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EARTHQUAKE DAMAGE AND RISK EXPERIENCE AND MODELLING IN NEW ZEALAND

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SUMMARY

This paper describes efforts made over the past decade or so to understand and model the primary causes of damage and casualties in New Zealand earthquakes, and summarises a wide range of applications for the research outcomes. The nature, cause and extent of damage and casualties have been reviewed in varying depth in ongoing studies of over 40 earthquakes with magnitudes in the range $5 < M_W \leq 8.2$.

The degree of damage to a given item is described as either a damage ratio (using costs) or as a damage state (using damage descriptions). The damage ratio, D_r, is defined as the Cost of Damage divided by the Value of the Item of Property concerned. Damage ratio distributions have been evaluated for a wide range of property classes, including houses, non-domestic buildings, equipment (plant) and stock.

Over 80% of deaths in New Zealand earthquakes since 1840 have been caused by building damage (nearly all of brick), and mostly at intensity MM10 (the maximum intensity used in New Zealand). Landslides have been the main other cause. An empirical log-linear model shows that the probability of death in brick buildings increases 10 fold per unit increase in intensity.

All 11 New Zealand earthquakes which have shaken c. 500 brittle concrete buildings strongly (PGAs 0.2-0.8g), have shown that such buildings of 1-3 storeys have been collapse-free, except that one soft-storey building collapsed. The rest had walls of concrete or brick infill and many were asymmetric.

INTRODUCTION

While New Zealand studies have collectively covered many aspects of damage to the built and natural environments, this paper concentrates on efforts in the past decade or so to understand and model the primary causes of damage and casualties. To that end the principal author has studied damage in over 40 New Zealand earthquakes, and in a few key overseas events that were applicable to New Zealand. As both qualitative and quantitative data are essential to full understanding, both these aspects have been given serious attention. Depending on the type of data available, the degree of damage is described as either a damage ratio (using costs) or a damage state (using damage descriptions).

DAMAGE RATIO STUDIES

Fully quantitative descriptions of the degree of damage to a given item of property are conveniently given by the damage ratio D_r, defined as:

$$D_r = \frac{\text{Cost of damage to an Item}}{\text{Value of that Item}} \tag{1}$$

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where “Value” is best expressed in terms of Replacement Value (used here except where noted). D_r is a function of the strength of shaking and the physical nature of the item being considered. Ideally, D_r would most helpfully be modelled in an attenuation function in terms of magnitude, distance and scatter, but because of the small number of good D_r data sets yet available, we are currently limited to describing D_r as a function of intensity.

All of the many distributions of D_r that we have examined fit the truncated lognormal form well (e.g., Figure 1). The lognormal distribution has the density function

$$f(x) = \frac{1}{\sigma x \sqrt{2\pi}} \exp\left[-\frac{1}{2} (\log_e x - \mu)^2 / \sigma^2 \right] \quad x > 0 \tag{2}$$

In the truncated form of the distribution as fitted to damage ratios, there is a “spike” at 1, i.e., $P(D_r = 1) = \int_1^\infty f(x)dx$. Here the parameters μ and σ are estimated by the sample mean and standard deviation of the natural logarithm of the damage ratio of damaged items.

The population of property items for any given distribution of D_r is taken from the zone between two adjacent isoseismals, so that the MM7 intensity zone (for example) is defined as the zone between the MM7 and the MM8 isoseismals.

In our damage ratio studies (ie. of the 1987 Edgecumbe and 1931 Hawke’s Bay earthquakes) it has been possible to assemble complete databases for all items of properties (damaged and undamaged) of various classes. This has enabled us to evaluate the statistical distributions and mean damage ratios D_{rm} (eg. Table 1) free of sampling errors for the populations concerned. The studies so far completed have included the vulnerability of houses (MM6-MM10), house contents (MM6-MM9), domestic vehicles (MM7-MM9), non-domestic buildings of various classes (MM7-MM9), and equipment, plant and stock of various classes (MM7 and MM9), and microzoning effects at MM10 have been evaluated, see Dowrick (1991), Dowrick & Rhoades (1993, 1995, 1997a, b) and Dowrick et al. (1995).

