# EFFECTS OF MICROZONING AND FOUNDATIONS ON DAMAGE RATIOS FOR DOMESTIC PROPERTY IN THE MAGNITUDE 7.2 1968 INANGAHUA, NEW ZEALAND EARTHQUAKE

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## ABSTRACT

In a recent study the present authors examined the damage ratios for houses and household contents in the Inangahua earthquake for intensities MM5-MM10, including the effects of chimney damage. The present study continues this work by examining the effects of ground class and construction type on damage levels. Houses from six towns are considered, i.e. Inangahua, Reefton, Westport, Greymouth, Runanga and Hokitika, covering a range of intensities from MM10.5 down to MM7.0. A range of ground classes is also considered, covering the three classes described in the New Zealand loadings standard. The structural types considered comprise two foundation types (piled vs. concrete perimeter wall footings), and number of storeys. Some complexities and difficulties of reliable microzoning are revealed and discussed.

## 1. INTRODUCTION

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

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

$D_r$ was determined across the range of Modified Mercalli (MM) intensities MM5-MM10 for one and two-storey houses and household contents, Comparisons were made also with the results of other New Zealand vulnerability studies by Dowrick (1991), Dowrick *et al.* (1995) and Dowrick and Rhoades (1997). The present study examines a subset of the 8000 insurance claims from the "global" study of the 1968 earthquake, so as to evaluate the different vulnerabilities of domestic property (houses and contents) on different ground classes, i.e. microzoning effects, and those of houses with different types of foundations and wall construction.

There have been previous studies of the effects of microzones on damage to houses in New Zealand earthquakes. The earlier two of these studies, those of Grant-Taylor *et al.* (1974) and Suggate and Wood (1979) did not use damage ratios or engineering ground classes as the basis of their comparisons, and hence were less quantitative in their approach than has been possible in the present study. The other previous study, that of Napier in the 1931 Hawke's Bay earthquake (Dowrick *et al.*, 1995) was carried out using damage ratios and ground classes in the same manner as used in the present study, but was limited to houses situated in a zone of Modified Mercalli intensity X (MM10).

The present study offers an opportunity to quantify microzoning effects for short period structures for four ground classes at MM7, two at MM8 and one ground class at MM9. This extends our knowledge of microzoning effects, as well as differentiating between houses of different structural type. We have also taken the opportunity of relating the above microzones to damage ratios for household contents, which to the best of our knowledge has not been done before.

## 2. DESCRIPTION OF THE HOUSES

The houses considered in this study were in the towns of Hokitika, Greymouth, Runanga (including Dunollie), Westport, Reefton and Inangahua (Figure 1). The houses were of one and two-storeys and were timber framed with a variety of wall claddings, including:

- Weatherboard (W)
- Corrugated iron (I)
- Fibrous (asbestos) cement (F)
- Stucco (roughcast) (R)
- Brick (B) {Veneer (V)}
- Artificial stone (S) {Veneer (V)}
- Concrete masonry (C)

A small number of houses were made of reinforced concrete blocks (C), and a few may have been of brick bearing wall construction (i.e. without timber frames).

From the above wall types, two vulnerability classes were adopted, namely:

Robust: W, I, F and C
Fragile: B and S (i.e. V)

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[2] *Fellow*
[3] *Member*

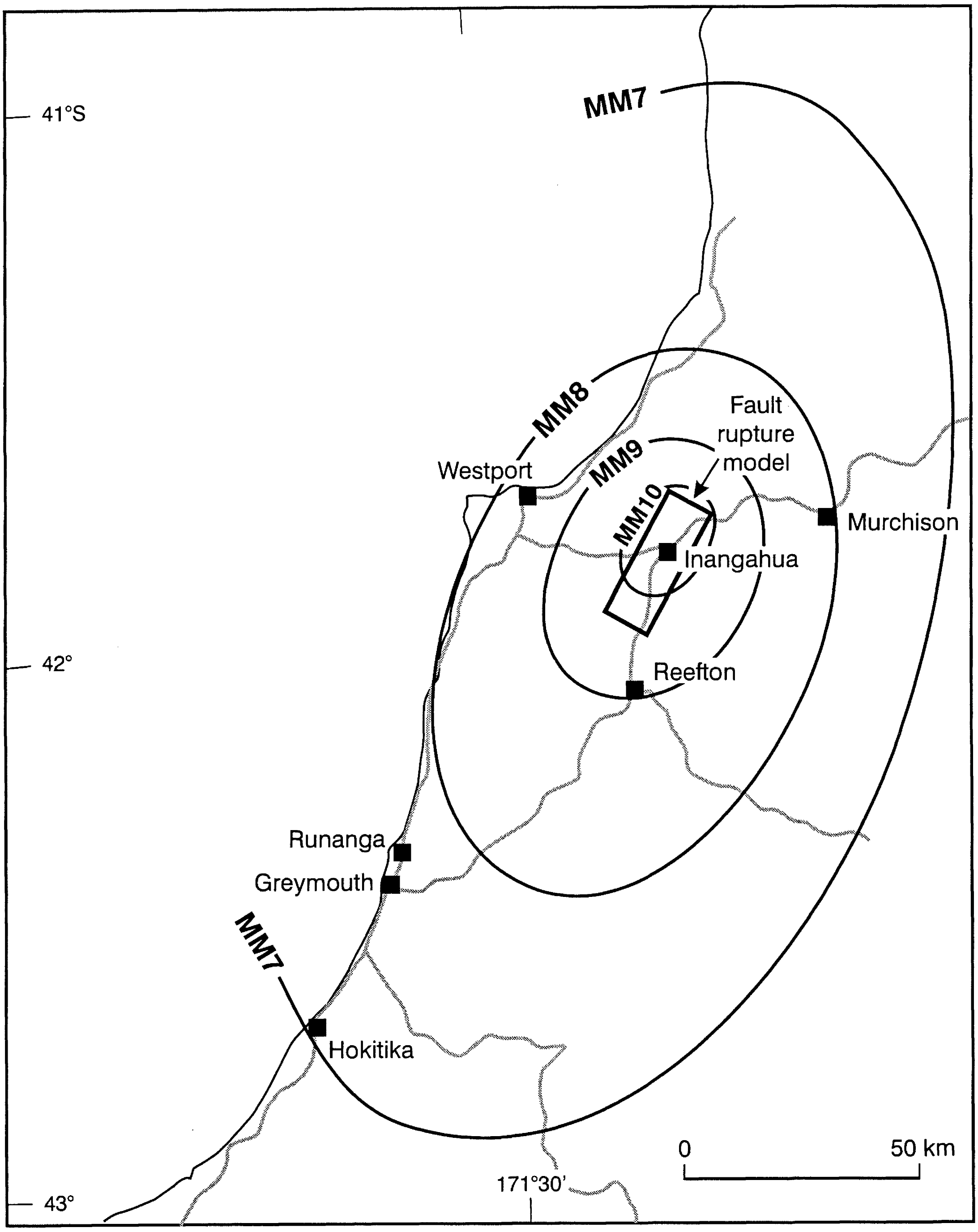


***Figure 1:*** ***Map showing inner isoseismals, state highways and key placenames for the 1968 Inangahua earthquake. The fault rupture model of Haines in Anderson et al., (1994) dips at 45°with the top on the east side.***

Although fibrous plaster sheets (F) are brittle to out-of-plane loads, they performed well as wall cladding, with few reports of damage. Stucco cladding (R) was mostly reinforced with fine mesh, and would often have been robust, but such houses were omitted from classification because of uncertainties in identification and performance.

Foundations of houses were of three types:

(i) Fully piled (generally unbraced) (Figure 2(a));
(ii) Concrete foundation wall around complete perimeter (Figure 2(b));
(iii) Partial concrete foundation walls.

Type (iii) foundations were not identified as a separate subset, but were lumped together with type (i). This decision was based on the inadequate performance of partial concrete foundations observed in the small sample of houses in the intensity MM10 zone reported on in our previous study (Dowrick *et al.*, 2001) of this earthquake. The number of houses with type (iii) foundations was a small fraction of the total.

While all houses with veneer walls (B and S) naturally have concrete foundations, robust walls (W, I, F and C) have all types of foundations. Considering the total population of WIFC houses in the present study, 23 percent had concrete foundations of type (ii) above.

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

*Figure 2(b): A pre-1968 one-storey West Coast house with tiled roof, stucco veneer walls and concrete perimeter wall foundations.*

## 3. THE MICROZONES

Six towns were microzoned in this study, with a range of intensities, as follows:

- Hokitika MM7.0
- Greymouth MM7.5
- Runanga MM7.8
- Westport MM8.5
- Reefton MM9.0
- Inangahua MM10.5

The above intensities were determined by linear interpolation of the locations of the centroids of the towns between the isoseismals, which are as determined by Adams *et al.* (1968). The basis of the microzones was the geology of any deposits overlying bedrock, as mapped in the earlier microzoning study of Suggate and Wood (1979). Their maps for four of the towns are reproduced here, slightly annotated, in Figures 3-6. Inangahua and Reefton, not shown here, are entirely Ground Class C (predominantly gravels overlying bedrock). The Ground Classes AB, C and D conform to the definitions used in the draft new joint Australian/New Zealand loadings standard. 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 Australian/New Zealand loadings standard.)

**Ground Class C - Shallow Soil**
Sites where the low amplitude natural period is less than or equal to 0.6 s, or sites with depths of soil not exceeding those listed in Table 1, but excluding very soft soil sites.

**Ground Class D - Deep or Soft Soil**
Sites where the low-amplitude natural period is greater than 0.6 s, or sites with depths of soils exceeding those listed in Table 1, but excluding very soft soil sites.

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

Note that few of the house sites are likely to be subject to topographical amplification effects.

