future earthquakes. For example, a feature of the Wellington casualties is the unnecessary high contribution likely from falls of dangerously stored goods in a few shops and warehouses.

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REFERENCES

- Begg, R.C. (1931). "The great Napier earthquake of 1931". *NZ Medical Journal* **30**: 93-109.
- Biggs, A.C. (1931). "The earthquake at Napier, 3rd February, 1931, as it affected the Napier Hospital and the medical services of the district". *NZ Medical Jnl* **30**: 84-92.
- Callaghan, F.R. (1933). "The Hawke's Bay earthquake – General description". *NZ Jnl of Science and Technology*, **XV**: 3-38.
- Conly, G. (1980). "The shock of '31 – The Hawke's Bay earthquake". A.W. and A.H. Reed, Wellington, New Zealand.
- Crudgington, T. (1973). "Men as moles". *NZ Listener*, July 30, 16-17.
- Downes, G.L. (1995). *Atlas of isoseismal maps of New Zealand*. Monograph 11, Institute of Geol and Nuc Sciences, Lower Hutt.
- Downes, G.L. Dowrick, D.J., van Dissen, R.J., Taber, J.J., Hancox, G.T. and Smith, E.G.C. (2001). "The 1942 Wairarapa, New Zealand, earthquakes: analysis of observational and instrumental data". *Bull NZ Soc for Earthq Eng* **34(2)**: 125-57.
- Downes, G.L., Dowrick, D.J. Smith, E.G.C. and Berryman, K.R. (1999). "The 1934 Pahiatua earthquake: analysis of observational and instrumental data". *Bull NZ Soc for Earthq Eng* **32(2)**: 221-45.
- Dowrick, D.J. (1994). "Damage and intensities in the magnitude 7.8 1929 Murchison, New Zealand, earthquake". *Bull NZ Nat Soc Earthq Eng* **27(3)**: 190-204.
- Dowrick, D.J. (1998a). "Earthquake risk for property and people in New Zealand". *Proc NZ Nat Soc Earthq Eng Tech Conf, Wairakei*, 43-50.
- Dowrick, D.J. (1998b). "Damage and intensities in the magnitude 7.8 1931 Hawke's Bay, New Zealand earthquake". *Bull NZ Nat Soc Earthq Eng* **31(3)**: 139-63.
- Dowrick, D.J. (2003a). "Earthquake risk reduction actions for New Zealand". *Bull NZ Soc for Earth Eng*, **36(4)**: 249-259.
- Dowrick, D.J. (2003b). *Earthquake risk reduction*. John Wiley & Sons, Chichester.
- Durkin, M.E. (1996). "Casualty patterns in the 1994 Northridge, California earthquake". *Proc Eleventh World Conf on Earthq Eng*, Paper No. 979, Elsevier Science Ltd.
- Eiby G.A. (1968a). "A descriptive catalogue of New Zealand earthquakes. Part I – Shocks felt before the end of 1845". *NZ Jnl Geol and Geoph* **11**: 16-41.
- Eiby, G.A. (1968b). "An annotated list of New Zealand earthquakes, 1460-1965". *NZ Jnl Geol and Geophys* **11**: 630-47.
- Eiby, G.A. (1973). "A descriptive catalogue of New Zealand earthquakes. Part 2 – Shocks felt from 1846 to 1854". *NZ Jnl Geol and Geoph* **16(4)**: 857-907.
- Grapes, R. and Downes, G. (1997). "The 1855 Wairarapa, New Zealand earthquake – Analysis of historical data". *Bull NZ Nat Soc for Earthq Eng* **30(4)**: 271-368.
- NZDH (1931a). "Progress report on patients from earthquake area as recorded by Department of Health at noon, 23 February, 1931", 23pp. (List held by the National Archives of New Zealand, Wellington, Reference HI 130/18, 24375.)
- NZDH (1931b). "Progress report on patients from earthquake area as recorded by Department of Health on 4/3/1931", 22pp. (List held by the National Archives of New Zealand, Wellington.)
- NZS (2004). "Structural design actions - Part 5: Earthquake actions - New Zealand". NZS 1170.5:2004. *Standards New Zealand*.
- NZSG (1983). "HB earthquake, Tuesday 3 February 1931 at 10.47 am. Force 7.9 Richter scale. Casualty lists". *New Zealand Society of Genealogists*, 48pp. (List held by the National Archives of New Zealand, Reference MISC 1/96.)
- Spence, R.J.S., Pomonis A, Dowrick, D.J. and Cousins, W.J. (1998). "Estimating casualties in earthquakes: The case of Wellington". In seismic design practice into the next century, Booth, E. (ed.), Balkema, Rotterdam 277-86.
- Stirling, M. *et al.* (2000). "Probabilistic seismic hazard assessment of New Zealand". Client Report 2000/53, prepared by the Institute of Geological and Nuclear Sciences for the EQC Research Foundation.
- Stirling, M., Yetton, M., Pettinga, J., Berryman, K. and Downes, G. (1999). "Probabilistic seismic hazard assessment and earthquake scenarios for the Canterbury Region, and historic earthquakes in Christchurch". Client Report 1999/53, prepared by the Institute of Geological and Nuclear Sciences for the Canterbury Regional Council.
- Van de Vorstenbosch, G, Charleson, A.W. and Dowrick, D.J. (2002). "Reinforced concrete building performance in the M_w 7.8 1931 Hawke's Bay, New Zealand earthquake". *Bull NZ Soc Earthq Eng* **35(2)**: 149-164.

