MICROZONING EFFECTS ON DAMAGE IN TWO MAJOR NEW ZEALAND EARTHQUAKES

D. J. Dowrick[1,2], D. A. Rhoades[1,3] and P. N. Davenport[1,3]

ABSTRACT

In a recent study the present authors examined the damage ratios for houses and household contents in the Inangahua, New Zealand, earthquake for intensities MM7-MM10, as affected by microzoning and structural types. The present study modestly revises this work, and extends it to include the localities of Nelson (MM6.4) and Murchison (MM8.1). Four ground classes and two foundation types, i.e. unbraced piles and concrete perimeter wall foundations were considered, and also number of storeys and wall cladding. Some complexities and difficulties of reliable microzoning are revealed and discussed.

INTRODUCTION

The Inangahua earthquake of M_s 7.4, M_w 7.2 occurred on 24th (L.T.) May 1968. In two recent studies of this event by the present authors (Dowrick *et al.*, 2001; 2003) of about 8000 insurance claims, the vulnerability of domestic property was evaluated in terms of damage ratios, D_r, defined as:

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

In the 2001 study, D_r was determined across the range of Modified Mercalli (MM) intensities MM5-MM10 for one and two-storey houses and contents, and comparisons were made with the results of other New Zealand vulnerability studies by Dowrick (1991), Dowrick *et al.* (1995) and Dowrick and Rhoades (1997). The second study of the Inangahua earthquake (Dowrick *et al.*, 2003) differed from that of 2001, by examining the effects of microzoning and foundations on damage levels for houses and contents. This was done for six towns, i.e. Inangahua, Reefton, Westport, Greymouth, Runanga and Hokitika, covering a range of intensities from MM10.5 down to MM7.0 (Figure 1). A range of up to four ground classes was considered, based on three of the five classes described in the draft new New Zealand loadings standard. The present study extends the 2003 microzoning study to Nelson, 116 km from the fault rupture, where the intensity was MM 6.4 (Figure 1), thereby extending the lower limit of the intensity range considered. Murchison (MM8.1) was also included. Also in the present study we have made modest revisions to the microzone boundaries in Greymouth and Westport, and reclassified the foundations of some of the houses in the 2001 database.

A previous study of the effects of microzones on damage to New Zealand houses (Dowrick *et al.*, 1995) was of Napier in the 1931 Hawke's Bay earthquake, where the intensity was MM10.5. The approach of using damage ratios and loadings code ground classes, was the same as that used here. The other previous study of the effects of microzones on damage to houses in the Inangahua earthquake (Suggate and Wood, 1979) did not use damage ratios or engineering ground classes as the basis of its comparisons.

The present study offers the opportunity of examining microzoning effects to short period structures over a wide range of strength of shaking (MM 6.4-10.5; PGA 0.08-0.7+g; see Table 1), from linear to non-linear behaviour in the weaker/softer soils. Problems relating to the reliability of microzoning methods are discussed.

DESCRIPTION OF THE HOUSES

The houses were basically of one and two-storeys, although some built on sloping ground had partial extra storeys (semi-basements). Nearly all of the houses considered were timber framed. They had a variety of external wall claddings, including:

- Weatherboard (W)
- Corrugated iron (I)
- Fibrous (asbestos) cement (F)
- Stucco (roughcast) (R)
- Veneer (V(BS)), either Brick (B) or Artificial Stone (S)
- Concrete masonry (C)

The latter category comprised a small number of houses which were of reinforced concrete blocks, and a very few older houses in Nelson may have been of brick bearing wall construction (i.e. without timber frames).

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[1] *Institute of Geological and Nuclear Sciences, Lower Hutt*
[2] *Fellow*
[3] *Member*

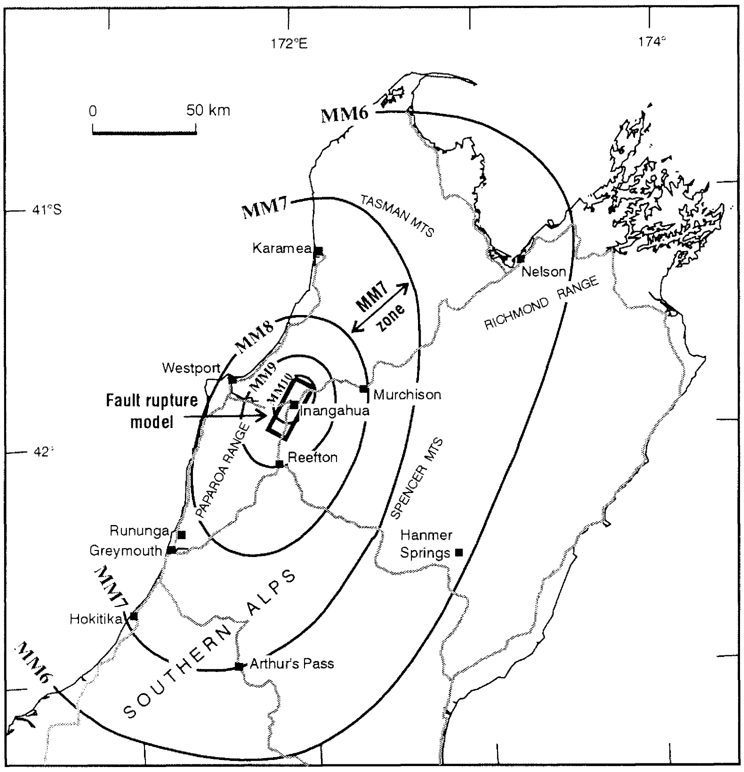

Figure 1. Map showing isoseismals, state highways and key place names for the 1968 Inangahua earthquake. The fault rupture model of Haines in Anderson et al. (1994) dips at 45°, with the top on the east side.

Table 1. Stronger horizontal component of peak ground accelerations from the 1968 Inangahua earthquake (from Dowrick and Sritharan, 1993).

Site Name	Shortest horizontal distance from source (km)	Ground Class	PGA (g)	MMI
Inangahua	1	C	0.70E	10.5
Reefton	22	C	0.58	9.0
Westport	22	C	0.30	8.5
Murchison	24	C	0.36	8.1
Greymouth	74	C	0.39	7.5
Hokitika	109	C	0.17	7.0
Nelson	116	C	0.080	6.4

Note: E indicates indicative estimate only

From the above wall types, three vulnerability classes were adopted, as discussed previously (Dowrick *et al.*, 2001), namely:

W, expected to be relatively Robust (unlike in the 2001 study, claddings I, F and C were not included) V (i.e. VB and VS), expected to be relatively Fragile R, of uncertain vulnerability.

Foundations of houses were initially divided into three classes, as follows:

(i) Unbraced piles. This class includes houses which were fully piled or where partial concrete restraints to foundation sway existed, such as localized concrete steps or verandah floor slabs (Figure 2).

(ii) Concrete foundation walls around the complete house perimeter. The lowest floor was mostly of timber construction supported internally by piles. Also included were concrete slab-on-grade foundations in houses on effectively flat sites.

(iii) Hybrid foundations, i.e. stiff, predominantly timber foundations, comprising piles braced by weatherboards (some with partial concrete walls) or timber pole construction. Most such houses were on sites which sloped more steeply than those of classes (i) and (ii) above, such that the foundation wall height on the lower side of the house exceeded about 1.2 m (i.e. $h_2 \geq 1.2$ m on Figure 3).

Nelson has some very steep terrain, and so has many houses with foundations of the "hybrid" class. Murchison has no such sites, being located on a gently sloping alluvial plain. In a sensitivity study it was found that the damage levels for houses with hybrid foundations were too variable to be considered as a class worth reporting on, so only the first two classes of foundations are considered here.