REPRESENTATIVE VULNERABILITY DATA

Typical values of the percentage of 1960’s (aseismic) buildings that are undamaged, as a function of intensity, are 85% (MM7) and 30% (MM9). In view of these percentages it is obvious that the above-mentioned consideration of complete (or statistically representative) populations of both damaged and undamaged property items is essential in both damage ratio and damage state studies, if false conclusions are to be avoided. For example in some early damage ratio studies it appears that undamaged property was not represented fully when estimating mean damage ratios.

A similar problem arises with the use of damage states. Data from reconnaissance reports is particularly suspect in this respect, because much of it is anecdotal and such reports tend to accentuate cases of damage. Some classes of construction may be unjustly vilified because attention is placed mainly on a relatively few cases of bad damage. For example, asymmetric buildings may not be a problem if they are low-rise, and brittle concrete buildings may also be satisfactory if they have structural walls (see below).

VULNERABILITY OF BRITTLE CONCRETE BUILDINGS

In view of safety concerns related to reinforced concrete buildings designed before the introduction of capacity design and ductility detailing, we are currently studying the performance of all pre-1976 New Zealand concrete buildings that have been subjected to moderate or strong shaking, ie. intensity ≥ MM8 and peak ground

Table 1: Basic statistics of the distributions of damage ratio for selected sub-classes of New Zealand property

Sub-class			n	N	μ	σ	D_{rm}
MM9 Zone (1987 Edgecumbe Earthquake)							
Buildings, 1-storey non-domestic:							
	Code era built in:	1935-1964	72	154	-3.29	1.69	0.063
		1965-1969/79	60	118	-3.28	1.62	0.054
		1969/79-1987	57	133	-3.71	1.67	0.033
Equipment:							
	Vulnerability class:	Robust	80	197	-3.64	1.34	0.023
		Medium	116	247	-3.13	1.59	0.052
		Fragile	11	16	-0.90	0.80	0.32
MM10 Zone (1931 Hawke's Bay Earthquake)							
1-Storey timber houses:							
	Ground class:	Rock*	417	417	-3.01	0.70	0.062
		Firm (beach)	281	281	-3.14	0.77	0.056
		Soft (reclaim)	945	945	-3.47	0.84	0.041

*Predominantly cemented limestone.

Table 2: Statistics of damage states of all pre-1976 concrete buildings subjected to strong shaking in New Zealand earthquakes.

Event Date	M_W	MMI	PGA (g)	Damage States									Asymmetric and Corner Buildings
				OK			Cracks			Collapse			
				No. of Bldgs per No. of Storeys									
				1	2	3+	1	2	3+	1	2	3+	
1922 Dec 25	6.4	8	0.3	1									1 Asym
1929 Jun 16	7.8	9	0.6	3			1	1					17 Asym
		8	0.4-0.15	12	11	1	2	3	1				
1931 Feb 2	7.8	10	0.8-0.5	9	27	9	12	18	4			1	Asym
		9	0.5	2	6								
		8	0.3	13	8	3	2	1					6 Corner
1932 Sep 15	6.8	8	0.5-0.3	9	3	3	2	2					*
1934 March 5	7.3	8	0.4			1							0
1942 Jun 24	7.1	8	0.5-0.4	56	16	2	5	8	2				30 Asym 7 Corner
1946 Jun 26	6.4	7+	0.3			1							0
1948 May 22	6.4	8	0.35	1	2								1 Asym
		7?	0.25	2	2								
1968 May 23	7.2	9	0.6	15									*
(prelim data)		8	0.5-0.2	26	2		20						
1987 Mar 2	6.5	9	0.4	86	5		44	16	2				*
		8	0.3	6	6	2							
1994 Jun 18	6.7	9	0.5	1	1								0
		8	0.4		1								
Totals				242	90	22	88	49	9			1	