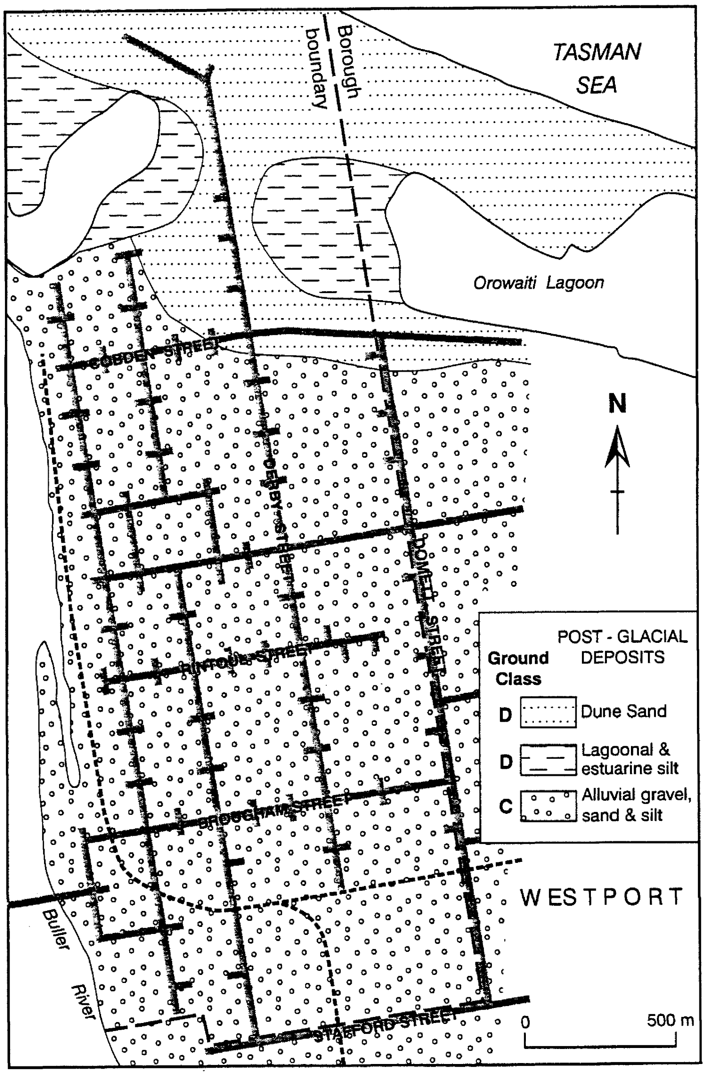


*Figure 3: Microzoning map of Greymouth developed from geology of Suggate and Wood (1979).*

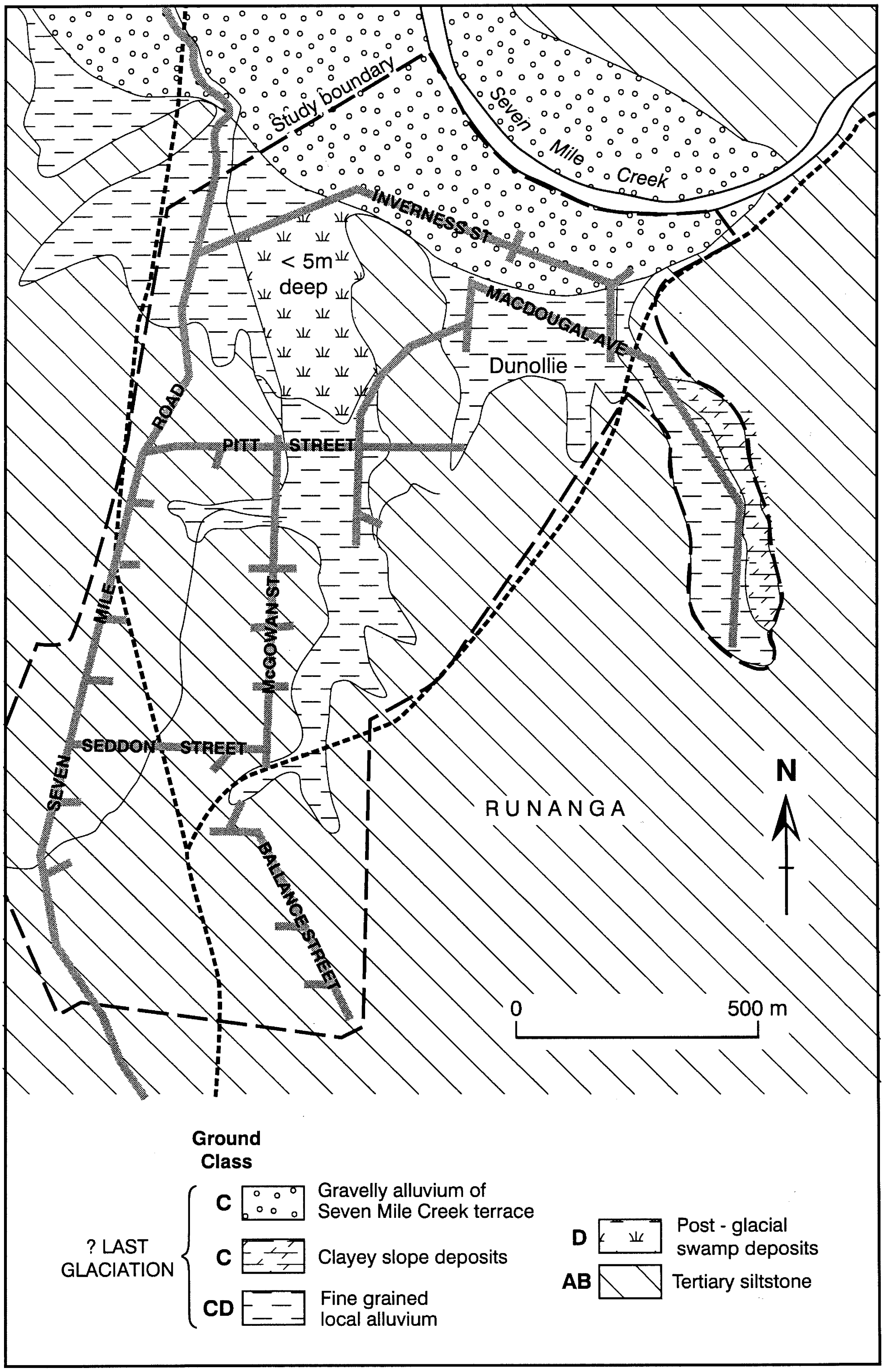


*Figure 4: Microzoning map of Runanga developed from geology of Suggate and Wood (1979).*

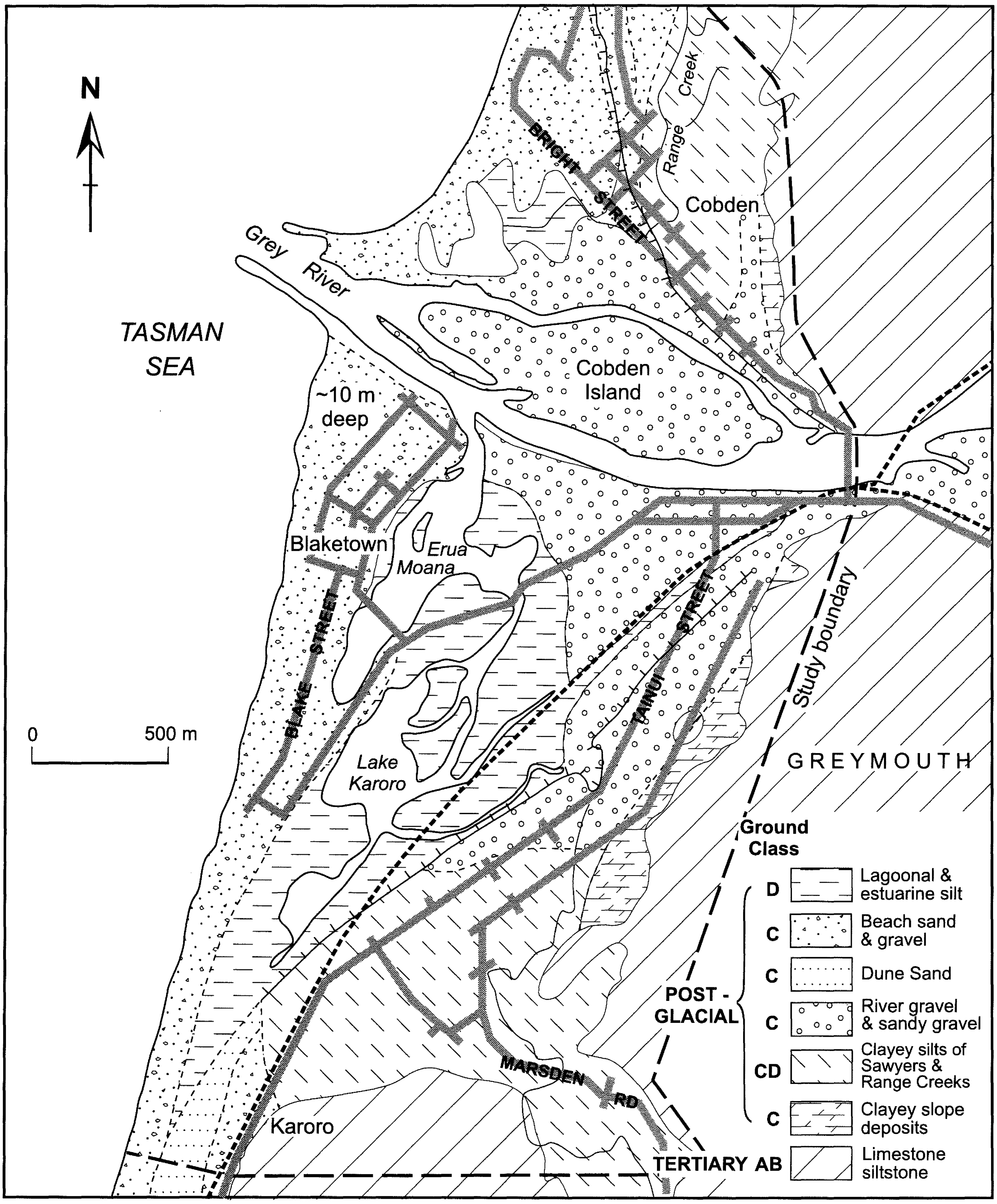


*Figure 5: Microzoning map of Westport developed from geology of Suggate and Wood (1979).*

