Estimated casualties in New Zealand earthquakes

Jim Cousins (GNS Science, Lower Hutt, New Zealand) (j.cousins@gns.cri.nz)
Robin Spence and Emily So (Cambridge Architectural Research Ltd., Cambridge, England)

Abstract

Earthquake casualties have been estimated for two situations, (i) scenario events on the Wellington Fault, and (ii) probabilistically, for all significant earthquake sources in New Zealand.

Because the southernmost segment of the Wellington Fault bisects a major urban area, and is believed capable of generating earthquakes of magnitude 7.5, it is regarded as the probable source of New Zealand's costliest and deadliest earthquakes. For a magnitude 7.5 earthquake on it we have estimated the mean numbers of deaths and hospitalised injured to be 600 and 4400 respectively for a working day event, and 200 and 3300 for a night-time event.

Probabilistically the total casualty exceedance numbers for return periods of 10, 100 and 1000 years were about 20, 300 and 4000, with deaths comprising 4 to 8 % of the casualties. Actual rates over the most recent 50 years have been very much lower than the long-term estimated rates, largely because there were no moderate or large earthquakes near urban areas during that period.

1.0 Introduction

Earthquake casualties are primarily caused by severe damage to and collapse of buildings. For estimating numbers of casualties we therefore needed to model the following:

- earthquake shaking (to define the two-dimensional pattern of shaking intensity about the epicentre of a specified model earthquake),
- buildings and fragilities (to give the damage state of a building as a function of shaking intensity),
- numbers of occupants of buildings (which depend on time of day, size and use of building), and
- casualty rates (proportions of occupants killed or injured as functions of building damage state).

There were two components to the work: worst-case scenario, and probabilistic. A rupture of the southern-most segment of the Wellington Fault is believed to be the worst-case earthquake scenario for New Zealand. This results from the coincidence of a major urban area and one of New Zealand's most active surface-rupturing faults. All urban parts of the Wellington Region, i.e. the cities of Wellington, Porirua, Hutt and Upper Hutt, will be shaken strongly when the fault ruptures, seriously affecting 350,000 people. A further 100,000 people in the more distant parts of the Wellington Region also will be at significant risk. The likelihood of casualties away from urban Wellington is small, however, because all other localities are sufficiently far from the fault rupture. Thus the scenario study concentrates on the urbanised parts of Wellington Region. The scenario work reported here updates a series of earlier, similar, studies (Spence et al 1997, 1998).

On its own, a scenario study does not provide information about the probability of casualties, because it lacks information about the probability of occurrence of the scenario, and ignores other earthquakes. A second phase of our study filled this gap by exposing simplified models for buildings and occupants, covering all of New Zealand, to all earthquakes expected over a 400,000-year period. The simplified models were calibrated with the results of the scenario model. The main output of the probabilistic study was the relationship between probability of exceedance and casualty numbers. A secondary output was identification of the earthquake sources primarily responsible for the casualties.

2.0 Earthquake shaking hazard – overview and modelling

Seismicity in New Zealand varies regionally from moderate to very high on a world scale. Wellington, the capital, lies in one of the most active of New Zealand's seismic regions and Auckland, New

Zealand's largest city, in one of the least active. Activity in the Christchurch and Dunedin areas is intermediate between that of Wellington and Auckland. These differences are illustrated by Figure 1, which shows the locations of the major shallow earthquakes that have occurred in the New Zealand area since 1840. Note that while there have been no major earthquakes close to large urban centres in recent times, prior to 1955 there were near-direct hits on Wellington and Napier. There were no significant injuries in the most recent damaging earthquake, Gisborne 2007.