Appendix A: List of New Zealand earthquakes (1840-2003) causing intensities \geq MM7 in populated areas.

No.	Date (UT)	Name	UT	LT	M	h_c km	MMI max ⁽¹⁾	References ⁽²⁾
1	1843 Jul 8	Wanganui	-	1645	7.5	12	MM8	Eiby (1968a)
2	1848 Oct 15	Marlborough	1410	0140	7.8	10	MM9	Eiby (1973)
3	1848 Oct 17	Marl. aftershock	0410	1540	6?	10	MM8	Eiby (1973)
4	1853 Jan 1	New Plymouth	0845	2015	6.7	10	MM7	Eiby (1973)
5	1855 Jan 23	Wairarapa	0932	2102	8.2	19	MM10	Grapes & Downes (1997)
6-10	1855 aftershocks	c.5 of M6-7	-	-	6-7	-	MM9	Grapes & Downes (1997)
11	1863 Feb 22	Central HB		0130	7.5	12	MM10?	
12	1868 Oct 18	Cape Farewell	1235	0005	7.2	10	MM8	
13-14	1868 aftershocks	2 of M~6	-	-	6?	-	MM7	
15	1869 Jun 4	Christchurch	1930	0800	5.0		MM7	Stirling <i>et al.</i> (1999)
16	1876 Feb 25	Oamaru	2115	0845	5.8	12	MM7	
17	1876 Apr 11	Oamaru	0010	1140	5.8	12	MM7	
18	1881 Jun 25	Palmerston Nth	1755	0525	6.5	25	MM7	
19	1881 Dec 4	Castle Hill	2017	0737	6.0	15	MM7	Stirling <i>et al.</i> (1999)
20	1882 sometime	nr Paekakariki	?	day	5-6	?	MM7-8	Crudgington (1973)
21	1888 Aug 31	Nth Canterbury	1645	0415	7.1	8	MM9	Cowan, pers comm
22	1893 Feb 11	Nelson	2030	0800	6.9	25	MM7	
23	1895 Aug 18	Taupo	0657	1827	c.6	6	MM8	Eiby (1968b)
24	1897 Dec 7	Wanganui	1510	0240	6.5	40	MM7	
25	1901 Nov 15	Cheviot	2015	0745	6.8	10	MM9	
26	1904 Aug 8	Cape Turnagain	2251	1021	6.7	30	MM8	Downes, pers comm
27	1913 Apr 12	Masterton	0742	1912	5.6	10	MM7	
28	1914 Oct 6	East Cape I	1916	0646	6.6	15	MM8	
29	1914 Oct 28	East Cape II	0016	1146	6.4	15	MM7	
30	1914 Nov 22	Bay of Plenty	0814	1944	7.3	300	MM7	Reyners, pers comm
31	1917 August 5	Wairarapa	1551	0321	6.6	20	MM7	
32	1922 Jul 4	Taupo swarm	0515	1645	4.9	3	MM7	
33	1922 Jul 14	Taupo swarm	0356	1526	5.1	3	MM7	
34	1922 Dec 25	Motunau	0333	1503	6.4	20	MM8	
35	1926 Nov 11	Morrinsville	2251	1021	5.0	5	MM7	
36	1929 Mar 9	Arthur's Pass	1050	2250	7.0	11	MM8	
37	1929 May 7	Hunterville	1614	0344	5.5	10	MM7	
38	1929 Jun 16	Buller	2247	1017	7.7	9	MM9	Dowrick (1994)

Appendix A continued:

No.	Date (UT)	Name	UT	LT	M	h_c km	MMI max ⁽¹⁾	References ⁽²⁾
39-41	1929 Buller	5 aftershocks M_w 5.3-6.3	-	-	-	-	MM7-8	
42	1930 Feb 12	Weber	0622	1822	6.2	25	MM7	
43	1931 Feb 2	Hawke's Bay	2247	1047	7.8	15	MM10	
44	1931 Feb 8	HB aftershock	0143	1343	6.3	15	MM8?	
45	1931 Feb 13	HB aftershock	0127	1327	7.2	16	MM9?	
46	1931 May 6	Gisborne	1458	0228	6.0	25	MM7	
47	1932 Sep 15	Wairoa	1355	0125	6.8	8	MM9	
48	1934 Mar 5	Pahiatua	1146	2346	7.4	12	MM9	Downes <i>et al.</i> (1999)
49	1934 Mar 15	Northern HB	1046	2246	6.4	22	MM7	
50	1938 Dec 15	Central HB	0912	2112	5.8	25	MM7	
51	1942 Jun 24	Wairarapa	1116	2316	7.1	12	MM7	Downes <i>et al.</i> (2001)
52	1942 Aug 1	Wairarapa	1234	0034	7.0	4.0	MM7	Downes <i>et al.</i> (2001)
53	1942 Dec 2	Wairarapa	0015	1215	6.0	20	MM7	Downes <i>et al.</i> (2001)
54	1946 Jun 26	Lake Coleridge	1234	0034	6.3	9	MM7	
55	1948 May 22	Waiau	1921	0721	6.4	4	MM8	
56	1953 Jul 4	Tokaanu	0207	1407	5.3	5	MM7	
57	1963 Dec 22	Peria	1335	0335	4.9	6	MM7	
58	1966 Mar 4	Gisborne	2358	1158	5.6	24	MM7	
59	1968 May 23	Inangahua	1724	0424	7.2	10	MM10	
60-61	1968 aftershocks	M_w 5.3-5.8	-	-	-	-	MM7	
62	1972 Jan 8	Te Aroha	2133	0933	5.3	7	MM7	
63	1976 Oct 27	Te Puke	2057	0857	5.0	5	MM7	
64	1976 Dec 5	Korakanui	0457	1757	5.1	5	MM8	
65	1977 May 31	Matata	1850	0650	5.4	6	MM7	
66	1983 Dec 14	Waiotapu	2056	0956	5.1	3	MM7	
67	1987 Mar 2	Edgecumbe	0142	1342	6.5	6	MM9	
68	1988 Jun 3	Te Anau	2327	1127	6.7	60	MM7	
69	1990 May 13	Weber II	0423	1623	6.4	13	MM8	
70	1994 Jun 18	Arthur's Pass	0325	1525	6.7	6	MM9 ⁽³⁾	
71	1995 Nov 24	Cass	0618	1918	6.3	5	MM8 ⁽³⁾	

Notes: (1) Maximum intensity in a populated area,
(2) Additional references widely used were newspapers and Downes (1995),
(3) Maximum intensity estimated from attenuation modelling.

Appendix B: An example of the 254 Certain Deaths, and the full list of the 16 Possible Deaths in the 1931 Hawke's Bay earthquake.

Example of a *Certain Death*

Williamson, Reginald, 55 yrs, killed by bricks from adjacent building falling into in his book shop, Emerson St, Napier (relative of D.J. Dowrick)

The 16 (unproven) Possible Deaths (developed from NZSG (1983)) :

Name	Location at time of death	Residential address	Source
Culshaw, Miss L	N/H		Newsp, OPL
Culshaw, Mrs T H	N/H		Newsp, OPL
Gannaway, Robert Edgar	Napier	Shakespeare Rd, N	(C) c. 3mths old
Goodall, William	Hastings		Newsp, OPL
Heeney, Roy	Hastings	302 Miller St, H	Newsp, OPL
Lincoln, Miss	Hastings		Newsp, OPL
McDonald, Hugh	Hastings		Newsp, OPL
Mitchell, Harry	N/H		(C+)
Patience, Mary	N/H		Newsp, OPL
Pierson, P J, <i>or</i>	N/H		Newsp, OPL
Pearson, Mr P J	N/H		Newsp
Poole, William	Hastings		Newsp, OPL
Ryan, Thomas Michael	N/H		(C)
Scott, Flora	N/H		(C)
Sims, Percy Reginald	N/H		(C+)
Thomas, Ray Grohard	Hastings		Newsp, OPL
Watt, James	N/H		Newsp, OPL

Notes: (C) Listed as buried on Community Grave Memorial, Park Is Cemetry, Napier.
 (C+) As (C), but not buried in Community Grave.
 Newsp. = Newspaper lists.
 N/H = Napier and Hastings and vicinity
 OPL = Official Police Lists

Appendix C: List of institutions at which injured or ill patients were treated after the 1931 Hawke's Bay earthquake.

Napier and Hastings Area:

Napier Field Hospital (Racecourse)

Dressing Stations at Fox's house (Awatoto), McLean Park and Nelson Park

Hastings: Hastings Memorial, Racecourse and Royston

Other Locations:

Dannevirke Public Hospital (PH)

Feilding PH

Gisborne: Awapuni Old People's Home

Hawera PH

Levin PH

Marton PH

Masterton PH

New Plymouth PH

Palmerston North PH, Convent, Maitland, Northcote, Sister Anderson's Private Hosp.

Wanganui PH

Waipukurau PH and Pukeora Sanitorium

Wairoa PH

Wellington PH, and Home of Compassion at Island Bay