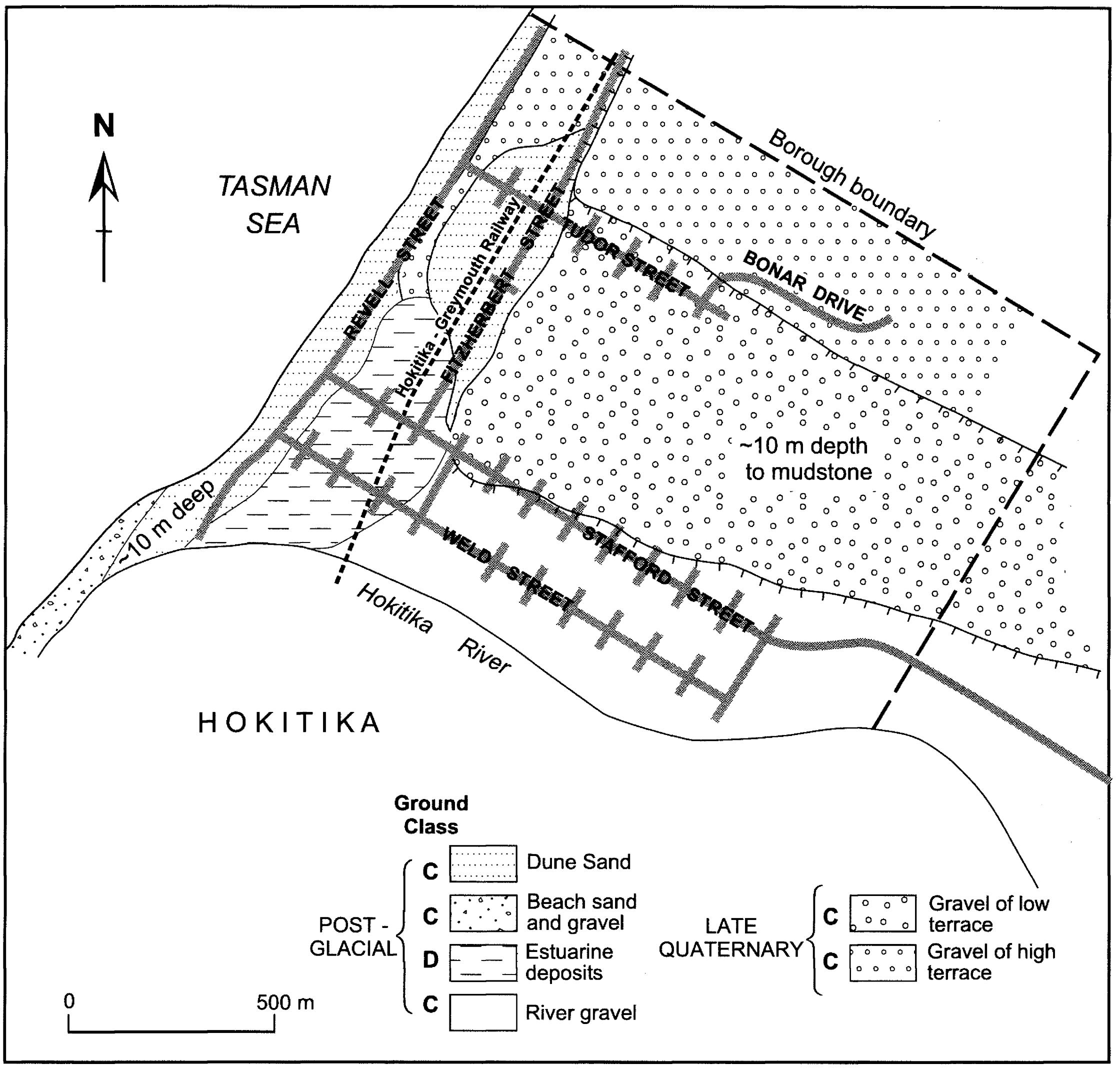


*Figure 6: Microzoning map of Reefton developed from geology of Suggate and Wood (1979).*

**Table 1: Depth limits for boundary between site subsoil classes C and D (from draft Australian/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 |

## 4. THE DATA

In each of the towns 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 effective limits adopted for the urban areas studied are marked on Figures 3-6. A database was then created for each town ordered alphabetically by street name and numerically by house number. The numbers of one- and two-storey houses in each of the six towns are listed in Table 2.

**Table 2: Numbers of houses studied in each town**

| Town | Houses | |
|---|---|---|
| | 1-storey | 2-storey[1] |
| Hokitika | 801 | * |
| Greymouth | 2254 | 54 |
| Runanga | 498 | * |
| Westport | 1316 | * |
| Reefton | 284 | * |
| Inangahua | 55 | 0 |

[1] Includes hotels and boarding houses of house style construction

- Not studied

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

(i) Publicly owned houses.

(ii) Privately owned uninsured houses. It was found in our previous study of this earthquake (Dowrick *et al.*, 2001) that 5.3% 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).

## 5. 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.

### 5.1 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.* (1995), 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. The lognormal distribution has the density function:

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

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 $\mu$ and $\sigma$ 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 $\mu$ and $\sigma$, found for the various data sets are given in Tables 3 - 5. Also tabulated are the number of damaged items *n*, and the total population (damaged + undamaged) *N*.

### 5.2 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

$$\overline{D}_r = \frac{\sum_{i=1}^{n}[\text{cost of damage to building i}]}{\sum_{i=1}^{N}[\text{value of building i}]} \qquad (3)$$

where *n* is the number of damaged buildings.

Secondly,

$$D_{rm} = \frac{\sum_{i=1}^{n}[D_{r_i}]}{N} \qquad (4)$$

In general, $D_{rm}$ with its associated confidence limits is a more reliable and useful tool than $\overline{D}_r$ [9]. 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 3 - 5.

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

**Table 3: 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**

| Property Class | $n$ | $N$ | $\mu$ | $\sigma$ | $D_{rm}$ | $\overline{D}_r$ |
|---|---|---|---|---|---|---|
| **MM7.0 Hokitika excl. chimney damage** | | | | | | |
| 1 storey houses, w/b*, piled | | | | | | |
| GC C | 76 | 472 | -6.18 | 1.29 | 0.00070 | 0.00056 |
| GC D | 3 | 28 | -6.84 | 0.78 | 0.00013 | 0.00015 |
| 1 storey houses, w/b, conc fdns | | | | | | |
| GC C | 16 | 263 | -6.42 | 1.17 | 0.00016 | 0.00019 |
| GC D | 0 | 9 | NA | NA | 0.0 | 0.0 |
| Household contents, piled | | | | | | |
| GC C | 43 | 483 | -5.07 | 1.05 | 0.00086 | 0.00070 |
| GC D | 1 | 30 | -6.91 | NA | 0.000033 | 0.000032 |
| **MM7.5 Greymouth excl. chimney damage** | | | | | | |
| 1 storey houses, w/b, piled | | | | | | |
| GC AB | 23 | 65 | -5.51 | 1.09 | 0.0021 | 0.0019 |
| GC C | 368 | 996 | -5.70 | 1.10 | 0.0021 | 0.0018 |
| GC CD | 219 | 433 | -5.45 | 1.14 | 0.0040 | 0.0039 |
| GC D | 19 | 61 | -5.55 | 1.01 | 0.0017 | 0.0015 |
| 1 storey houses, w/b, conc fdns | | | | | | |
| GC AB | 16 | 62 | -6.08 | 1.35 | 0.00087 | 0.0011 |
| GC C | 69 | 214 | -5.86 | 1.26 | 0.0017 | 0.0018 |
| GC CD | 85 | 244 | -5.65 | 1.08 | 0.0019 | 0.0021 |
| GC D | 2 | 4 | -5.37 | 0.92 | 0.0026 | 0.0030 |
| Household contents, piled | | | | | | |
| GC AB | 22 | 71 | -4.99 | 1.01 | 0.0030 | 0.0030 |
| GC C | 258 | 1046 | -4.74 | 1.08 | 0.0038 | 0.0033 |
| GC CD | 166 | 444 | -4.52 | 1.11 | 0.0070 | 0.0070 |
| GC D | 13 | 65 | -5.42 | 0.88 | 0.0013 | 0.00095 |

*w/b = weatherboard

### 5.3 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) WIF and C, (ii) B, S and V, and (iii) R as defined in Section 2. $D_{rm}$ values for these three groups were considered for houses of the same foundation type, ie concrete perimeter walls, at one intensity MM8.5 (Westport). At this intensity the first group WIFC was thought to be relatively *robust*, the second group BSV was thought to be relatively *fragile*, while the stucco houses R were of uncertain vulnerability.

These cases are plotted in Figure 7 for the condition where costs of chimney damage are excluded. It is seen that $D_{rm}$ is smallest for houses with WIFC wall claddings. The mean damage ratio for the BSV wall case is nearly 4 times that for WIFC walls. However, this difference is not statistically significant. 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 (BSV) are less robust than WIFC 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.

### 5.4 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 perimeter wall foundations perform better than those on piled foundations right through the intensity range MM7.0 to MM10.5. At most intensities $D_{rm}$ for houses on piled 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 piled 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 4: 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**

| Property Class | $n$ | $N$ | $\mu$ | $\sigma$ | $D_{rm}$ | $\overline{D}_r$ |
|---|---|---|---|---|---|---|
| **MM7.8 Runanga excl. chimney damage** | | | | | | |
| 1 storey houses, w/b*, piled | | | | | | |
| GC AB | 106 | 247 | -5.23 | 1.06 | 0.0036 | 0.0028 |
| GC C | 22 | 60 | -5.12 | 1.16 | 0.0035 | 0.0033 |
| GC CD | 43 | 95 | -5.43 | 1.36 | 0.0035 | 0.0026 |
| 1 storey houses, w/b, conc fdns | | | | | | |
| GC AB | 7 | 34 | -5.01 | 1.56 | 0.0019 | 0.0012 |
| GC C | 5 | 12 | -4.89 | 1.11 | 0.0037 | 0.0027 |
| GC CD | 4 | 10 | -4.82 | 1.43 | 0.0059 | 0.0034 |
| Household contents, piled | | | | | | |
| GC AB | 107 | 261 | -4.47 | 1.12 | 0.0087 | 0.0064 |
| GC C | 28 | 62 | -4.27 | 1.00 | 0.0096 | 0.0083 |
| GC CD | 37 | 102 | -4.48 | 0.89 | 0.0056 | 0.0050 |
| **MM8.5 Westport excl. chimney damage** | | | | | | |
| 1 storey houses, w/b, piled | | | | | | |
| GC C | 348 | 818 | -5.44 | 0.96 | 0.0029 | 0.0025 |
| GC D | 97 | 179 | -4.81 | 1.19 | 0.0096 | 0.0081 |
| 1 storey houses, w/b, conc fdns | | | | | | |
| GC C | 36 | 93 | -5.74 | 1.13 | 0.0020 | 0.0025 |
| GC D | 6 | 12 | -5.24 | 1.86 | 0.0050 | 0.0072 |
| Household contents, piled | | | | | | |
| GC C | 522 | 882 | -4.39 | 0.94 | 0.011 | 0.0095 |
| GC D | 78 | 191 | -4.31 | 1.04 | 0.0082 | 0.0065 |

*w/b = weatherboard

**Table 5: Sample of basic statistics of the distribution of damage ratio by class of domestic property, in the 1968 Inangahua earthquake, for intensities MM9.0 and MM10.5**

| Property Class | $n$ | $N$ | $\mu$ | $\sigma$ | $D_{rm}$ | $\overline{D}_r$ |
|---|---|---|---|---|---|---|
| **MM9.0 Reefton excl. chimney damage** | | | | | | |
| 1 storey houses, w/b*, piled | | | | | | |
| GC C | 84 | 179 | -5.19 | 1.28 | 0.0047 | 0.0034 |
| 1 storey houses, w/b, conc fdns | | | | | | |
| GC C | 16 | 50 | -5.62 | 1.32 | 0.0019 | 0.0021 |
| Household contents, piled | | | | | | |
| GC C | 99 | 289 | -4.25 | 0.96 | 0.0077 | 0.0059 |
| **MM10.5 Inangahua excl. chimney damage** | | | | | | |
| 1 storey houses, w/b, piled | | | | | | |
| GC C | 52 | 52 | -1.70 | 1.51 | 0.32 | 0.33 |
| 1 storey houses, w/b, conc fdns | | | | | | |
| GC C | 3 | 3 | -3.47 | 0.61 | 0.034 | 0.033 |
| Household contents, piled | | | | | | |
| GC C | 53 | 53 | -1.38 | 0.66 | 0.30 | 0.28 |

*w/b = weatherboard

Further effects of foundation types are discussed in the following two sections.