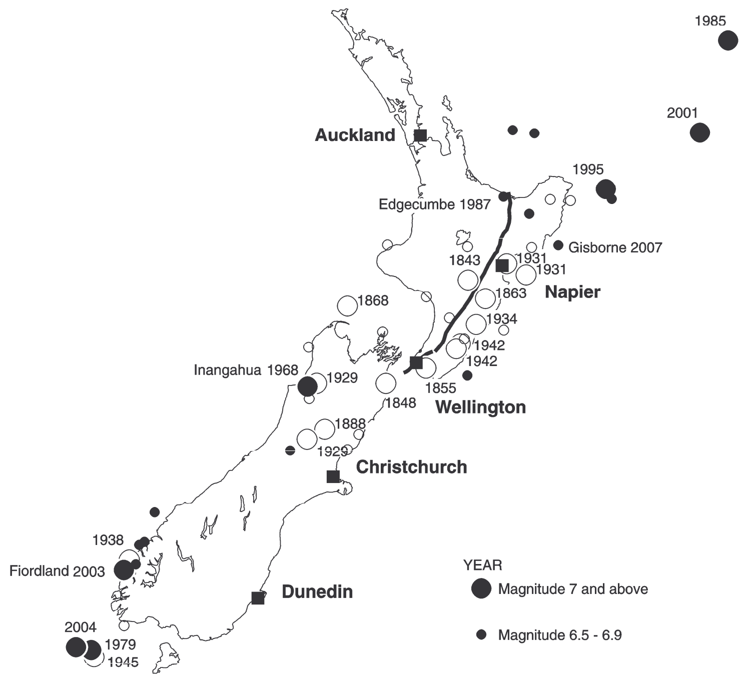

Figure 1: Occurrence of moderate-large shallow earthquakes in New Zealand since 1840. Filled circles are for recent earthquakes, 1955 to 2007 inclusive, and open circles for pre-1955 events. The Wellington Fault and associated structures are shown as a heavy black line.

The Wellington Fault is the southernmost part of a distinct fault structure that extends northwards from Cook Strait, adjacent to Wellington (Figure 1). It is a segmented structure, of which the various segments probably rupture independently, though a rupture of any one may influence the timing of rupture of its neighbours. Seismological characteristics of the Wellington-Hutt Valley (WHV) segment are: magnitude of earthquake: 7.5 ± 0.3, horizontal offset in rupture: 4 m, average recurrence interval (time between ruptures): 600 years, and time since last rupture: 400 years

The strength of earthquake shaking was quantified with the Modified Mercalli Intensity (MMI) scale. In order to estimate the expected severity of ground motion (intensity) at any given place, due to an earthquake elsewhere, we used the MMI attenuation model of Dowrick and Rhoades (1999). An important point about the Dowrick and Rhoades model is that it predicts shaking intensities for average ground. Actual intensities on non-average ground, i.e. soft soil or rock, can be higher or lower than the average-ground case as a result of microzonation phenomena. Allowance was made for microzonation by adjustments to the fragility functions of the buildings affected.

In order to obtain probabilistic estimates of earthquake losses we exposed the assets of interest to shaking from each event in a 400,000-year long synthetic catalogue of earthquakes. The catalogue, which is a way of representing the seismic hazard model of New Zealand, takes account of both known active faults and distributed seismicity (Smith 2003). It provides a powerful means of estimating earthquake risk: the procedure is to estimate the likely effects of every earthquake in it, then to estimate how much damage ensues, and how often.

3.0 Assets models – buildings and people

Underpinning data on buildings and populations were sourced mainly from QV (a property valuation company), the Ministry of Education, Statistics NZ, and websites for large properties like universities and hospitals. Two buildings and occupancy models were developed, one relatively detailed for the Wellington Region, and one less detailed for all of New Zealand. The level of detail varied from building-by-building for large (> 300 m^2) buildings in urban Wellington, to "Meshblock", for smaller buildings and locations other than urban Wellington. Data were further aggregated to "Area Unit" scale for computation. (The meshblock is a standard statistical unit used in New Zealand. Typically it contains around 50 houses or 5 workplace buildings. An area unit comprises about 20 meshblocks.)

For the Wellington scenario study, buildings were assigned to one of 43 fragility classes, depending on construction type (e.g. moment-resisting frame), construction era, height, and presence of any critical structural weaknesses. For the All of New Zealand probabilistic study the classes were coalesced to just four, viz. timber frame, pre-1980 concrete, post-1980 concrete (both reinforced), and unreinforced masonry.

Where suitable statistical data were available, people were allocated to buildings in proportion to the available floor area. Otherwise reasonable assumptions were invoked, for example, numbers of shoppers were assumed to equal the numbers of people working in occupations "retail", "wholesale" and "hospitality". Numbers of people outdoors at 11 a.m. were assumed to equal 20% of the total population. The resultant average occupancy rates for day-time scenarios in the Wellington Region were as listed in Table 1. An additional 92,000 people were outdoors.

Table 1: Day-time occupancies for buildings in the Wellington Region

Building Use Category	Commercial	Industrial	Agricultural	Educational	Residential
Occupancy Rate (m^2/pers)	59	134	98	13	230
Number of occupants	133,000	29,000	4,000	104,000	100,000

For night-time scenarios, people indoors at home were allocated to residential buildings at a rate of 52 square metres per person (well supported by statistical data). Based on worldwide surveys, 3% of the total population was assumed to be indoors at work and 1% was assumed to be outdoors (Spence et al, 1998). Workplace occupants were allocated at the daytime rates to workplace buildings with known high night-time occupancies, like hospitals, prisons, police stations, major fire stations, and 24-hour medical centres. Other workplace occupants were allocated to randomly selected workplace buildings, at randomly selected rates in the range 400 to 1000 m^2 per person.