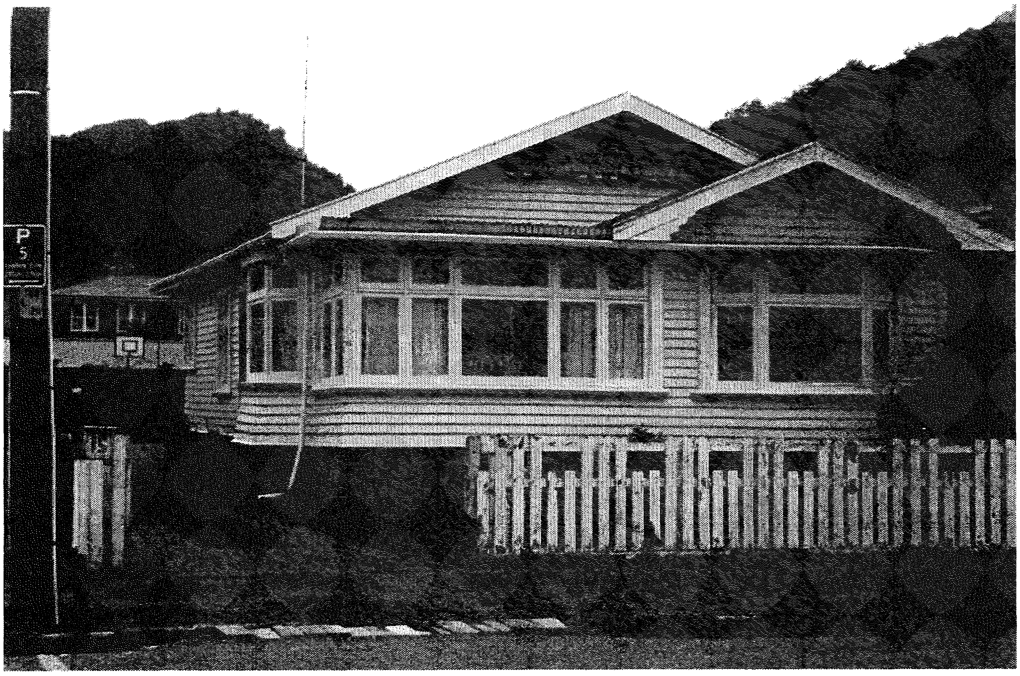

Figure 2. ***The most common type of pre-1968 West Coast house, one-storey with a corrugated iron roof, weatherboard cladding and (unbraced) pile foundations.***

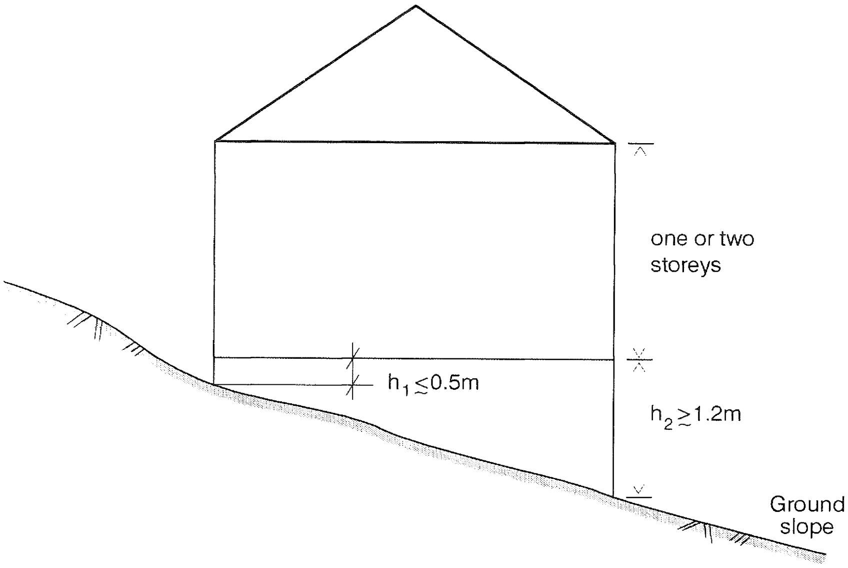

Figure 3. Geometry of "hybrid" foundation type for weatherboard houses, the piles of which were found to be effectively braced, and equivalent to concrete perimeter wall foundations.

THE MICROZONES

For the purposes of this study, Nelson and Murchison were assigned intensities of MM6.4 and MM8.1, determined by linear interpolation of the locations of the centroids of their urban areas between the isoseismals of Figure 1, which were determined by Adams *et al.* (1968).

The basis of the microzones was the geology of any deposits overlying bedrock, as mapped for Nelson by Johnston (1979) and for Murchison by Suggate and Wood (1979). The geology was converted to ground classes for the purposes of this study by our colleague R.D. Beetham using the definitions for Ground Classes A, B, C and D of the draft new New Zealand loadings standard, which are similar to those used in the USA. These definitions are as follows:

Ground Class AB – Rock
Rock with less than 3 m thickness of stiff overburden. (Classes A and B in the draft new New Zealand loadings standard, NZS 1170.5.)

Ground Class C – Shallow Soil
Sites where the low amplitude natural period is less than or equal to 0.6s, or sites with depths of soil not exceeding those listed in Table 2, but excluding very soft soil sites.

Ground Class D – Deep or Soft Soil
Sites where the low-amplitude natural period is greater than 0.6s, or sites with depths of soils exceeding those listed in Table 2, but excluding very soft soil sites.

Ground Class CD
Soil sites, which were uncertain, but would be either Class C or D.

Table 2. Depth limits for boundary between site subsoil classes C and D (from draft New Zealand loadings standard).

Soil type and description		Maximum depth of soil (m)
Cohesive soil	**Representative undrained shear strengths (kPa)**	
Soft	12.5-25	20
Firm	25-50	25
Stiff	50-100	40
Very stiff or hard	100-200	60
Cohesionless soil	**Representative SPT (N) values**	
Loose	6-10	40
Medium dense	10-30	45
Dense	30-50	55
Very dense	>50	60
Gravels	>30	100

For Nelson, the resulting ground class (i.e. microzone) map is shown in two pieces in Figures 4 and 5. The complexity of the map arises from Nelson's varied terrain which includes a number of steep-sided valleys with varying depths of alluvium in them, plus a margin of coastal deposits. Murchison, by contrast, is built solely on new gravels from the last glaciation period, all of which is Ground Class C.

Brief descriptions of the geological formations assigned to the various Nelson ground classes are given in Table 3.

THE DATA

In each of the localities studied, **every** house was accounted for, either to be included in or excluded from the database. First the study area for each town was defined, such that only houses within the borough boundary were considered. The limits adopted for the Nelson urban area studied are marked on Figures 4 and 5. A database was then created for each town ordered alphabetically by street name and numerically by house number. In the Nelson data set there are 5367 one-storey and 861 two-storey houses. The number of houses accounted for in each locality is given in Table 4.