### 5.5 Effects of microzoning on damage to houses

On Figure 10 are plotted the mean damage ratios for one-storey weatherboard houses, (excluding chimney damage) in Greymouth at intensity MM7.5, with the two types of foundation, and on the four different ground classes described in Section 3. Two very different patterns are seen. First, 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. Second, 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).

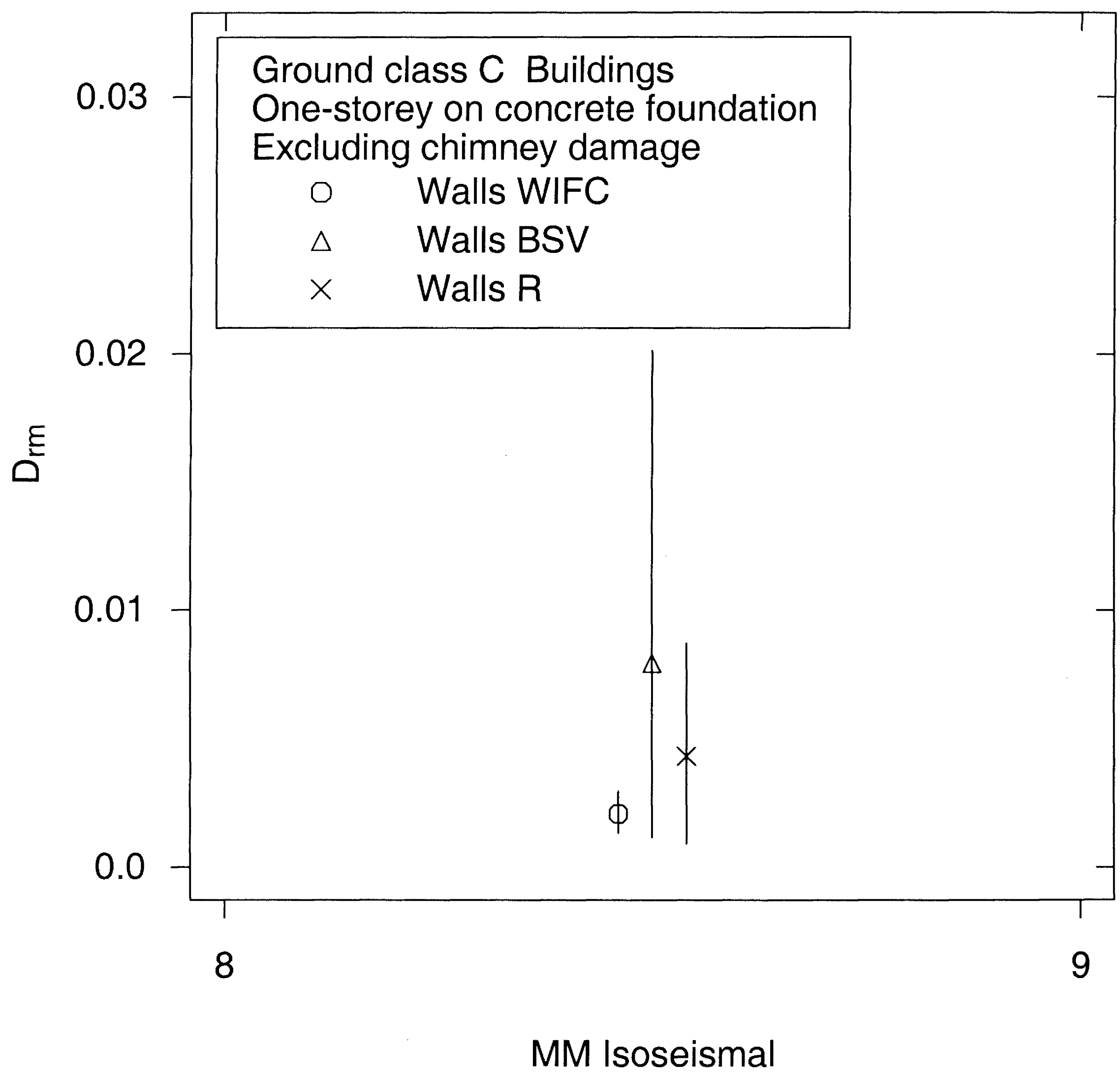


*Figure 7: Comparison of vulnerabilities of houses with different wall claddings. Mean damage ratios with their associated 95% confidence limits for one-storey houses subjected to intensity MM8.5.*

The behaviour of the houses on piles in Figure 10 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.

On Figure 11 are plotted the mean damage ratios for one-storey weatherboard houses in Westport at intensity MM8.5, with two types of foundation, and on Ground Classes C and

D. Where the chimney damage is excluded (Figure 11(a)) or chimney damage included (Figure 11(b)), $D_{rm}$ is greater on Ground Class D than on Ground Class C, and in both the piled foundation cases this difference is statistically significant.

On Figure 12 are plotted the mean damage ratios for one-storey weatherboard houses in Hokitika at intensity MM7.0, with two types of foundation and on Ground Classes C and D. Where the chimney damage is excluded (Figure 12(a)) or chimney damage included (Figure 12(b)), $D_{rm}$ is less on Ground Class D than on Ground Class C, and in three of the four cases plotted this difference is statistically significant. This result is the opposite of that found at the stronger intensity of MM8.5, shown in Figure 11, and similar to that found in very strong shaking (MM10) in Napier (Dowrick *et al.*, 1995). The effect shown in Figure 12 is surprising as it might be expected that the low amplitudes of shaking at MM7.0 would produce the same responses on soft soils as those observed for the moderately strong shaking of MM8.5.

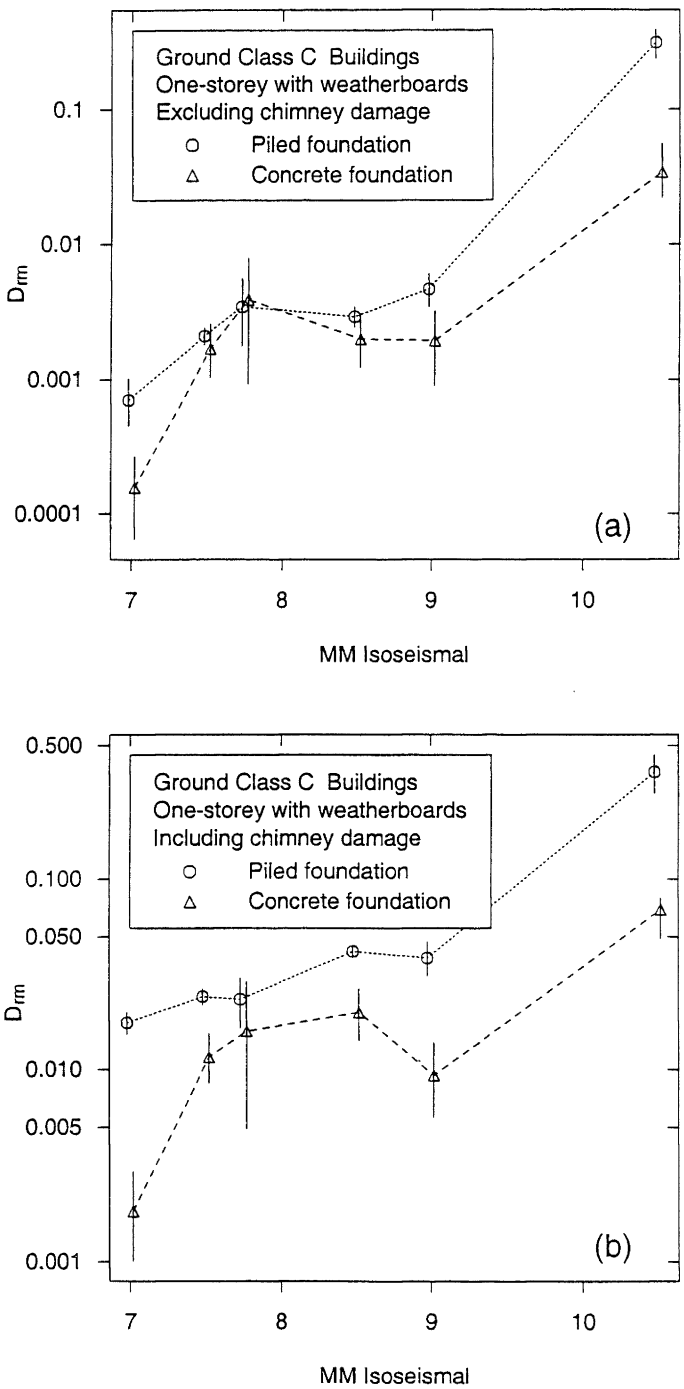


***Figure 8:** Comparison of vulnerabilities of one-storey houses with two types of foundation. Mean damage ratios with their associated 95% confidence limits for weatherboard houses on Ground Class C over a range of intensities.*