4.0 Casualties modelling

The general procedure for the casualties computation was as follows:

- define the earthquake, and estimate the shaking intensities over the region of interest,
- estimate the mean damage ratios at each location using the formula of Cousins (2004), then the probabilities of buildings being in each of five damage states, and
- estimate the numbers of casualties using formulae linking damage state to casualty class.

Five building damage states were defined, ranging from S1 (no damage) to S5 (collapse), and also five injury classes, viz. dead (class 5), critical (person will die without expert medical attention), serious (expert medical attention needed but life not threatened), moderate (doctor/nurse only) and light to none (class 1). A set of "M" parameters linked the two, such that, for example, the number of dead (N5) in any given building fragility class and MM intensity zone was:

$$N5 = O.\ NB.\ (M51.pS1 + M52.pS2 + M53.pS3 + M54.pS4 + M55.pS5)$$

where O = the total number of occupants per building in the class and zone, NB was the number of buildings in the class and zone, and pS1 to pS5 were the probabilities of the building being in each damage state as a result of the given scenario. The M parameters varied from one building class to another. Similar formulae gave the numbers in each of the other injury categories, except for class 1 where numbers were obtained by subtracting totals of the other classes from occupancies.

The set of injury state parameters used in the model were derived from a review of collated data from recent earthquakes such as Kobe, Kocaeli and Chi Chi. Casualty rates from loss estimation models such as HAZUS and ATC13 from the United States were used as reference (Spence 2007).

Of critical importance to the calculation was the relatively low value of parameter M55 applied to timber-framed buildings. We believe the low value was justified by worldwide experience of such buildings. Numbers of critically injured were set at 5-10% of the severely injured, again in line with the latest data from earthquake casualty studies.

The damage states were derived indirectly. For each of the building classes, the formula

$$MDR = A.10^{(B/(MMI-C))}$$

was used to determine the mean damage ratio MDR at intensity level MMI (Cousins, 2004), where constants A, B and C were defined for each of the 43 building classes. Data that underpinned the formula were derived from New Zealand and Californian earthquakes (e.g. Dowrick et al 2001).

Using an analysis of its worldwide damage data, Cambridge Architectural Research developed the following formula for estimating the probability of the loss exceeding any given loss ratio, given the MDR,

$$\Phi^{-1}(R) = a\,\Phi^{-1}(MDR) + b\,\Phi^{-1}(LR)$$

where Φ^{-1} refers to the inverse of the standard cumulative Gaussian distribution, R is the proportion of the sample with a loss ratio exceeding LR, and a and b are constants. In this formula, constants a and b are dependent on the building class.

The loss ratio is closely related to damage state, and so the same formula can be used to estimate probability of occurrence of each damage state, if we define the corresponding loss ratios. We used the definitions shown in Table 2. The assumed loss ratios took account of observed collapse ratios in New Zealand, and worldwide damage data.

Table 2: Adopted correspondence between damage state and loss ratio.

Damage state	Description	Loss ratio
S1	Light	1 to 10%
S2	Moderate	10 to 35%
S3	Severe	35 to 75%
S4	Partial collapse	75 to 90%
S5	Collapse	> 90%

All of the above parameters are subject to a level of uncertainty, and a key aspect of the scenario study was to allow for the cumulative effect of the uncertainties on the casualty estimates. For the scenario study this was done by carrying out a Monte Carlo type simulation, examining the total building stock of the city building by building over a number of simulations. Variability was incorporated at three stages, viz. earthquake definition, casualty estimation and time of day. Nine earthquake models were defined to cover low, mean and high magnitudes, and southern, central and northern locations along the fault for the highest intensity shaking. For each model earthquake, twenty damage/casualty simulations were conducted with various parameters being selected from probability distributions, notably those defining the damage states and the M parameters. The results of each run were combined, with weightings, to give a composite exceedance probability curve. Finally, all of the above was repeated for day and night occupancy models.

For the probabilistic modelling, a very useful feature of the synthetic catalogue method is that each particular event, such as the Wellington Fault earthquake, is repeated many times in a suitably long catalogue, which makes modelling natural variability and uncertainty very easy. All that is required is to change the uncertain parameters from one run of the earthquake to another. Parameters that were treated in this way included the magnitude and epicentral location of the earthquake, and the attenuation of shaking. Uncertainty in the casualty computation was not included, however.