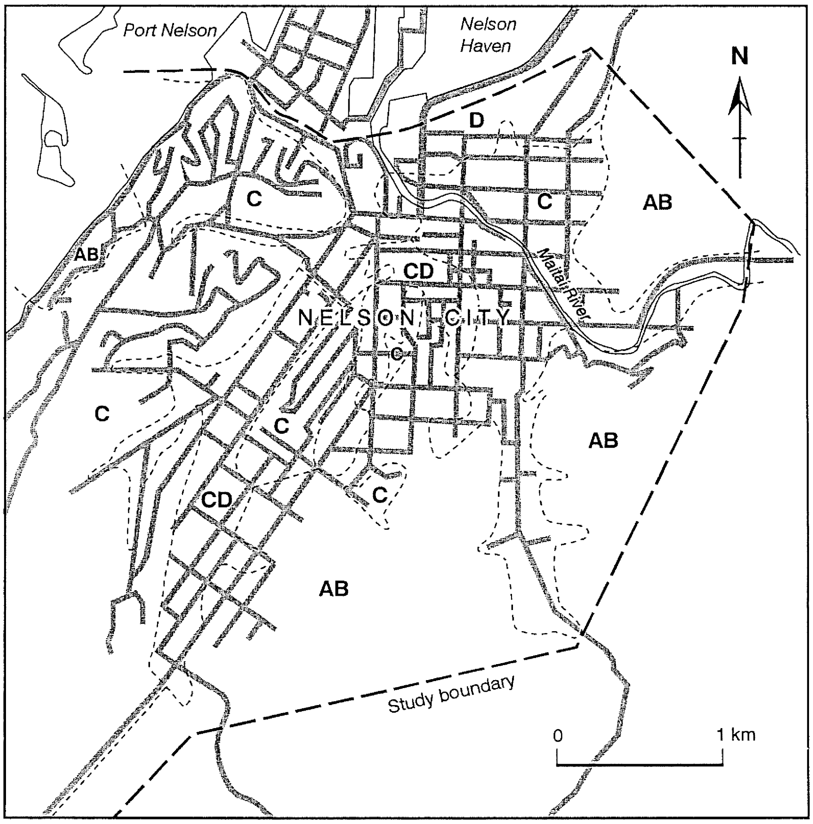

Figure 4. Microzoning map of northern Nelson developed from geology map of Johnston (1979). See also Figure 5.

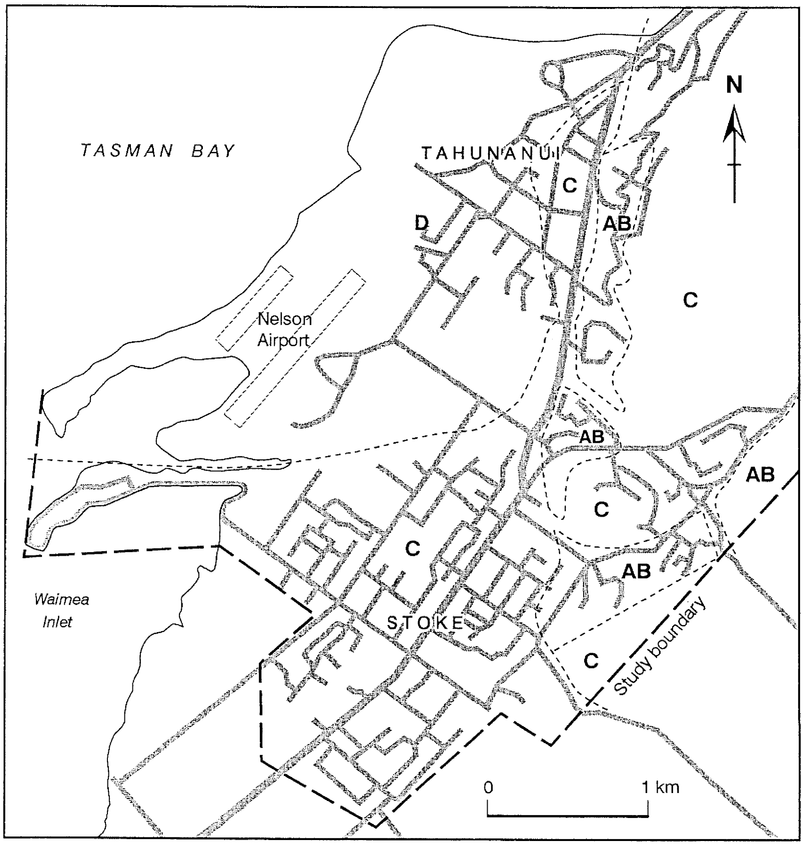

Figure 5. Microzoning map of southern Nelson. See also Figure 4.

Table 3. Descriptions of ground classes in the Nelson study area, from geology map of Johnston (1979).

Ground Class[1]	Description
AB	Various rock types, including sandstone, siltstone, mudstone, limestone and conglomerate, plus volcanic breccia and tuff.
C	Various gravels and scree, mostly clay-bound.
D	Tahunanui sand (forming beach ridges and dunes; estuarine and swamp deposits). Reclaimed land.
CD[2]	Nelson alluvium. Very poorly sorted, fine-grained gravel, clay and silt with local estuarine deposits.

Notes: [1] Ground Classes AB, C and D conform to definitions of the draft New Zealand loadings standard.

[2] Ground Class CD could conform to the definitions of either Ground Class C or D.

Table 4. Numbers of houses studied.

Locality	Houses	
	1-storey	2-storey
Napier (1931)	1610	187
Inangahua	55	0
Murchison	151	*
Westport	1316	33
Greymouth	2254	54
Hokitika	801	21
Nelson	5367	861

Note: * indicates not studied (too few houses)

In order to obtain valid damage ratios from the insurance data, all houses uninsured at the time of the earthquake had to be omitted from the database. Such houses consisted of three types:

i) Publicly owned houses.
ii) Privately owned houses. It was found in our first study of this earthquake (Dowrick *et al.*, 2001) that 5.3 percent of privately owned houses were uninsured.
iii) Houses built since the earthquake.

For each house in the database the following information was gathered:

- Number of storeys,
- Foundation type,
- Wall construction, and
- Ground class

For the determination of damage ratios for contents the number of uninsured households was assumed to be 30 percent, as adopted previously (Dowrick *et al.*, 2001; 2003).

DAMAGE RATIOS

The damage ratios presented below were calculated from equation (1) in terms of the Replacement Values for houses and Insured Values for contents. The Replacement Values used were those determined in our previous study.

Statistical Distributions Of Damage Ratios

The damage ratio (D_r) for each house and each parcel of contents was calculated as defined by equation (1) above. All other studies by two of the present authors, e.g. Dowrick (1991) and Dowrick *et al.* (2001), of damage in other earthquakes, have shown the shape of the statistical distribution of non-zero damage ratios for various classes of property to be well approximated by a truncated lognormal distribution (Figure 6). The lognormal distribution has the density function:

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

In the truncated form of the lognormal distribution as fitted to damage ratios, there is a "spike" at $D_r = 1$, i.e.,

$$P(D_r = 1) = \int_1^\infty f(x)dx. \tag{3}$$

Here the parameters μ and σ are approximated by the sample mean and standard deviation of the natural logarithm of the damage ratio of damaged items.

The estimates of the parameters μ and σ, found for the various data sets are given in Tables 5-7. Also tabulated are the number of damaged items n, and the total population (damaged + undamaged) N.