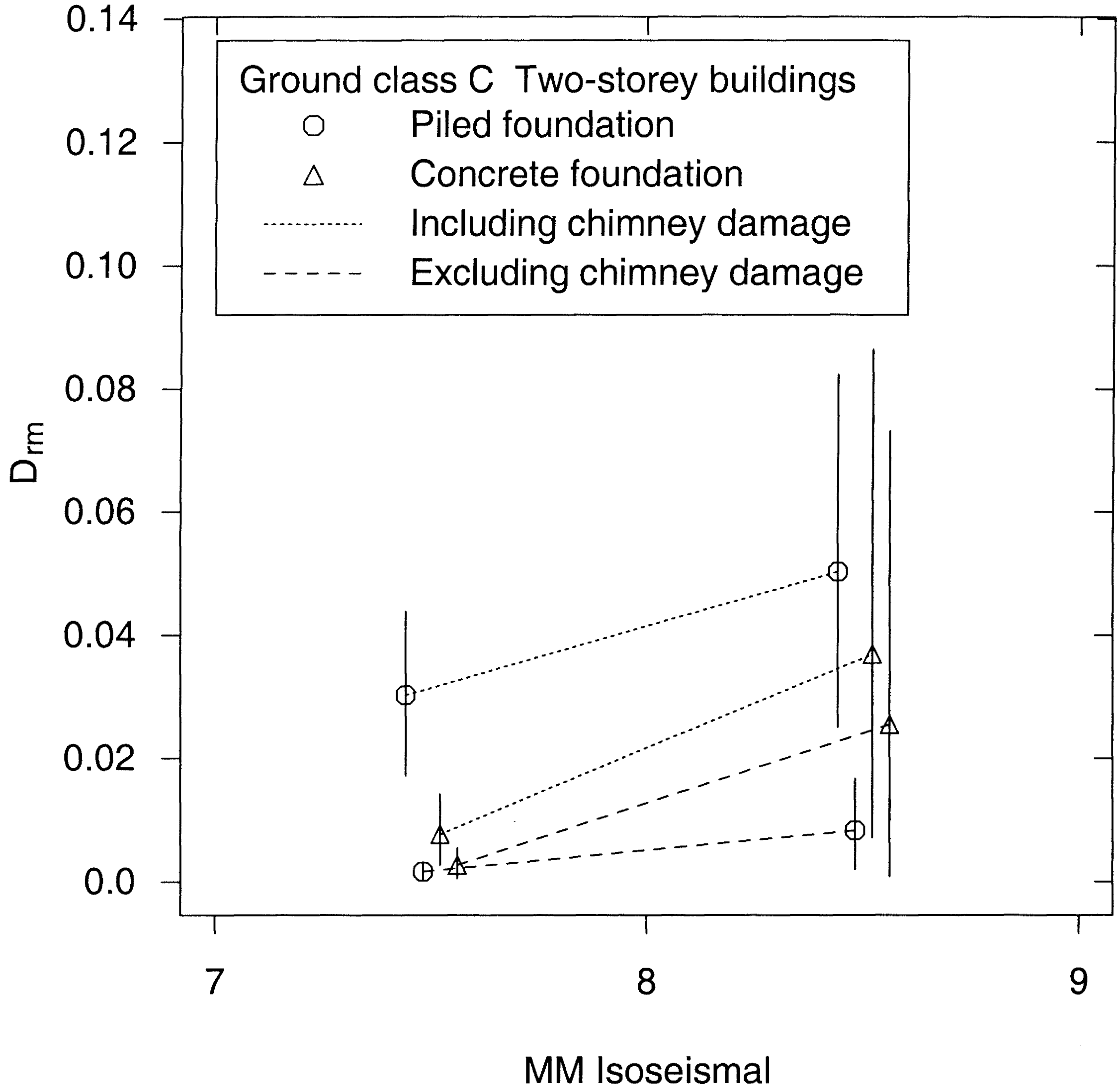


***Figure 9:** Comparison of vulnerabilities of two-storey houses with two types of foundation. Mean damage ratios with their associated 95% confidence limits for weatherboard houses on Ground Class C subjected to intensity MM8.5 (Westport).*

It is of interest to compare the results for MM8.5 and MM7.0 (Figures 11 and 12) with the results for Ground Classes C and D, at the intermediate intensity of MM7.5 as plotted in Figure 10. It is seen that at intensity MM7.5 the results are equivocal, there being no significant statistical difference between $D_{rm}$ for these two ground classes for either type of foundation. Thus the MM7.5 responses are transitional between the opposing responses at MM7.0 and MM8.5 (See also contents, Figure 15). This suggests that the apparently anomalous results for MM7.0 are real, and are presumably caused by dynamical soil-structure interaction effects.

### 5.6 Household contents

The effects of foundation construction type on mean damage ratios for household contents over a range of intensities are shown in Figure 13. Here the data used has been limited to that for contents of one-storey weatherboard houses, on Ground Class C. It is seen that household contents in houses with concrete perimeter wall foundations are less damaged than those in houses with piled foundation. The trends are similar to those for the houses themselves, particularly the case when chimney damage is included, as seen in Figure 8(b).

On Figure 14 are plotted the mean damage ratios for contents of one-storey houses with two types of foundation, at intensity MM8.5 (Westport), on Ground Classes C and D. Here the mean damage ratio for contents is less in houses situated on soft soil (Ground Class D) than on the stiffer Ground Class C. This is the reverse of the results for the houses themselves shown in Figure 11. For the contents of houses on piles, the difference between $D_{rm}$ for the two ground classes is statistically different at the 0.05 level.

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. Also similarly to Figure 10, the contents of piled houses on Ground Class D are least damaged, their $D_{rm}$ for contents of all houses (with piled and concrete foundations), on Ground Classes C and CD.

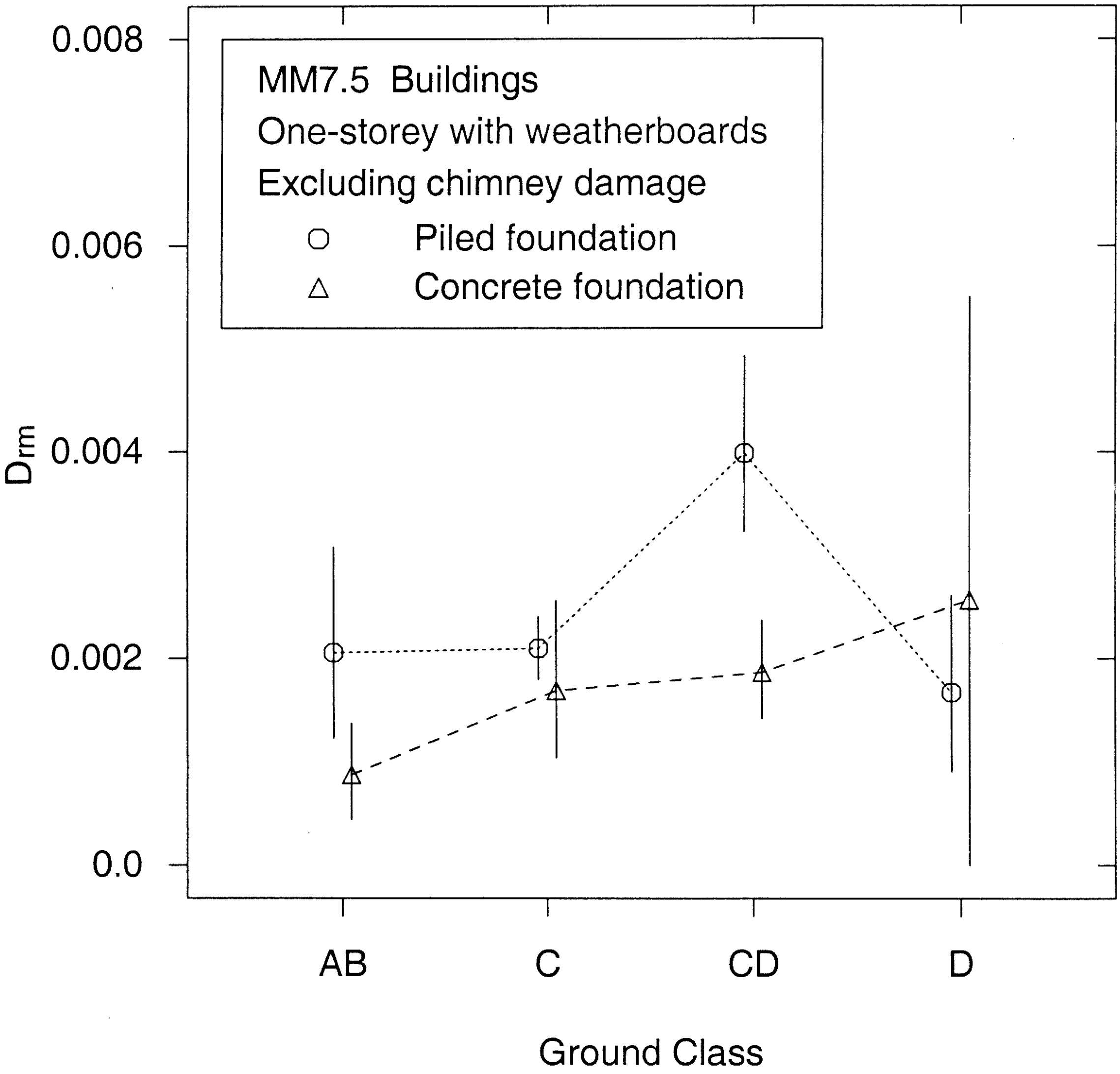


*Figure 10: Comparison of vulnerabilities of houses on four different ground classes and two types of foundation. Mean damage ratios with their associated 95% confidence limits for one-storey weatherboard houses subjected to intensity MM7.5 (Greymouth).*

On Figure 16 are plotted the mean damage ratios for the contents of one-storey houses in Hokitika at intensity MM7.0, with two types of foundation and on Ground Classes C and D. For both foundation types, $D_{rm}$ is less for Ground Class D than for Ground Class C, the differences being statistically significant. This surprising result is similar to that found for the houses themselves, as seen on Figure 12.

### 5.7 Percentage of items damaged

We restrict ourselves to discussing a much more limited selection of cases of percentages of items damaged than we have considered above for $D_{rm}$. First, on Figure 17 are plotted the percentages of one-storey weatherboard houses damaged, over a wide range of intensities (MM7.0-10.5), on Ground Class C, and excluding chimney damage. In most cases the percentage damaged is higher for piled houses than for those on piled foundations, the trend being similar to those shown for $D_{rm}$ on Figure 8(a).

Next, on Figure 18 are plotted the percentages of one-storey weatherboard houses damaged, in Greymouth at intensity MM7.5, excluding chimney damage, and on two types of foundation. Here the same pattern is seen as found for mean damage ratio on Figure 10, with the same peak (apparently due to resonance) for piled houses built on Ground Class CD.