All of the above modelling relates to casualties due to building damage caused primarily by earthquake shaking. Casualties due to buildings sheared by the fault rupture, and to other effects, including post-earthquake fire, landslides, liquefaction, tsunami, collapse of civil engineering structures (bridges, elevated motorways, tunnels and dams), and falling objects (glass glazing, brick parapets and gables, and contents) were estimated separately and added to the primary casualties. The numbers and characteristics of buildings sheared by the fault rupture (and hence severely damaged) were estimated by walking the length of the fault and inspecting the buildings individually. Estimating the numbers of casualties from the “other effects” was very much an opinion-based exercise, and for each effect the numbers involved were small, even though the totals were significant.

5.0 Summary of scenario results

Estimated casualties from a Wellington Fault earthquake are summarised in Table 3. Points of note are the relatively low death rates in New Zealand’s probable worst earthquake disaster, and the differences between the day and night situations. Two reasons for the former are (a) the long tradition of earthquake resistant design in New Zealand, and (b) policies for the removal or upgrading of known earthquake-risk buildings, mostly of pre-1940 age, which have been pursued vigorously by City Councils in the Wellington area. The main reason for the much lower expected numbers of night-time deaths is that, although more people are indoors at night, most are in the comparative safety of timber-frame residential buildings.

Table 3: Estimated numbers of casualties from a magnitude 7.5 earthquake on the Wellington Fault (WHV segment). The population at risk was about 450,000.

Time of Day		Workday (11 a.m.) Event				Night-time (2 a.m.) Event			
Cause of casualties		Deaths	Critical	Serious	Mod	Deaths	Critical	Serious	Mod
Earthq. shaking damage	Mean	455	7	341	3903	114	3	203	3130
	90^{th} pcl	850	11	630	7000	180	4	460	5800
	10^{th} pcl	160	2	130	1500	30	1	65	1170
Bldg sheared by fault		76	1	16	94	22	0	9	63
Miscel. other causes		93	1	63	205	43	1	34	102
Totals (rounded)	Mean	600	9	400	4000	200	4	250	3000
	90^{th} pcl	1000	15	700	7000	250	5	500	6000
	10^{th} pcl	300	4	200	2000	100	2	100	1500

6.0 New Zealand-Wide Probabilistic Casualties

The buildings and occupants model covering all of New Zealand was exposed to the nearly 2,000,000 model earthquakes in a 200,000-year synthetic catalogue of earthquakes developed from the current seismicity model for New Zealand. For each earthquake, the shaking intensity was estimated at each of 1840 aggregated-asset locations and then the numbers of deaths and injuries were estimated. This was done for both day and night conditions for each earthquake, giving an effective catalogue length of 400,000 years. Finally, simple counting was used to determine how often, over the 400,000-year period, the per-earthquake numbers of deaths and injuries equalled or exceeded various levels. Results are given in Figure 2 and Table 4.

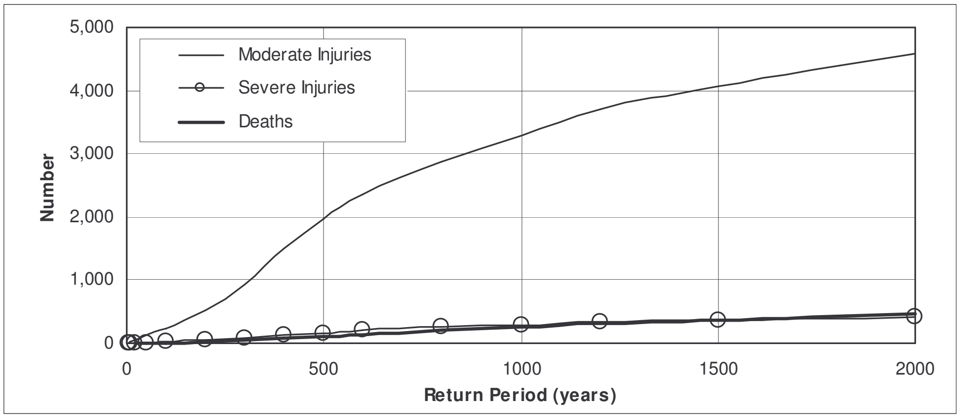

Figure 2: Estimated numbers of deaths and injuries in New Zealand earthquakes as a function of return period. Numbers of critical injuries were too small to plot. In all cases "Number" is the number that was equalled or exceeded for the given return period.

Table 4: Likelihood of casualties from earthquakes in New Zealand. The population at risk was about 4,000,000.

