Lessons from the Performance of Buildings in the MW 7.8 Hawke’s Bay Earthquake of 1931

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**ABSTRACT:** The powerful (MW 7.8) shallow Hawke's Bay earthquake of 1931 was a direct hit on two provincial towns (Napier and Hastings) and was the most damaging in New Zealand's history, causing the most casualties, major fires, and much damage to the built and natural environments. A series of studies of the effects of the earthquake on buildings and the consequences of those effects for human casualties has resulted in important findings, including surprising insights into the good performance of brittle pre-code concrete buildings, ground-related effects in very strong shaking, and the spatial distribution of near source ground shaking.

1 INTRODUCTION

With a magnitude of $M_w$ 7.8, the Hawke's Bay earthquake is the second largest New Zealand historical earthquake, and caused the most damage to the built environment and the most casualties of any New Zealand earthquake. It was felt over most of the country, from Auckland in the north to Invercargill in the south. The intensities reached Modified Mercalli X (MM10) in the central area. The inner isoseismals as plotted by Dowrick (1998b) are shown on Figure 1. Considering intensities of strong shaking, it is seen that the MM8 isoseismal extends along the line of strike of the fault rupture from Takapau in the southwest to almost Gisborne in the northeast, a distance of approximately 200 km. These inner isoseismals are well constrained in shape and size, the best of those for New Zealand's large earthquakes. It is seen on Figure 1 that the innermost isoseismal (MM10) is much shorter than the fault rupture. This is contrary to the outcome of current attenuation models of strong ground motion, which are artificially constrained to result in the strongest ground motion iso-lines always being longer than the fault rupture (Dowrick & Rhoades, 2005b).

This was New Zealand's most damaging earthquake. The total direct cost of damage was estimated at the time as approximately £7.3 million, which equates to $590 million in 2005 values. The next worst damage cost is that of the $M_w$ 6.5 1987 Edgecumbe earthquake, at $363 million in 2005 values.

In this paper we will restrict ourselves to considering the earthquake performance of buildings in Napier and Hastings, where the intensity was assessed as MM10 (Dowrick, 1998a). Note that the intensity seems to saturate at MM10 (Dowrick & Rhoades, 2005a).

2 OVERVIEW OF DAMAGE TO BUILDINGS AT INTENSITY MM10

In a previous study (Dowrick, 1998b; 2003) of 616 non-domestic buildings of 1-3 storeys in the Napier/Hastings area, the buildings were divided into five vulnerability classes (all pre-code), ie:

(a) Unreinforced masonry (URM) and reinforced concrete with a weak (soft) storey (SSRC); (Buildings Types I & II);
(b) URM walls and RC ring beams; (Buildings Type III (1);
(c) RC beams and columns & brick infill; (Buildings Type III (2);
(d) Concrete walled; (Buildings Type III (3));
(e) Timber (Pre-code).

The degree of damage to each building was assessed according to a scale of four damage states, namely:
1. OK: Damage zero or slight;
2. Damaged: Cracked or racked, parapets and gables fall (Volume Loss = 0);
3. Partial Collapse: Volume Loss < 50%;
4. Collapse: Volume Loss ≥ 50%.

The data from this assessment are plotted in histograms on Figure 2. It is seen very clearly that the buildings of class (a) are much more severely damaged than any of the other four classes. The percentages of buildings suffering some degree of collapse (damage states 3 and 4) are 71%, 23%, 0%, 0% and 1% for building vulnerability classes (a) to (e) respectively.

As damage states 3 and 4 cause most casualties (see next section), these figures confirm the correctness of New Zealand priorities to reduce the risk of collapse of URM buildings. While this is well understood by engineers, as is the safety of timber construction (class (e)), what has not previously been widely recognised is the almost collapse-free performance at intensity MM10 of pre-code low-rise reinforced concrete buildings with walls (see Section 4). This is true not only for buildings with concrete walls (class (d)), but, more remarkably, also for concrete beam and column buildings with brick infill (class c).