Finally, on Figure 19 are plotted the percentages of contents parcels damaged in Greymouth at intensity MM7.5, on two types of foundation. We again see a similar pattern to that found for $D_{rm}$ of contents as plotted on Figure 15.

## 6. DISCUSSION OF MICROZONING EFFECTS

Most of the relative damage levels found for houses (Figures

10-12) and household contents (Figures 14-16) on Ground Classes C and D at low to moderately strong (MM7-MM8.5) levels of shaking are the reverse of what was expected. Regardless of foundation type, the mean damage ratio is mostly lower for Ground Class D than it is for Ground Class C, the difference being statistically significant in 10 of the 16 comparisons seen on the five figures. The results for intensity MM7 for houses (Figure 12) and contents (Figure 16) are consistent with each other, but awkwardly the results for contents at MM8.5 (Figure 14) are the inverse of those found for the houses themselves (Figure 11), the result for houses on piles being statistically significant.

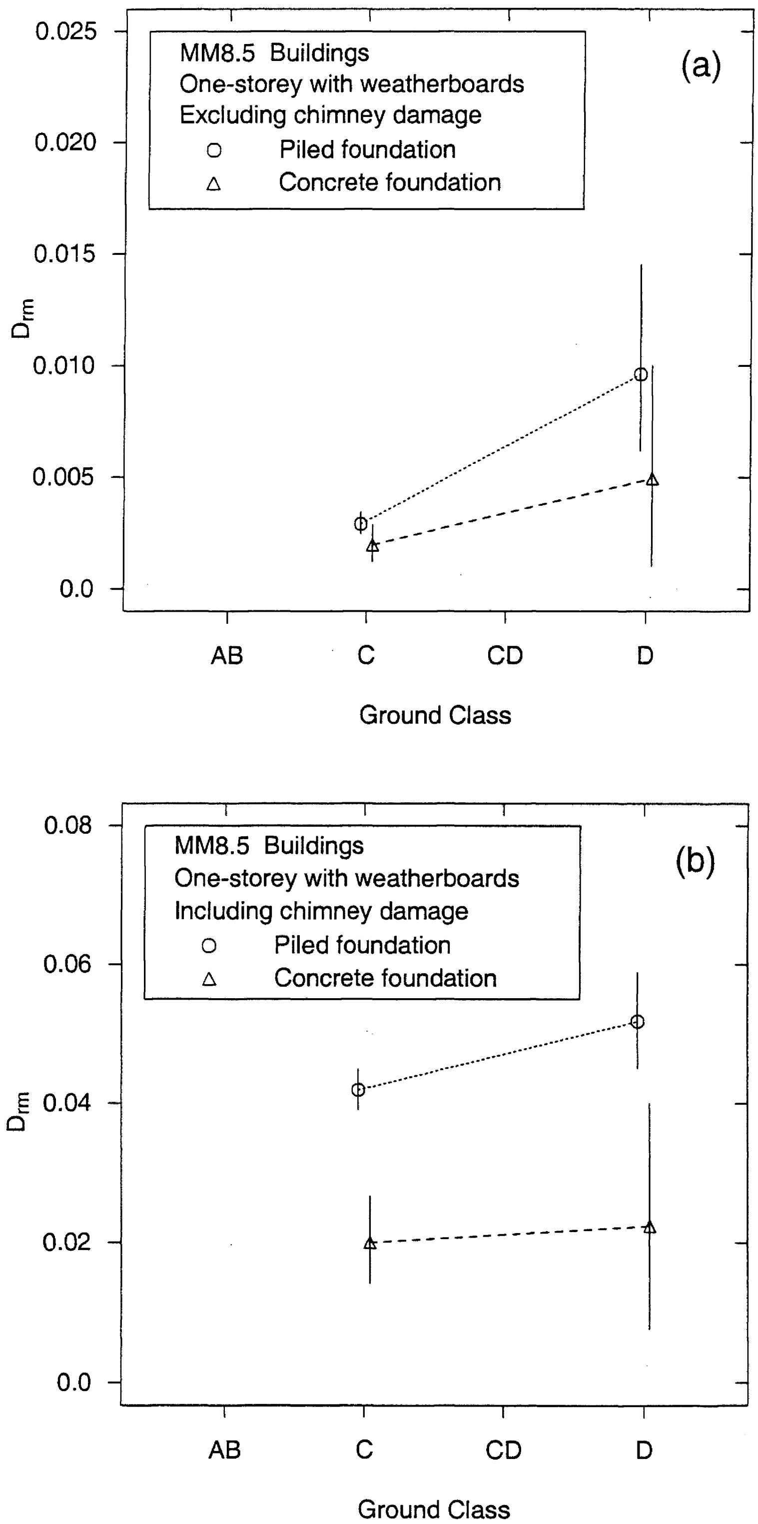


*Figure 11: Comparison of vulnerabilities of one-storey weatherboard houses on two ground classes and two types of foundation subjected to intensity MM8.5 (Westport): (a) excluding chimney damage, and (b) including chimney damage.*

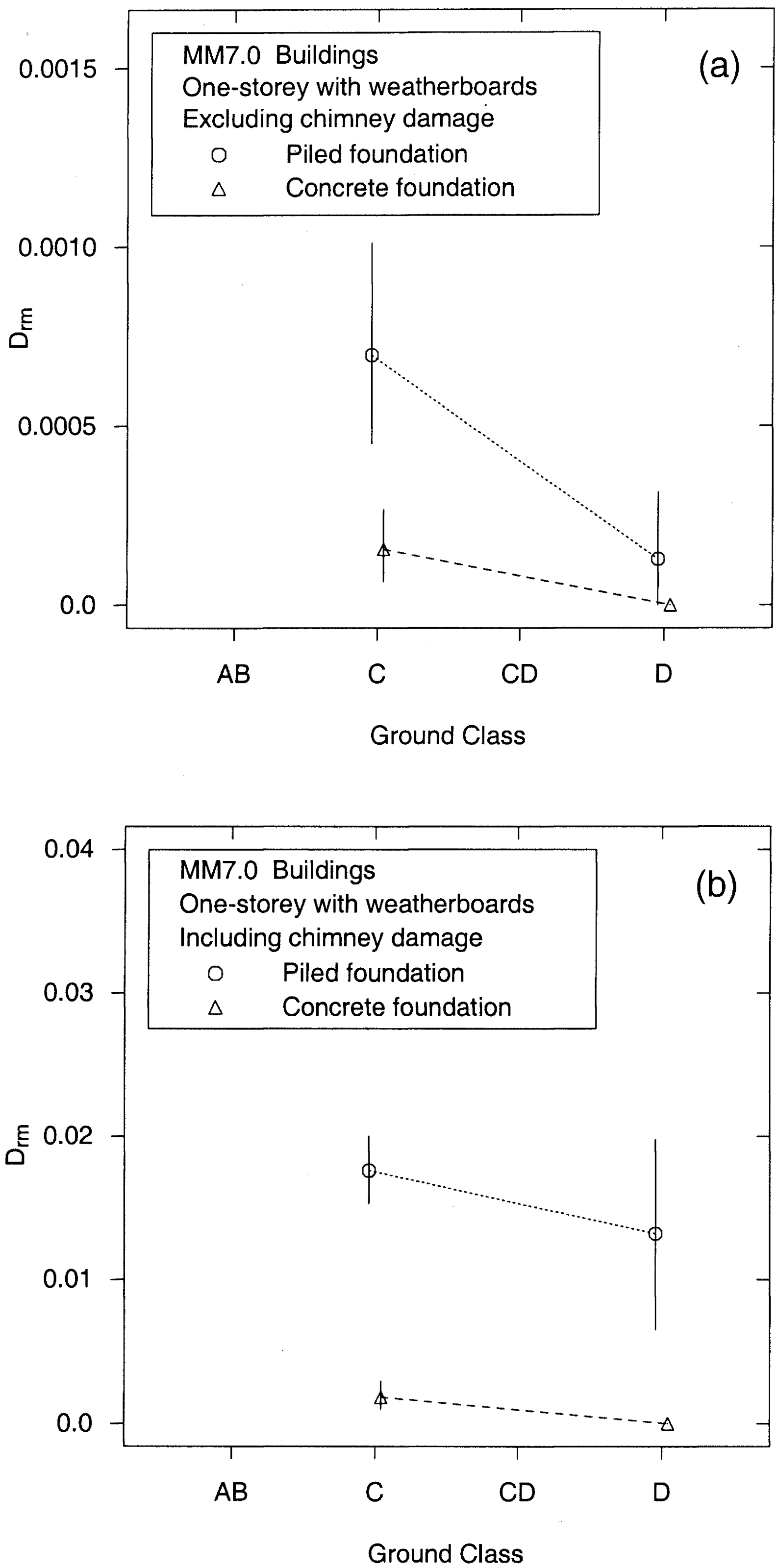


*Figure 12: Comparison of vulnerabilities of one-storey weatherboard houses on two ground classes and two types of foundation subjected to intensity MM7.0 (Hokitika): (a) excluding chimney damage, and (b) including chimney damage.*

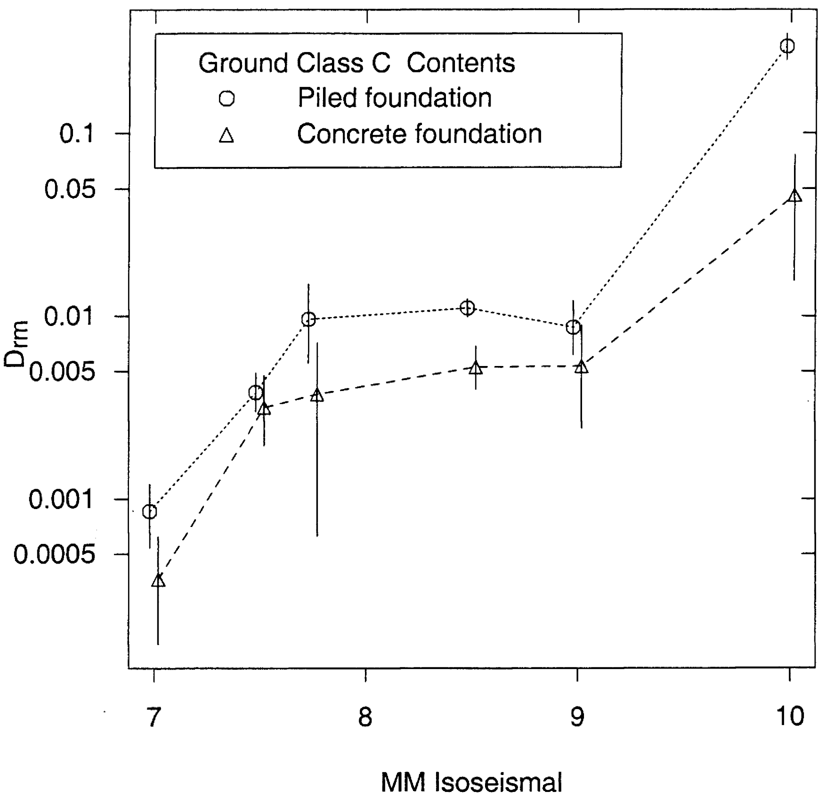


*Figure 13: Comparison of vulnerabilities of contents of houses with two types of foundation. Mean damage ratios with their associated 95% confidence limits for contents on Ground Class C over a range of intensities (Compare also with Figure 8).*