Notes: Tallest building 5 storeys
* Not yet evaluated

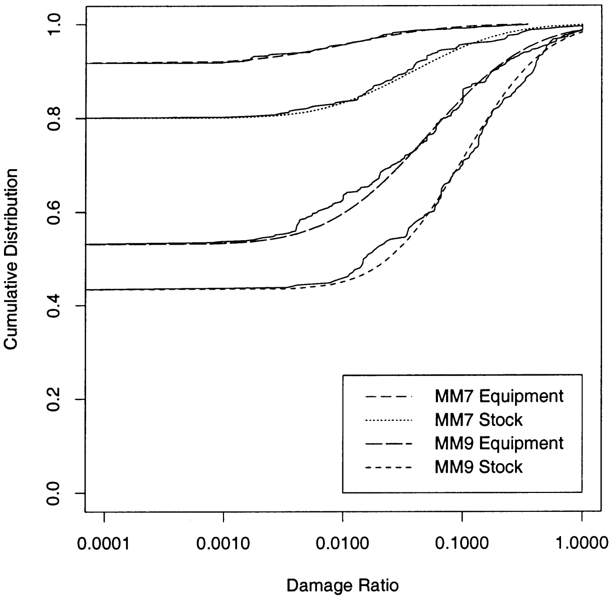

Figure 1: Empirical and fitted lognormal cumulative probability distribution for equipment and stock, in the intensity MM7 and MM9 Zones of the 1987 Edgecumbe earthquake. (From Dowrick and Rhoades, 1995)

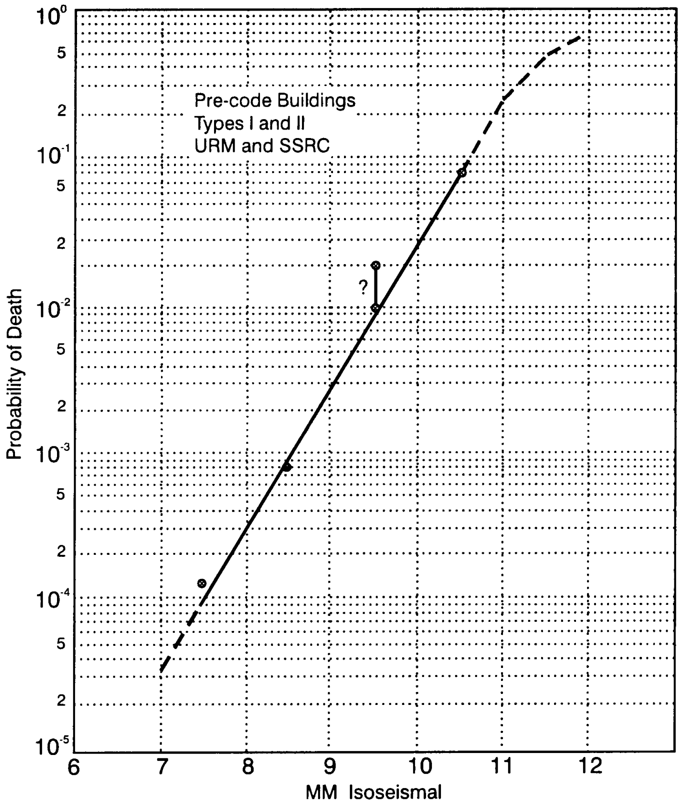

Figure 2: Probability of death in or beside URM and SSRC buildings as a function of MM intensity in New Zealand (SSRC = soft storey pre-code reinforced concrete). (From Dowrick, 1998)

accelerations (PGA) in the range approximately 0.2-0.8g, in 11 earthquakes of $M_W \geq 6.4$ from 1922 to 1994. Damage levels observed in this study are described in terms of the following damage states, (i) OK (zero or slight damage. D_r (structure) ≤ 0.01 if available); (ii) Moderate damage, with no falls of concrete structure; (iii) Serious damage with partial collapse of structure; (iv) Collapse, volume loss > 50%.

New Zealand's experience of the performance of buildings in strong shaking has so far been limited to low-rise construction. This is not surprising, and is also of great value, as about 95% of New Zealand's buildings are of one to five storeys. Although data gathering is not yet complete, most of the key data is in hand, and has enabled the compilation of the overall findings of Table 2. This shows that only one brittle concrete building out of the 500 or so subjected to strong shaking has had any falls of concrete structure. The building which collapsed was the only soft-storey structure (Dowrick, 1998), while most of the rest were predominantly walled structures.