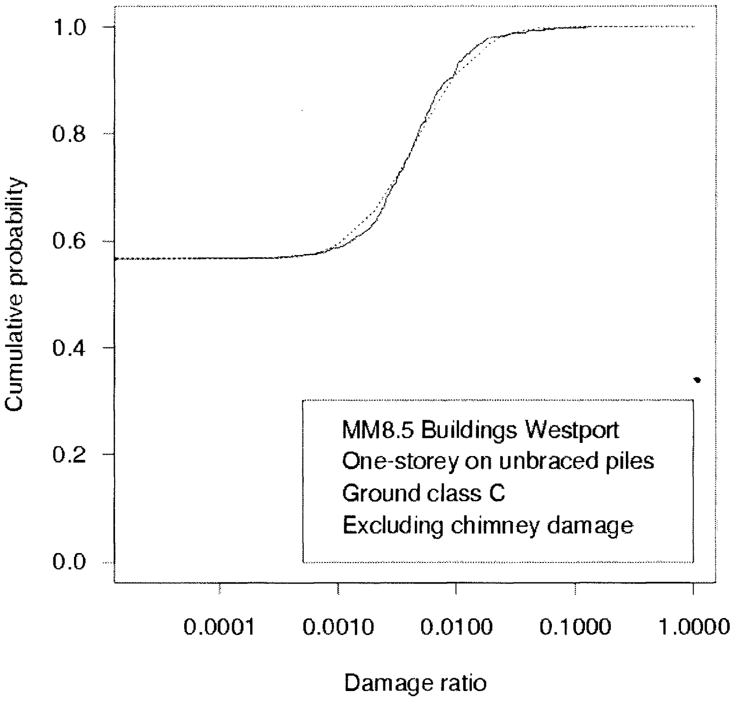

Figure 6. Typical cumulative probability distribution damage ratio for houses in Westport at intensity MM8.5 showing the good fit of the lognormal model (dashed line).

Mean Damage Ratios

The mean damage ratio for all buildings in a given MM intensity zone is a useful parameter for various purposes, e.g. in comparing the earthquake resistance of different classes of property. Considering all N buildings (damaged and undamaged) in an MM intensity zone, we give here two principal ways of defining the mean damage ratio. Firstly,

$$\overline{D}_r = \frac{\sum_{i=1}^{n}[\text{cost of damage to building } i]}{\sum_{i=1}^{N}[\text{value of building } i]} \qquad (4)$$

where n is the number of damaged buildings.

Secondly,

$$D_{rm} = \frac{\sum_{i=1}^{n}[D_{r_i}]}{N} \qquad (5)$$

In general, D_{rm} with its associated confidence limits is a more reliable and useful tool than $\overline{D}_r$ (Dowrick and Rhoades, 1997). If derived from large, homogeneous populations, $\overline{D}_r$ and D_{rm} tend to be similar in value, while for more inhomogeneous populations (with large ranges of replacement values and vulnerabilities) $\overline{D}_r$ and D_{rm} may differ widely. The values of $\overline{D}_r$ and D_{rm} for the various classes of domestic property considered in this study are presented in Tables 5-7.

Next we compare the vulnerability of different subsets of property in terms of their mean damage ratios, and percentages of populations damaged.

Effects of Wall Construction on Damage to Houses

The influence of wall construction on damage to houses was examined by comparing the mean damage ratio of houses with three groups of wall cladding, (i) W, (ii) V, and (iii) R as defined earlier. D_{rm} values for these three groups were considered for houses of the same foundation type, i.e. concrete perimeter walls, at one intensity MM8.5 (Westport). The first group W was thought to be relatively *robust*, the second group V was thought to be relatively *fragile*, while the stucco houses R (c. 20 mm thick ferro-cement) were of uncertain vulnerability.

The relative vulnerabilities of the various claddings of houses on concrete foundations are compared at three different strengths of shaking MM6.4, MM7.5 and MM8.5 in Figure 7.

It is seen that while weatherboard houses are the least vulnerable at all intensities, the vulnerabilities of houses with other claddings are dependent not only on the strength of shaking, but also on ground class. Houses with walls with brittle veneers V are intermediate in vulnerability to those with weatherboards and those with stucco at least at MM7.5 and MM8.5. Here, as in previous studies, confidence limits and statistical significance are calculated by bootstrap resampling (e.g. Dowrick and Rhoades, 1997).

As anticipated, the brittle wall claddings (V) are less robust than W walls.

As houses with weatherboard walls are much more numerous than those with any of the other wall materials, the following comparisons of foundations and microzoning effects are made generally in terms of damage to weatherboard houses.

Table 5. Sample of basic statistics of the distribution of damage ratio by class of domestic property, in the 1968 Inangahua earthquake, for intensities MM6.4 and MM8.1

Property Class	n	N	μ	σ	D_{rm}	$\overline{D}_r$
MM6.4 Nelson excl. chimney damage						
1 storey houses, w/b*, unbraced piles						
GC AB**	6	174	-5.96	1.13	1.3×10^{-4}	0.9×10^{-4}
GC C	14	1141	-5.56	1.57	0.8×10^{-4}	0.6×10^{-4}
GC CD	9	418	-5.85	1.31	1.2×10^{-4}	1.0×10^{-4}
GC D	6	218	-5.99	0.87	0.8×10^{-4}	0.7×10^{-4}
1 storey houses, w/b, concrete foundations						
GC AB	3	224	-5.20	0.76	0.8×10^{-4}	0.9×10^{-4}
GC C	9	599	-6.17	0.98	0.4×10^{-4}	0.4×10^{-4}
GC CD	2	92	-6.68	1.15	0.3×10^{-4}	0.2×10^{-4}
GC D	3	53	-6.02	1.27	2.0×10^{-4}	1.6×10^{-4}
2 storey houses, w/b, unbraced piles						
GC AB	5	45	-5.87	2.28	10×10^{-4}	10×10^{-4}
GC C	6	187	-6.53	1.84	1.2×10^{-4}	1.4×10^{-4}
2 storey houses, w/b, concrete foundations						
GC AB	2	63	-5.93	1.54	1.1×10^{-4}	1.0×10^{-4}
GC C	8	131	-6.12	1.46	2.0×10^{-4}	2.1×10^{-4}
MM8.1 Murchison excl. chimney damage						
1 storey houses, w/b, unbraced piles						
GC C	19	64	-5.86	1.37	16×10^{-4}	11×10^{-4}
1 storey houses, w/b, concrete foundations						
GC C	10	50	-5.67	0.72	8.0×10^{-4}	11×10^{-4}
Household contents, unbraced piles						
GC C	16	69	-4.24	1.28	50×10^{-4}	40×10^{-4}

Notes: * w/b = weatherboard; ** GC = Ground Class

Effects of Foundation Construction on Damage to Houses

The effects of foundation construction type on mean damage ratio over a wide range of intensities are shown in Figure 8. The comparisons are made for one-storey houses on Ground Class C, with weatherboard wall cladding, and excluding and including chimney damage. It is seen that houses with concrete foundations perform better than those on unbraced pile foundations right through the intensity range MM6.4 to MM10.5. At most intensities D_{rm} for houses on unbraced pile foundations is several times greater than it is for houses with concrete foundations. The separation is wider for the cases which include chimney damage (Figure 8(b)), except at intensity MM10.5.

When two-storey houses are considered, the picture is more complicated (Figure 9). When chimney damage is excluded, two-storey houses on unbraced pile foundations perform better than those on concrete foundations, while when chimney damage is included the reverse is superficially the case. However, the differences are not statistically significant, except for the case of houses at intensity MM7.5 when chimney damage costs are included.