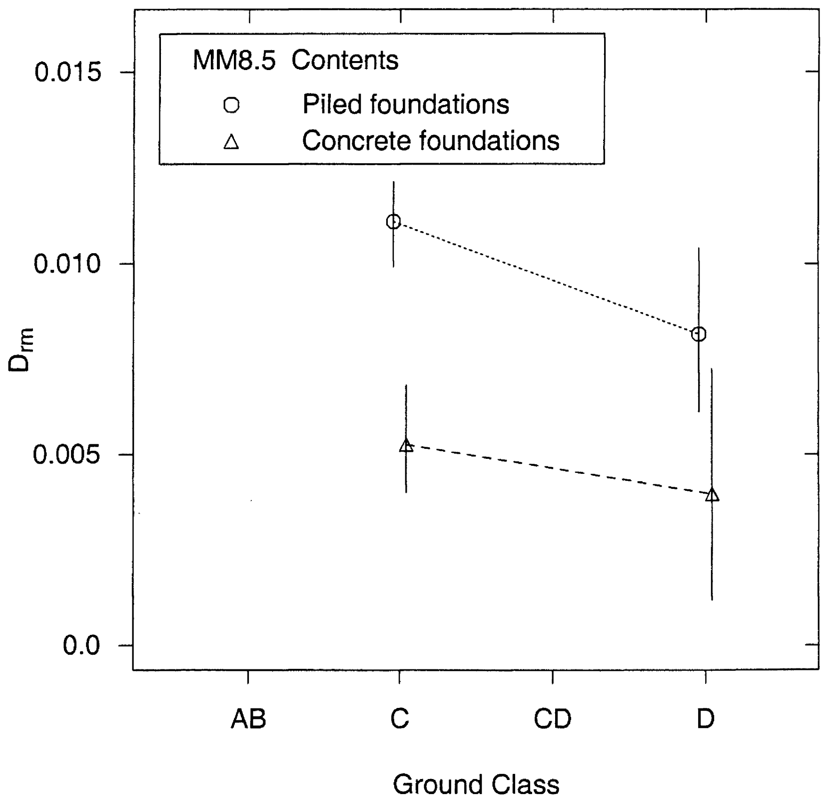


*Figure 14: Comparison of vulnerabilities of contents of houses on two ground classes and two types of foundation. Mean damage ratios with their associated 95% confidence limits for contents of houses subjected to intensity MM8.5 (Westport).*

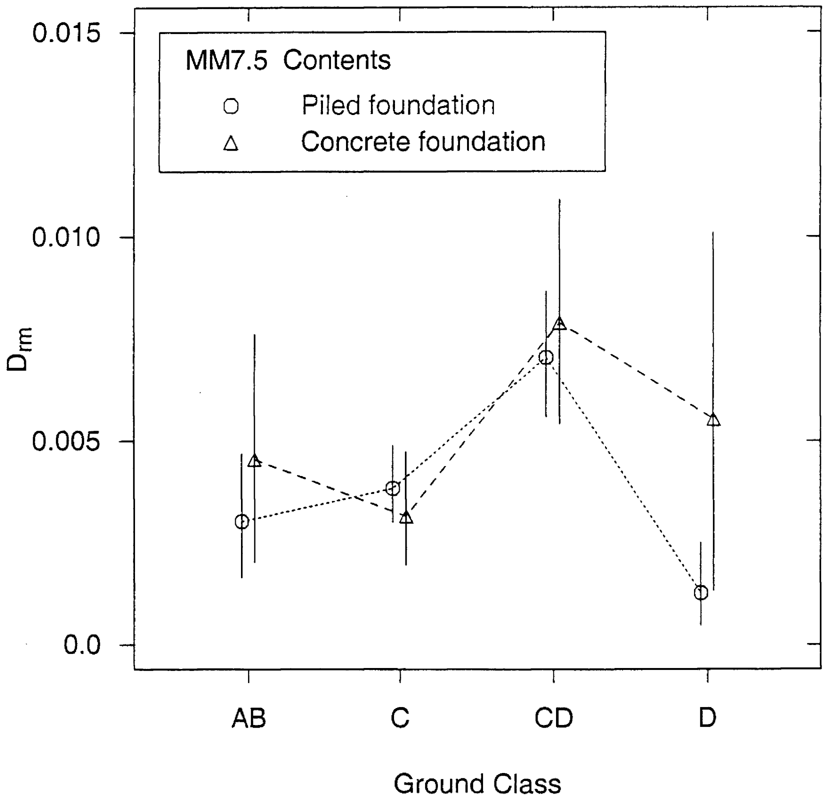


*Figure 15: Comparison of vulnerabilities of contents of houses on four ground classes and two types of foundation. Mean damage ratios with their associated 95% confidence limits for contents of houses subjected to intensity MM7.5 (Greymouth), (Compare Figure 10).*

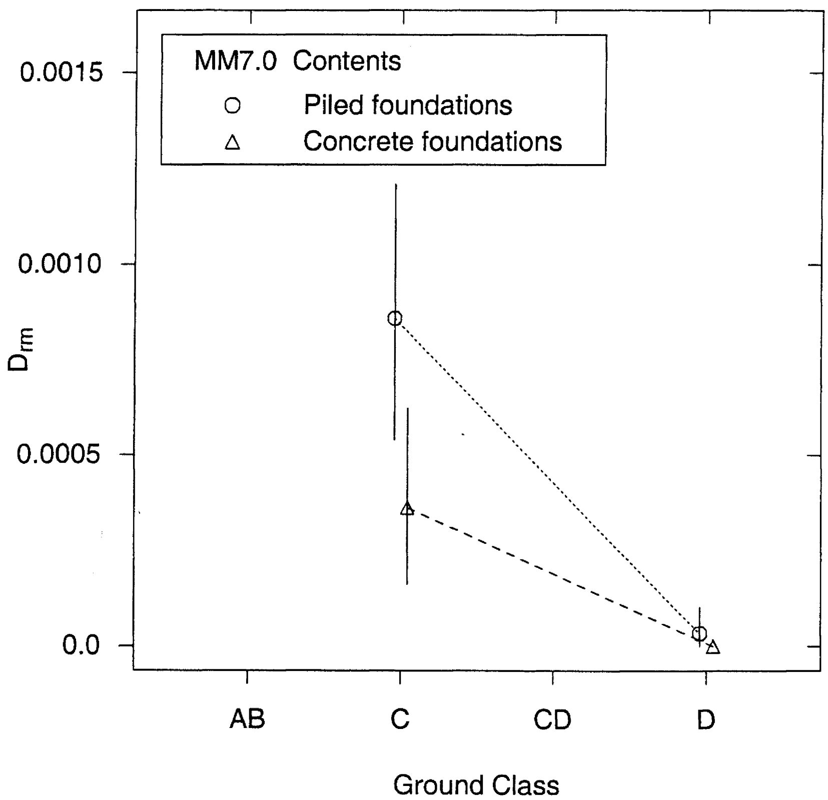


*Figure 16: Comparison of vulnerabilities of contents of houses on two ground classes and two types of foundation. Mean damage ratios with their associated 95% confidence limits for contents of houses subjected to intensity MM7.0, (Compare Figure 12).*

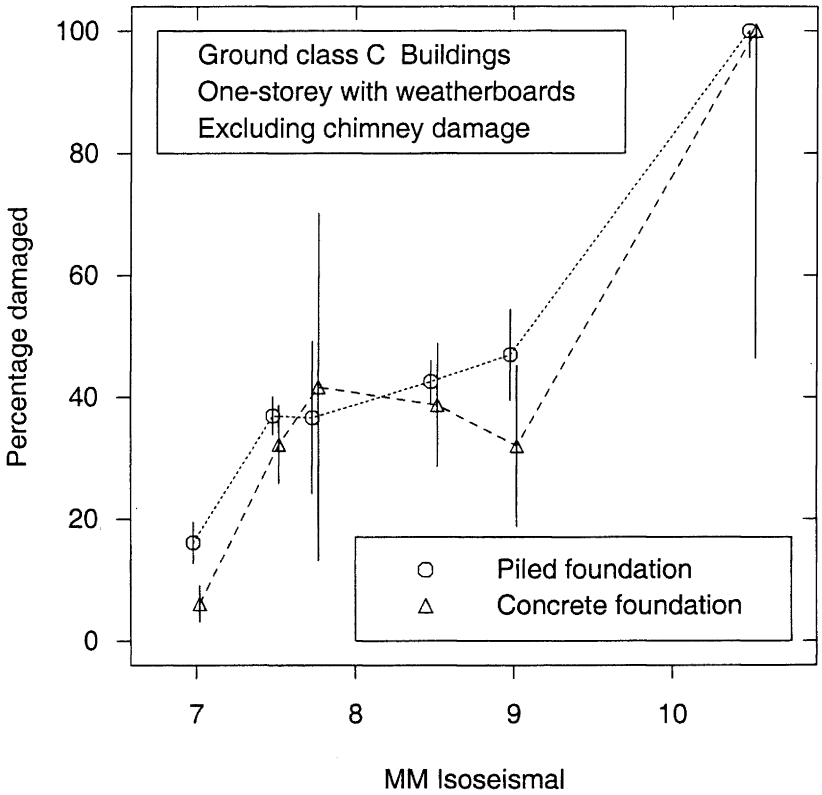


*Figure 17: Percentage damaged and its 95% confidence limits for single storey weatherboard houses on Ground Class C, excluding chimney damage, as a function of MM intensity and two types of foundation, (Compare Figure 9).*