Return Period (years)	Annual Probability of Exceedance	Deaths	Critical Injuries	Severe Injuries	Moderate Injuries
5	0.2	0	0	1	8
10	0.1	1	0	2	21
50	0.02	4	0	10	120
100	0.01	8	0	20	250
500	0.002	110	3	160	2,000
1,000	0.001	250	6	300	3,300
5,000	0.0002	810	12	570	5,700
10,000	0.0001	1,000	16	700	6,300

Although not large, the rates of deaths and injuries of Figure 2 and Table 4 are higher than recent history would indicate. The reason for this is that the last 50 years has been a most fortunate period for New Zealand, at least in so far as earthquake losses are concerned. There have been earthquakes of magnitude 7 and greater during that period, but they have either been offshore (e.g. Fiordland 2003, Figure 1) or in very sparsely populated places (e.g. Inangahua 1968). Even the moderate earthquakes have been located in rural areas or offshore (e.g. Edgecumbe 1987, Gisborne 2007). No urban area has experienced even moderate-strength shaking in that time.

In order to calibrate our modelling, to some extent, the All-of-New Zealand buildings and occupants model was exposed to the catalogue of magnitude 5 or greater New Zealand earthquakes recorded in the 50 years from 1955 to 2004 inclusive. The results, Table 5, indicate much lower rates than the long-term average rates of Table 4. Given the short time period and the high degree of natural variability involved, they compare about as well as can be expected with the known numbers of deaths and hospitalised injuries for the 50-year period, i.e. 2 deaths and 2 injuries (Dowrick & Rhoades 2005).

Table 5: Estimated numbers of earthquake casualties for New Zealand, for period 1955 to 2004.

Return Period (years)	Annual Probability of Exceedance	Deaths	Critical Injuries	Severe Injuries	Moderate Injuries
5	0.2	0	0	0	1
10	0.1	0	0	0	2
50	0.02	0	0	1	10

It is often important to recognise which earthquake sources contribute most to the risk. For any given portfolio of assets it is possible to rank sources in order of importance using a process called "deaggregation". Table 6 shows the deaggregation for 10 or more deaths in New Zealand, i.e. the earthquake sources that can cause 10 or more deaths and the relative contribution that each makes to the total of such deaths over a 400,000-year period. The dominance of the Wellington Fault (WHV segment) is clear. Also clear is the dominance of urban Wellington, which as an affected locality contributes at least 80% of the total deaths.

Table 6: Relative importance of earthquake sources that can cause 10 or more deaths.

Fault Name	Contribution (%)	Locality Most Affected
Wellington (Wellington - Hutt Valley segment)	69	Wellington Urban
Wairarapa 1855	6	Wellington Urban
Napier1931	4	Napier & Hastings
Ohariu	3	Wellington Urban
Wellington (Pahiatua segment)	2	Palmerston North
All other sources (incl. distributed seismicity)	16	Various

7.0 Acknowledgements

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8.0 References

Cousins, W.J., 2004. "Towards a first-order earthquake loss model for New Zealand". Proceedings, 2004 Conference of the New Zealand Society for Earthquake Engineering, 19-21 March 2004, Rotorua. New Zealand Society for Earthquake Engineering. Paper No. 29, (available online from www.nzsee.org.nz).

Dowrick, D.J. and Rhoades, D.A., 1999. "Attenuation of Modified Mercalli intensity in New Zealand earthquakes". Bulletin of the New Zealand Society for Earthquake Engineering, 32(2): 55-89.

Dowrick. D.J, Rhoades, D.A. and Davenport, P.N., 2001. "Damage ratios for domestic property in the magnitude 7.2 1968 Inangahua, New Zealand, earthquake". Bulletin of the New Zealand Society for Earthquake Engineering, 34(3): 191-213.

Dowrick, D.J. and Rhoades, D.A., 2005. "Risk of casualties in New Zealand earthquakes". Bulletin of the New Zealand Society for Earthquake Engineering, 38(2): 53-72.

Spence, R. (Editor) 2007. "Earthquake disaster scenario prediction and loss modelling for urban areas". LESSLOSS Report 2007/07, IUSS Press, Parvia, Italy.

Spence, R.J.S., Pomonis, A., Dowrick, D.J. and Cousins, W.J., 1997. "Wellington area casualty estimation 1997" Client report for the New Zealand ACC.

Spence, R.J.S., Pomonis, A., Dowrick, D.J. and Cousins, W.J., 1998. "Estimating human casualties in earthquakes: the case of Wellington". in Proceedings of the Sixth SECED Conference on Seismic Design Practice into the Next Century, Oxford, 26-27 March 1998. p277-286.

Smith, W.D., 2003. "Earthquake hazard and risk assessment in New Zealand by Monte Carlo methods". Seismological Research Letters, 74(3): 298-304.