Table 6. Sample of basic statistics of the distribution of damage ratio by class of domestic property, in the 1968 Inangahua earthquake, for intensities MM7.0 and MM7.5 (from Dowrick et al. (2003), revised)

Property Class	n	N	μ	σ	D_{rm}	$\overline{D}_r$
MM7.0 Hokitika excl. chimney damage						
1 storey houses, w/b, unbraced piles						
GC C**	44	276	-6.08	1.24	7.0×10^{-4}	6.1×10^{-4}
GC D	7	37	-7.30	1.08	1.6×10^{-4}	1.5×10^{-4}
1 storey houses, w/b, concrete foundations						
GC C	10	133	-6.51	1.38	2.0×10^{-4}	2.2×10^{-4}
GC D	0	11	N/A	N/A	0	0
Household contents, unbraced piles						
GC C	33	356	-4.97	1.09	10×10^{-4}	7.9×10^{-4}
GC D	1	39	-6.91	N/A	0.3×10^{-4}	0.2×10^{-4}
MM7.5 Greymouth excl. chimney damage						
1 storey houses, w/b, unbraced piles						
GC AB	22	62	-5.51	1.11	21×10^{-4}	19×10^{-4}
GC C	358	971	-5.73	1.12	21×10^{-4}	18×10^{-4}
GC CD	201	396	-5.44	1.15	41×10^{-4}	40×10^{-4}
GC D	14	41	-5.45	1.12	20×10^{-4}	17×10^{-4}
1 storey houses, w/b, concrete foundations						
GC AB	14	60	-6.16	1.41	7.6×10^{-4}	10×10^{-4}
GC C	70	216	-5.84	1.25	17×10^{-4}	18×10^{-4}
GC CD	84	242	-5.67	1.08	18×10^{-4}	21×10^{-4}
GC D	0	0	N/A	N/A	N/A	N/A
Household contents, unbraced piles						
GC AB	21	66	-5.03	1.01	30×10^{-4}	31×10^{-4}
GC C	238	985	-4.78	1.07	36×10^{-4}	31×10^{-4}
GC CD	151	399	-4.45	1.10	75×10^{-4}	73×10^{-4}
GC D	6	41	-4.32	1.68	34×10^{-4}	20×10^{-4}

Notes: w/b = weatherboard; ** GC = Ground Class

Effects of Microzoning and Structure on Damage to Houses

On Figure 10 are plotted the mean damage ratios for one-storey weatherboard houses (excluding chimney damage) at intensities MM6.4 and MM7.5, with two types of foundation, and on the four different ground classes described above. Very different and complex patterns are seen.

First consider the simplest case, at intensity MM7.5 houses with concrete foundations have steadily increasing damage levels as the ground becomes more flexible. This pattern follows the well established trends of peak ground acceleration (PGA) and peak spectral acceleration (SA), both of which usually but not always (eg Seed, 1975) increase (at this intensity) as the ground becomes more flexible. However, at the lower intensity of MM6.4 the pattern is quite different, albeit not statistically significant.

Second, at intensity MM7.5 houses with piled foundations respond very differently, with those on Ground Class CD being the most damaged, and the least damaged being on the most flexible soil (Ground Class D). The behaviour of the houses on piles in Figure 10(b) is surprising, but is presumably explained by dynamic response effects. The peak response at Ground Class CD may mean that some resonance is occurring i.e. that the fundamental periods of the houses and the ground are similar in value. In fact it is likely that the natural period of vibration for piled weatherboard houses and Ground Class CD are both about 0.4 seconds.

Next consider two storey weatherboard houses (excluding chimney damage) at intensity MM6.4, with two types of foundation, on ground classes AB and C (Figure 11). No clear trends in D_{rm} with ground class are seen, because the numbers of houses damaged are too small (Table 5).

Table 7. Sample of basic statistics of the distribution of damage ratio by class of domestic property, in the 1968 Inangahua earthquake, for intensities MM7.8 and MM8.5 (from Dowrick *et al.* (2003), revised).

Property Class	*n*	*N*	μ	σ	D_{rm}	$\overline{D}_r$
MM7.8 Runanga excl. chimney damage						
1 storey houses, w/b, unbraced piles						
GC AB**	101	228	-5.18	1.06	3.9×10^{-3}	3.0×10^{-3}
GC C	22	60	-5.12	1.16	3.5×10^{-3}	3.3×10^{-3}
GC CD	43	95	-5.43	1.36	3.5×10^{-3}	2.6×10^{-3}
1 storey houses, w/b, concrete foundations						
GC AB	7	35	-5.01	1.56	1.8×10^{-3}	1.2×10^{-3}
GC C	5	12	-4.89	1.11	3.9×10^{-3}	2.8×10^{-3}
GC CD	4	10	-4.82	1.43	5.9×10^{-3}	3.4×10^{-3}
Household contents, unbraced piles						
GC AB	99	242	-4.47	1.11	8.6×10^{-3}	6.2×10^{-3}
GC C	28	62	-4.27	1.00	9.6×10^{-3}	8.2×10^{-3}
GC CD	37	102	-4.48	0.86	5.6×10^{-3}	5.0×10^{-3}
MM8.5 Westport excl. chimney damage						
1 storey houses, w/b, unbraced piles						
GC C	466	1063	-5.32	1.05	4.0×10^{-3}	3.2×10^{-3}
1 storey houses, w/b, concrete foundations						
GC C	52	156	-5.66	1.09	1.8×10^{-3}	24×10^{-3}
Household contents, unbraced piles						
GC C	600	1077	-4.38	0.94	11×10^{-3}	8.9×10^{-3}

Notes: w/b = weatherboard; **GC = Ground Class

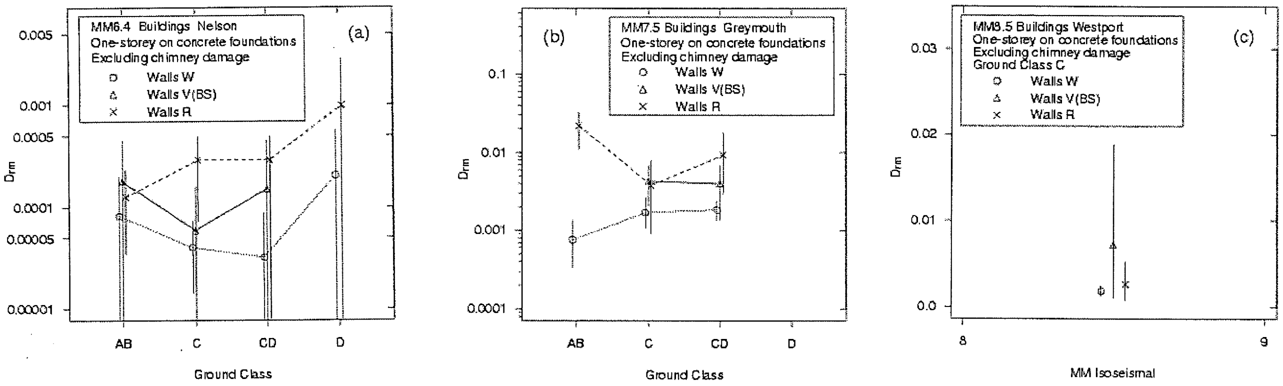

Figure 7. Comparison of vulnerabilities of one-storey houses on concrete foundations for different wall claddings on different ground classes and different strengths of shaking, Nelson (MM6.4), Greymouth (MM7.5) and Westport (MM8.5). Mean damage ratios with their associated 95% confidence limits.