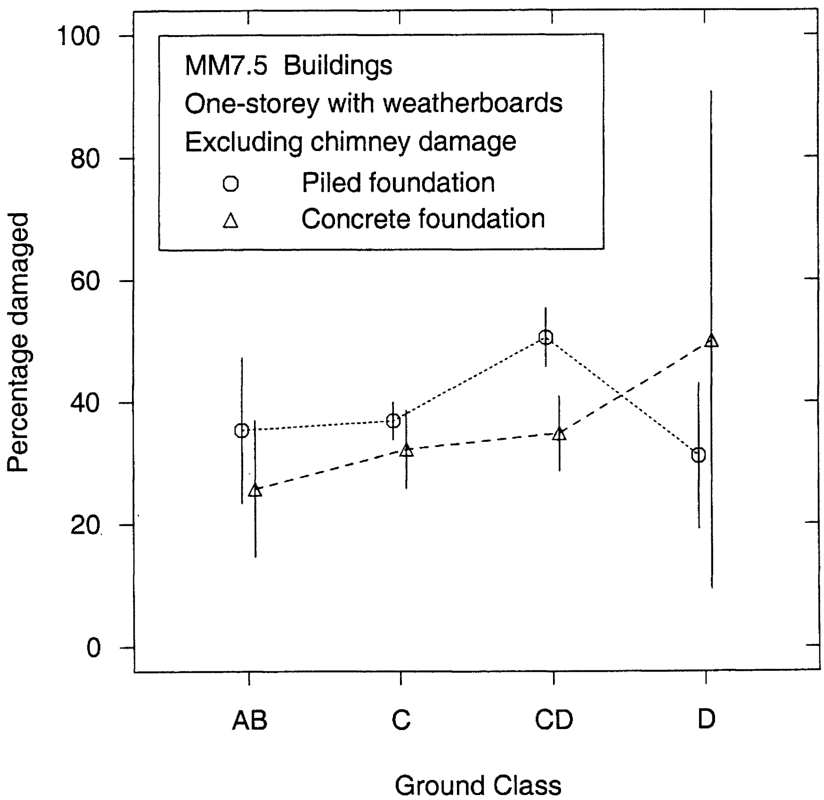


*Figure 18: Percentage damaged and its 95% confidence limits for single storey weatherboard houses, excluding chimney damage, at intensity MM7.5 (Greymouth) for two types of foundation and four ground classes, (Compare Figure 15).*

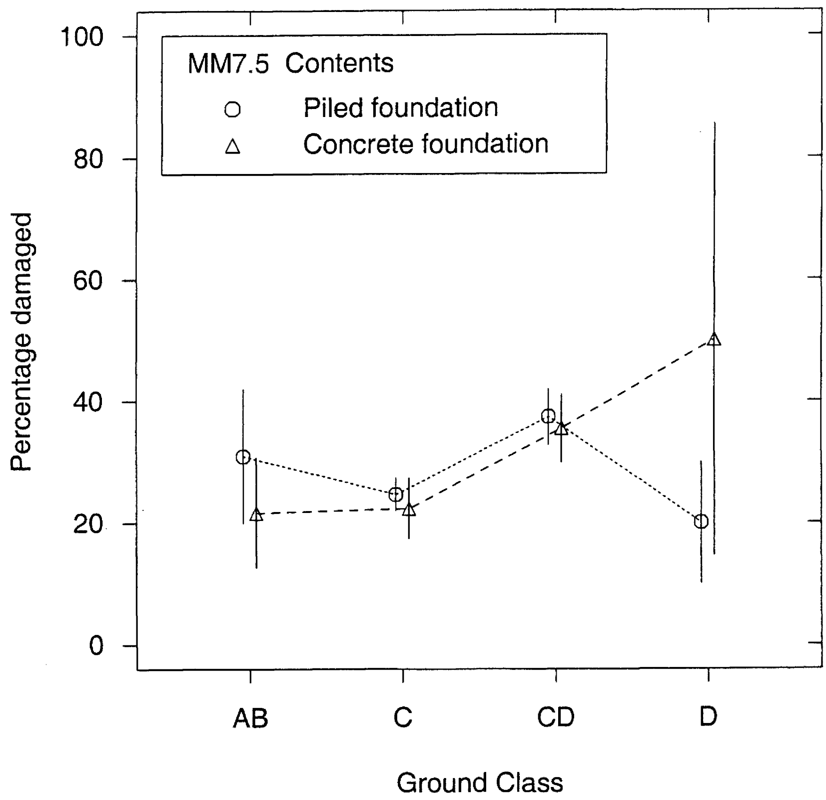


***Figure 19: Percentage damaged and its 95% confidence limits for parcels of household contents, in houses on piled and concrete foundations, at intensity MM7.5 (Greymouth).***

A parallel case to the above situation with more flexible sites having smaller responses during low amplitude shaking is that reported by Seed (1975) from the 1957 San Francisco earthquake. Here at the nearby site PGAs were 0.10g at two rock sites and 0.05g on two deep soil sites, and peak values of SA on the rock were also substantially less on the soil sites.

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 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 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 variability 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 town appears 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, particularly those shown on Figures 10 and 15?

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 present and the Napier studies, but was demonstrated most sharply (and ironically) in the Lake Bed Zone of Mexico City in 1985, where Dowrick observed that unreinforced masonry buildings were undamaged next door to heavily damaged modern high-rise buildings.

## 7. CONCLUSIONS

As a result of this study of the Inangahua earthquake the following conclusions have been drawn:

*One-storey houses*

1. At the moderately strong ground shaking of intensity MM8.5, $D_{rm}$ for houses on concrete perimeter wall foundations with walls of the claddings group WIFC (weatherboard, corrugated iron, fibre board and concrete masonry) is less than it is for houses with claddings group BSV (brick and artificial stone veneer).

2. Over the range of intensities MM7.0 and MM10.5, $D_{rm}$ for weatherboard houses on piled foundations is generally several times higher than it is for houses on concrete perimeter wall foundations.

3. At intensity MM7.5, $D_{rm}$ for weatherboard houses on piled 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 probably indicates that some soil-structure resonance occurs on Ground Class CD. This effect is also seen in the contents of the houses.

4. In Greymouth at intensity MM7.5, $D_{rm}$ for weatherboard houses on concrete foundations excluding chimney damage increases 2.2 times with increasing ground flexibility (or decreasing strength) 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. In Westport at intensity MM8.5, $D_{rm}$ for weatherboard houses is greater on Ground Class D than on Ground Class C. For piled houses, $D_{rm}$ for Ground Class D is 3.6 times that for Ground Class C when chimney damage is excluded, the difference being statistically significant at the 0.01 level.

6. In Hokitika at intensity MM7.0, $D_{rm}$ for weatherboard houses is less on Ground Class D than on Ground Class C. For piled houses $D_{rm}$ for Ground Class C is 6.0 times that for Ground Class D when chimney damage is excluded, the difference being statistically significant at the 0.01 level. This result is surprising, being the opposite of that found at intensity MM8.5, and may be an effect of frequency content of the ground shaking.

7. Regardless of foundation type, $D_{rm}$ is mostly lower for houses and contents for Ground Class D than for Ground Class C, for intensities MM7.0 to MM8.5, the difference being statistically significant in 10 of the 16 comparisons made. This may result from differences in frequency content of the ground shaking.

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

*Two-storey houses*

9. When chimney damage is excluded, two-storey houses on piled 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.

*Household contents*

10. Considering one-storey houses on Ground Class C, and the range of intensities MM7-MM10.5, household contents in houses with concrete perimeter wall foundations are less damaged than those in houses with piled foundations.

11. Considering the contents of one-storey houses at intensity MM8.5, $D_{rm}$ for the contents of houses on softer sites (Ground Class D) is less than that for contents of houses on stiffer sites (Ground Class C), and the difference is statistically significant at the 0.05 level). This (surprisingly) is the reverse of the results for the houses themselves. At intensities MM7.5 and MM7.0, contents of houses are also generally less damaged on Ground Class D than on Ground Class C (as also are the houses themselves).

*Microzoning and risk assessment methodology*

12. Microzoning maps need to be based on more information than that on surface geology maps, and the required extra criteria (such as engineering properties of the soil) need to be better understood.

13. 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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## REFERENCES

Adams, R.D., Eiby, G.A. and Lowry, M.A. (1968). "Inangahua earthquake - Preliminary seismological report. In: Preliminary reports on the Inangahua earthquake, New Zealand, May 1968", NZ Department of Scientific and Industrial Research Bulletin 193.

Anderson, H., Beanland, S., Blick, G., Darby, D., Downes, G., Haines, J., Jackson, J., Robinson, R. and Webb, T. (1994). "The 1968 May 23 Inangahua, New Zealand, earthquake: an integrated geological, geodetic, and seismological source model". *N.Z.J. Geol. Geophys.*, **37**, 59-86.

Dowrick, D.J. (1991). "Damage costs for houses and farms as a function of intensity in the 1987 Edgecumbe earthquake", *Earthq Eng and Struct Dynamics,* **20**, 455-469.

Dowrick, D.J. and Rhoades, D.A. (1997). "Vulnerability of different classes of low-rise buildings in the 1987 Edgecumbe, New Zealand, earthquake", *Bull. NZ National Society for Earthquake Engineering,* **30(3)**, 227-241.

Dowrick, D.J., Rhoades, D.A., Babor, J. and Beetham, R.D. (1995). "Damage ratios and microzoning effects for houses in Napier at the centre of the magnitude 7.8 Hawke's Bay, New Zealand, earthquake of 1931", *Bull. NZ Nat Soc Earthq Eng,* **28(2)**, 134-145.

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". *Bull. NZ Nat Soc Earthq Eng,* **34(3)**, 191-213.

Dowrick, D.J. and Sritharan, S. (1993). "Peak ground accelerations recorded in the 1968 Inangahua earthquake and some attenuation implications", *Bull. NZ Nat Soc for Earthq Eng,* **26(3)**, 349-355.

Grant-Taylor, T.L., Adams, R.D., Hatherton, T., Milne, J.D.G., Northey, R.D. and Stephenson, W.R. (1974). "Microzoning for earthquake effects in Wellington, NZ". Bulletin 213, NZ Department of Scientific and Industrial Research, Wellington.

Seed, H.B., (1975). "Earthquake effects on soil-foundation systems". In Foundation Engineering Handbook (Eds H.F. Winterkorn and H.-Y. Fang) Van Nostrand Reinhold Company, New York, 700-32.

Suggate, R.P. and Wood, P.R. (1979). "Inangahua earthquake – damage to houses", Report N.Z.G.S. 85, New Zealand Geological Survey, Department of Scientific and Industrial Research.