DAMAGE VERSUS CASUALTIES

Almost all casualties in New Zealand earthquakes have been caused by damage to buildings and (a few percent only) by landslides. All the deaths due to building damage have been associated with falling unreinforced masonry (URM), and one soft-storey pre-code building. About 94% of the building-related deaths have occurred at intensity MM10. The data on which the above statements are based enabled Dowrick (1998) to relate probability of deaths in or beside URM buildings to MM intensity. As seen in Figure 2, the data fit quite well to a log-linear line, such that the probability of death increases 10-fold per one unit increase in intensity.

The above 1000-fold increase in mortality risk from intensity MM7 to MM10 is consistent with the model of Coburn & Spence (1992) derived considering data on brick buildings from other parts of the world.

LANDSLIDES

In the last 150 years landslides have been the second largest contributor (c. 6%) to casualties in New Zealand earthquakes. With much steep terrain in New Zealand urban as well as rural areas, earthquake-induced landslides constitute an important earthquake risk affecting land-use planning issues in many parts of the country. The most recent research in this subject area (Hancox et al., 1998) was a study of landsliding (and liquefaction) in 22 earthquakes in the past 150 years. It produced revised environmental response criteria and ground classes for landsliding in earthquakes, and their relationship to the MM intensity scale, for use in risk modelling.

APPLICATIONS IN DESIGN, INSURANCE & PLANNING

Many applications are made of the results of damage studies such as those given above, not only for improving the design of new elements of the built environment, but for appropriate retrofitting, lifelines studies, mitigation of existing risk, earthquake insurance, land-use planning and disaster response planning.

A wide-ranging application is the estimation of casualties in a magnitude 7.5 earthquake on the Wellington fault (Spence et al, 1998) for the NZ Accident Compensation Commission for their reinsurance purposes. In a daytime event the estimated deaths comprised 463 from building collapse due to shaking, 101 in buildings sheared by the fault and 93 from all other causes (including 22 from unsecured brick parapets and gables and 6 from landslides). If the earthquake occurred in the middle of the night, the model estimated that the number of deaths would be much smaller, (i.e. 137), because most people would be inside relatively safe timber houses.

Local government agencies in New Zealand are much involved in seismic risk mitigation and planning civic emergency response to natural disasters, including earthquakes. As well as landmark studies of lifelines by various authorities, eg. Wellington and Christchurch, emergency planning procedures are being developed with advanced modelling tools. The powerful Geographic Information Systems computer tools in particular are proving their worth for dealing with a range of hazards as well as earthquakes. Wellington and Auckland are leading the way in the latter work.

CONCLUSIONS

Standout results from some of the above studies are:

- 2-storey buildings are significantly more vulnerable than 1-storey buildings.

- Some types of non-domestic buildings designed after c. 1975 are significantly less vulnerable than buildings designed to earlier codes.
- Short period buildings are less damaged on more flexible (softer) ground than on stiffer ground in very strong shaking, ie. near the source of the M_W 7.8 Hawke's Bay earthquake of 1931 (intensity MM10 and PGA ~ 0.8g on rock). This is the reverse of the general amplification effects found on flexible soils at lower amplitudes of shaking. This finding is consistent with that of Trifunac and Todorovska (1998) for the strongest shaking zone of the 1994 Northridge California earthquake.
- Pre-1976 (ie. brittle) concrete low-rise buildings ($\leq$ 3 storeys), including buildings not designed for earthquake loads, have been collapse free (except for one soft-storey building) in all New Zealand earthquakes, eleven having intensities in the range MM8-MM10. This excellent performance is evidently because the c. 500 buildings so far involved in strong shaking, have mostly had structural walls (of in-situ concrete, concrete blocks, or brick infill).
- Asymmetric (including "corner") buildings of up to 3 storeys did not suffer any more damage than did symmetrically walled buildings.
- Distributions of damage ratio fit the truncated lognormal form well.
- There is zero correlation between the damage ratio for buildings and their contents on a building-by-building basis.

ACKNOWLEDGEMENTS

The work behind this paper has been funded over a number of years by FRST, with support for some parts by the EQC and the ACC. The most recent FRST Contract was No. CO5804. In-house reviews of this paper were made by J Cousins and G Dellow.

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