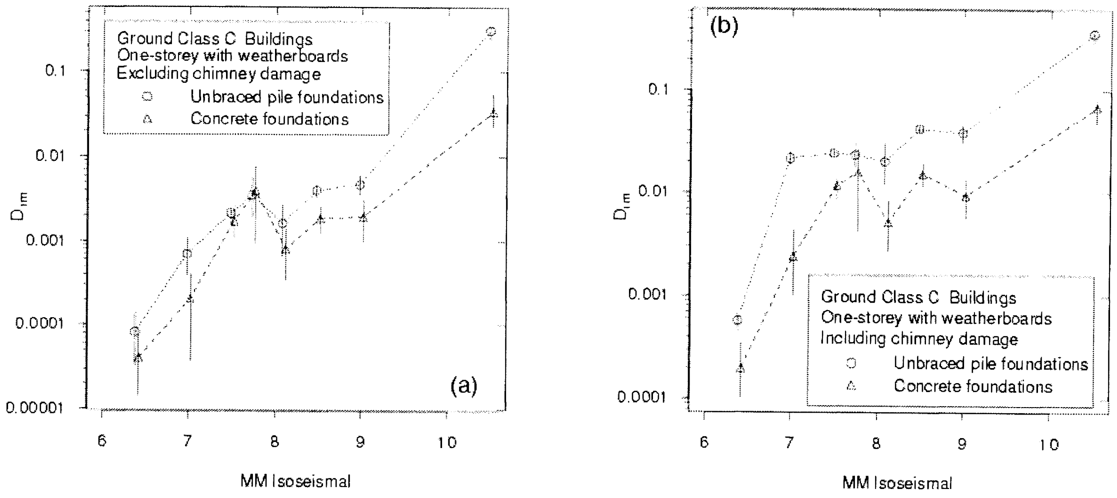

Figure 8. Comparison of vulnerabilities of one-storey weatherboard houses with two types of foundation, and with and without chimney-related damage. Mean damage ratios with their associated 95% confidence limits for houses on Ground Class C over a wide range of intensities.

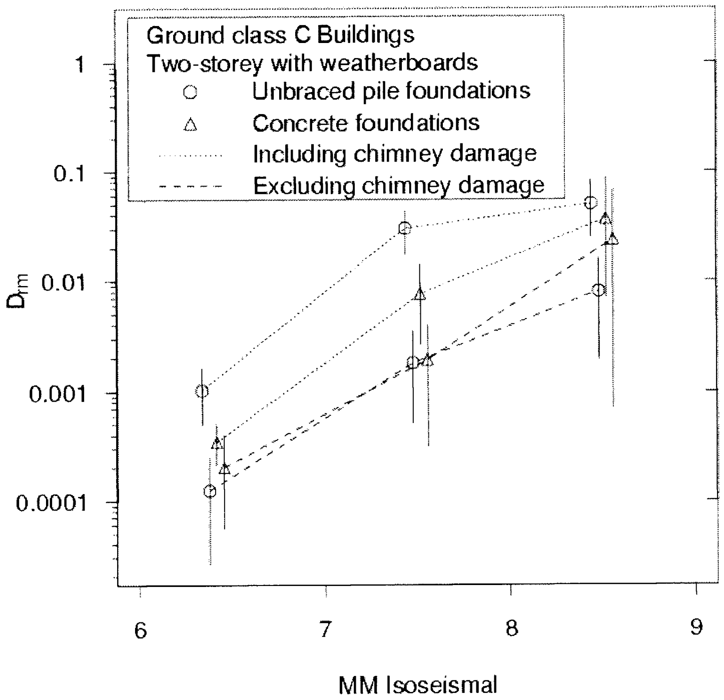

Figure 9. Comparison of vulnerabilities of two-storey weatherboard houses with two types of foundation. Mean damage ratios with their associated 95% confidence limits on Ground Class C in Nelson (MM6.4), Greymouth (MM7.5) and Westport (MM8.5).

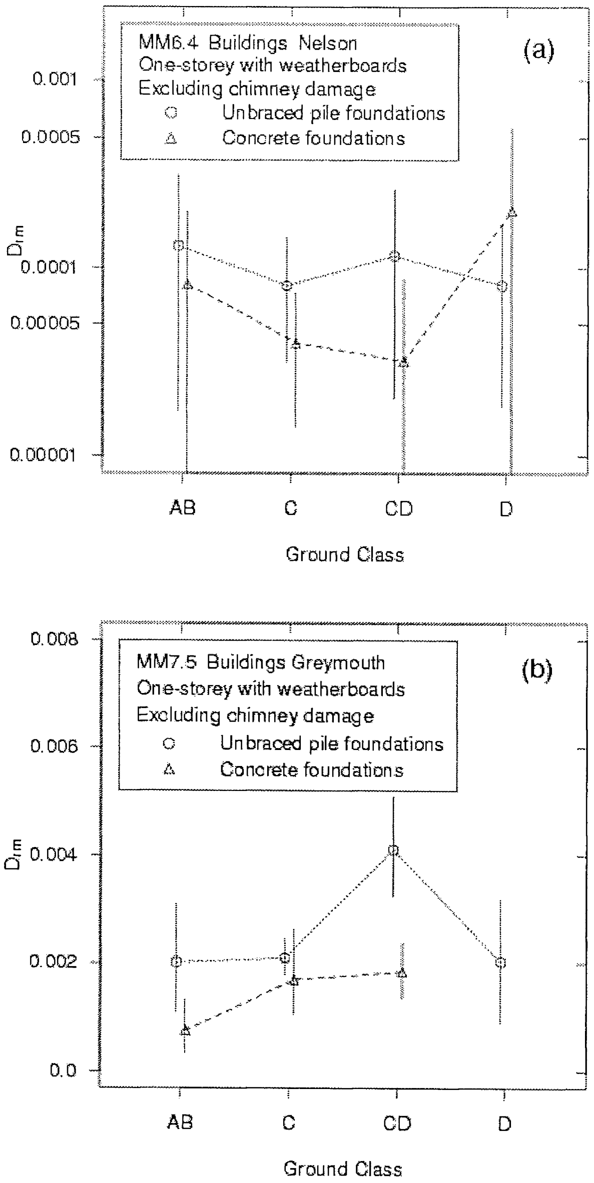

Figure 10. Comparison of vulnerabilities of one-storey weatherboard houses on four different ground classes and two types of foundation. Mean damage ratios with their 95% confidence limits for houses in (a) Nelson (MM6.4), and (b) Greymouth (MM7.5).

In contrast, in very strong shaking, in the MM10 zone of the 1931 Hawke's Bay earthquake, houses on unbraced piles were found (Dowrick *et al.,* 1995) to be decreasingly damaged with decreasing ground modulus of elasticity, as seen for one-storey houses on Figure 12. The exception to this trend is seen on Ground Class D for the subset of houses on sites at which ground damage occurred. The differences between the mean damage ratios of the four subsets of one-storey houses are statistically different at the 0.01 level.

A feature of Figure 12 is the difference in the D_{rm} trends between one and two-storey houses, with the latter being less damaged than one-storey houses only on Ground Class C. Only the differences on Ground Class C is significant at the 0.01 level.

Next we turn our attention to differences in damage levels on Ground Classes C and D over a wide range of intensities, MM6.4-MM10.5, as plotted on Figure 13. The different response characteristics of houses with the two different foundations are clearly seen. Houses on unbraced pile foundations generally are less damaged on Ground Class D than those on Ground Class C (Figure 13(b)), while at intensity MM6.4 the reverse is the case for houses on concrete pile foundations (Figure 13(a)). This phenomenon appears to us to be a result of the difference in fundamental periods of vibration of the houses depending on their foundation type.

One anomalous point warrants discussion. Consider houses with concrete foundations on Ground Class D and at intensity MM7.0 (Figure 13(a)), for which D_{rm} is zero. It is clear that this data point, based on only 11 houses, is not representative, and that a larger sample could have resulted in a D_{rm} value greater than that found for houses on Ground Class C.

A feature of Figure 13(b) requiring explanation is the values of D_{rm} for Napier at intensity MM10.5. These values are much lower than that of 0.30 for piled houses in the village of Inangahua, at the same intensity. The damage ratios for houses in Napier are lower than they might have been if repair costs had not been minimized by the economic slump at the time of the earthquake in 1931 (Dowrick *et al.*, 1995).

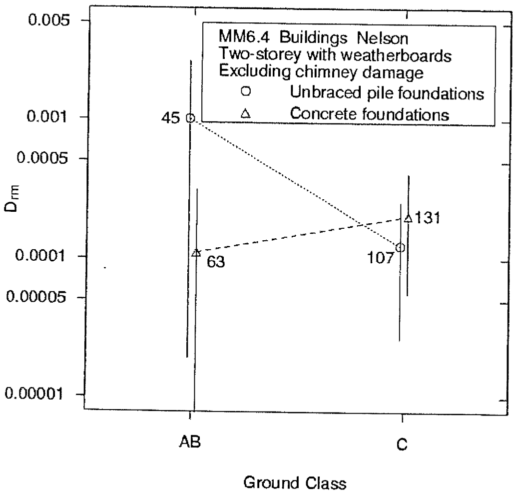

Figure 11. Comparison of vulnerabilities of two-storey weatherboard houses on Ground Classes AB and C, on two types of foundation, in Nelson MM6.4. Mean damage ratios with their 95% confidence limits.

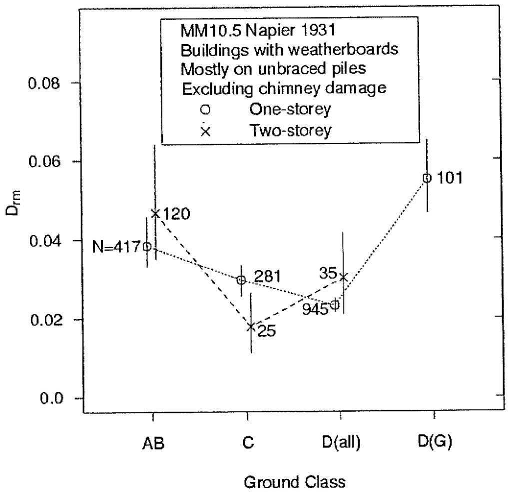

Figure 12. Comparison of vulnerabilities of one and two-storey weatherboard houses on three different ground classes at intensity MM10.5 in Napier in the 1931 Hawke's Bay earthquake. Ground Class D (all) indicates the total subset of houses including those on sites with and without ground damage, while Ground Class D(G) indicates the subset of houses on ground Class D with ground damage. Mean damage ratios are plotted with their 95% confidence limits (from Dowrick et al., 1995).

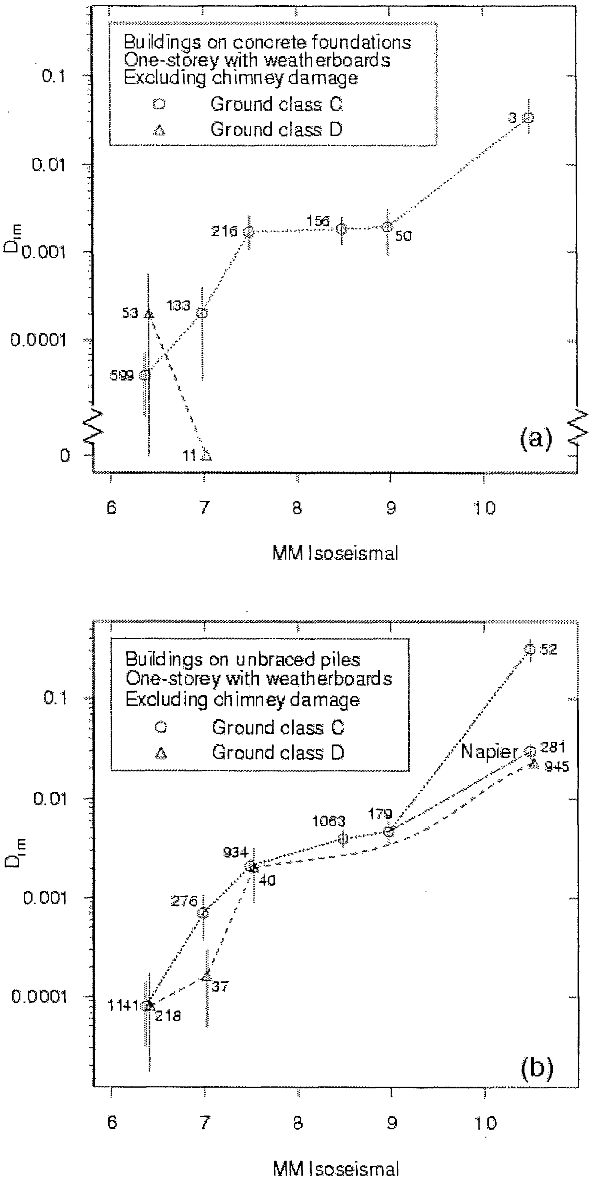

Figure 13. Comparison of vulnerabilities of one-storey weatherboard houses on Ground Classes C and D over a wide range of intensities. Mean damage ratios with their associated 95% confidence limits for houses with (a) concrete foundations, and (b) unbraced piles.

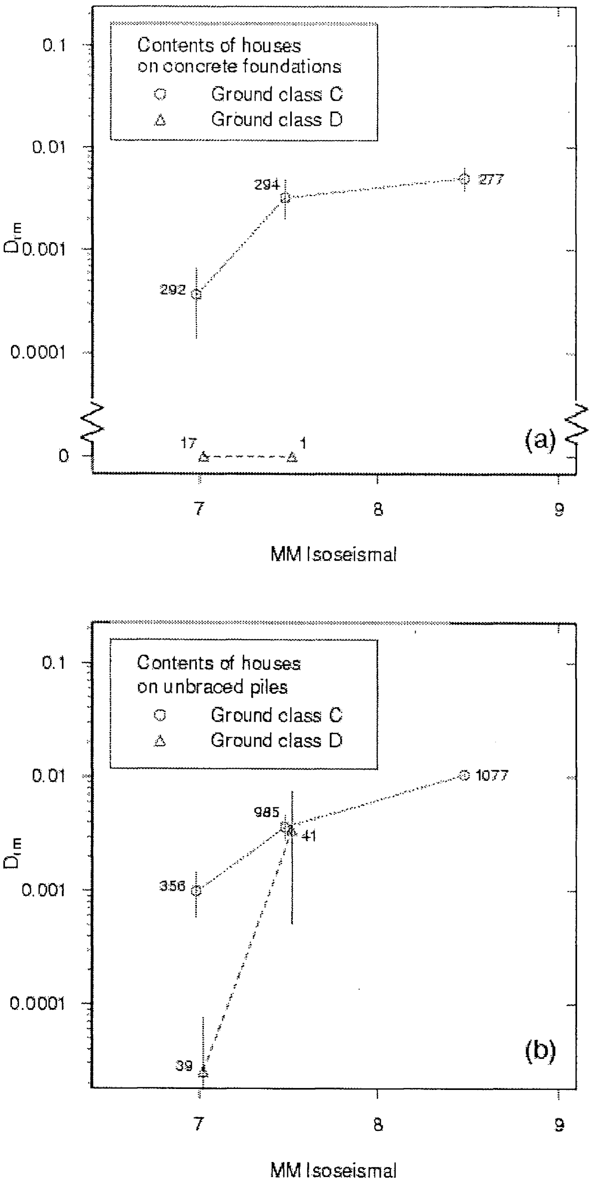

Figure 14. Comparison of vulnerabilities of the contents of one-storey houses on unbraced piles and on concrete foundations on Ground Classes C and D. Mean damage ratios with their 95% confidence limits. Compare with the damage to houses in Figure 13.

Household Contents

On Figure 14 are plotted the mean damage ratios for the contents of one-storey houses on unbraced piles at intensities MM7.0 and MM7.5 for Ground Classes C and D. On Figure 14(b) it is seen that the contents of houses on unbraced piles on the firmer ground at intensity MM7.0 are significantly more damaged than those on Ground Class D. This is consistent with the findings for the houses themselves, as discussed earlier in relation to Figure 13(b). In the case of contents of houses on concrete foundations (Figure 14(a)), it is thought that the results for Ground Class D are unrepresentative (too few houses in these subsets), compare the results for houses themselves on Figure 13(a).

On Figure 15 are plotted the mean damage ratios for contents of one-storey houses at intensity MM7.5 (Greymouth), with two types of foundation and four different ground classes.

Here we observe the same effect (perhaps due to resonance) on Ground Class CD discussed for houses in relation to Figure 10(b).

Percentage of Items Damaged

The findings for mean damage ratios discussed above were consistent with trends in the percentage of items damaged. This effect is discussed with appropriate plots in Dowrick *et al.* (2003).

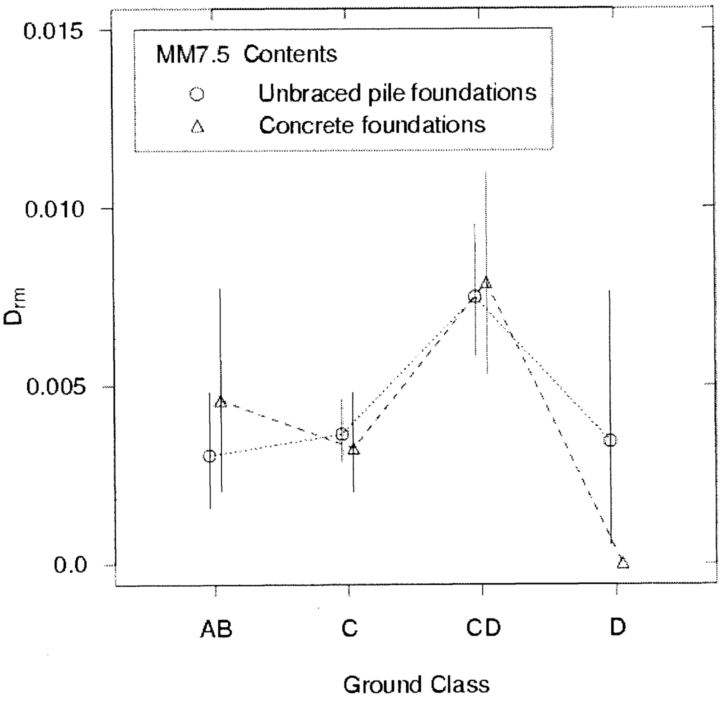

Figure 15. ***Comparison of vulnerabilities of contents of houses on four ground classes and two types of foundation at intensity MM7.5 (Greymouth). Mean damage ratios with their associated 95% confidence limits. Compare with the damage to houses in Figure 10(b).***

DISCUSSION

The relative damage levels found for one storey houses on unbraced piles (Figure 13(b)) and their contents (Figure 14(b)) on Ground Classes C and D are the reverse of what was expected. The mean damage ratio is lower for Ground Class D than it is for Ground Class C, the difference being statistically significant at the 0.01 level in three of the six comparisons seen on these two figures.

A possible explanation for Ground Class D showing smaller responses than Ground Class C (particularly for MM7.0 and MM7.5) is that it is a frequency content (filtering) effect. In these cases the response spectrum amplitudes at periods close to the fundamental period of the houses may have been much smaller on Ground Class D than on Ground Class C. Unfortunately, no spectral contents data are available, as no accelerograms were recorded during this earthquake, although some peak ground accelerations were measured (Dowrick and Sritharan, 1993). In addition, the fundamental periods of the various types of house as a function of MM intensity is not yet known.

A feature of the microzoning carried out in this study (as in that for Napier, Dowrick *et al.*, 1995) which is not ideal, is that the ground classes were assigned only from interpretation of the surface geology and minimal good subsurface information on material properties and depths to bedrock. The engineering properties of the soil profiles and their shear wave velocities, and site periods, have not been measured because of the enormity of the task. This, of course, is a common problem in the creation of microzoning maps, except in limited areas.

It follows that in order to understand properly the complex behaviour observed in this study, much more insight into the physical nature and dynamical properties of a representative range of sites in each locality, as well as the periods of vibration of the structures, appear to be necessary. It also seems that the ground classes themselves should be examined, including the intermediate class CD, and the most appropriate criteria determined for them.

The question also needs to be asked as to what are the minimum information and modelling which would be required to predict theoretically the results found here.

To be able to use microzoning maps in predicting damage levels in future earthquakes, it would appear that vulnerability models should be functions not only of structural type and strength of shaking, but also of ground class. This is evident from the results of the Inangahua and Napier studies, but was demonstrated most sharply in the Lake Bed Zone of Mexico City in 1985, where Dowrick (among many) observed that unreinforced masonry buildings were undamaged next door to heavily damaged modern high-rise buildings.

CONCLUSIONS

As a result of this study some revisions were made to the data used in our previous study of the Inangahua earthquake (Dowrick *et al.*, 2003), and the following conclusions have been drawn:

One-storey houses

1. It was found that weatherboard houses are less vulnerable than houses with brittle cladding veneers, which in turn are less vulnerable than houses with stucco cladding.

2. Over the range of intensities MM6.4 and MM10.5 on Ground Class C, D_{rm} for weatherboard houses on unbraced pile foundations is generally higher than it is for houses on concrete foundations, sometimes by a factor of two or three.

3. At intensity MM7.5, D_{rm} for weatherboard houses on unbraced pile foundations is twice as high on Ground Class CD as on Ground Classes AB, C and D. This difference is statistically significant at the 0.01 level, and could mean that some soil-structure resonance occurs on Ground Class CD. This effect is also seen for the contents of the houses.

4. In Greymouth at intensity MM7.5, D_{rm} for weatherboard houses on concrete foundations excluding chimney damage increases 2.4 times with decreasing ground flexibility modulus of elasticity from Ground Class AB to CD, the difference between D_{rm} for Ground Classes CD and AB being statistically significant at the 0.01 level.

5. For houses on unbraced piles, D_{rm} is mostly lower for houses and contents for Ground Class D than for Ground Class C, for intensities MM6.4 to MM10.5 (except when ground damage occurs), the difference being statistically significant at the 0.01 level in four of the 11 comparisons made. This may result from differences in frequency content of the ground shaking.

6. The percentages of houses and contents parcels damaged follow the same trends as those found for mean damage ratio.

Two-storey houses

7. When chimney damage is included, two-storey houses on unbraced pile foundations perform worse than those on concrete foundations, the differences being statistically significant at the 0.01 level at intensities MM6.4 and MM7.5.

Household contents

8. The contents of houses on unbraced piles on Ground Class C at intensity MM7.0 are significantly more damaged than those on Ground Class D.

Microzoning and risk assessment methodology

9. The creation of reliable microzoning maps appears to be even more complex than previously believed.

10. Microzoning maps need to be based on more information than that provided by surface geology maps, and the required extra criteria (such as engineering properties of the soil and structures) need to be better understood. The role of soil-structure resonance needs to be clarified.

11. Vulnerability models used in estimating earthquake losses should be functions not only of structural type and strength of shaking, but also of ground class.

ACKNOWLEDGEMENTS

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