The extreme difference in performance of class (a) (URM) and class (d) (concrete walled) construction is illustrated by the mixed performance of the three storey Empire Hotel in Shakespeare Road in Napier. As seen in Figure 3, the original front half of the building was of URM and destroyed by the earthquake, while the rear end of the building had been rebuilt, after a fire prior to the earthquake, in reinforced concrete. After the earthquake, the brick portion of the building was rebuilt in concrete, while only minor repairs of the concrete portion were needed. The whole building still exists today.

3 CASUALTIES

In a study of all known casualties in New Zealand earthquakes (in the period 1840-2003), Dowrick & Rhoades (2005c) found that, due to building damage, 266 people had died, and that there had been 636 hospitalized injured. Of these totals, nearly all (ie. 254 and 594 respectively) had occurred in the MM10 zone of the 1931 Hawke's Bay earthquake. Of the deaths, 240 had resulted from damage to URM buildings, six from the collapse of brick chimneys, and eight from the collapse of the Napier Nurses Home (made of defective concrete). People were injured from the same causes, with those due to damage to URM numbering 580. These casualties were drawn from a total population estimated at 30,000.

Using all the New Zealand casualty data at intensities MM8 -MM10, coupled with estimates of the populations exposed in four risk situations, enabled estimates of death rates to be found by Dowrick & Rhoades (2005c), as plotted on Figure 4. These risk situations are respectively in or near:
(1) Houses (excluding URM);
(2) Non-domestic (excluding URM) buildings;
(3) URM buildings;
(4) Brick chimneys (domestic).

It is seen on Figure 4 that to date there has been zero deaths associated with New Zealand non-URM houses, even at intensity MM10. The few deaths due to domestic brick chimneys are treated separately. Brick veneers are of course potentially (modestly) hazardous, but while there were none in Napier/Hastings in 1931, they are included in the statistics of other earthquakes where appropriate (eg. in Westport, MM8 in the 1968 Inangahua earthquake). In 1931 Napier there were about 45 URM houses, but they are included in the URM buildings case.

Also on Figure 4, it is seen that at intensity MM10 the mean death rates for brick chimneys, non-domestic non-URM buildings and URM buildings are 0.0004, 0.0011, and 0.054 respectively. It should be noted that these statistics are predominantly from the pre-code Hawke’s Bay earthquake (see Dowrick & Rhoades, 2005c). Even so, it shows that the risk of death in or near URM buildings was 50 times higher than that for pre-code non-domestic non-URM buildings.
4 DAMAGE TO REINFORCED CONCRETE BUILDINGS

Low-rise brittle concrete buildings in New Zealand have performed well in earthquakes. This was demonstrated in a study (Dowrick & Rhoades, 2000) of all known pre-1976 concrete buildings subjected to intensities $\geq$ MM8 in past New Zealand earthquakes. It was found that such buildings (c. 500 of 1-3 storeys) have been collapse free, except for one soft-storey building. The rest had walls of concrete or brick infill, and many were structurally asymmetric in plan. The most severely shaken of these buildings were those in the MM10 zone of the 1931 Hawke's Bay earthquake. In the above study it was reported that 45 buildings suffered little or no structural damage, with a further 34 suffering some modest cracking. This is illustrated by the similar findings illustrated in a slightly different way by the histograms of Figure 2(c) and (d).

Because the performance of the Napier/Hastings buildings was surprisingly so much better than might be expected of pre-code buildings, a more detailed analytical study was subsequently carried out on a selection of the buildings (van de Vorstenbosch et al., 2002). The buildings studied comprised 25 2- and 3-storey buildings of the c. 45 (of the original 80+) concrete buildings that still existed at the time of the study (1999-2000). In the structural analysis the buildings were subjected to loading spectrum provided by G McVerry for near source shaking on the appropriate Ground Class in an earthquake of Mw 7.8. This shaking is about twice the strength of that required by the 500 year loading of the then valid code (NZS 4203:1992). The ductility factor was assumed to be $\mu = 1.0$, based on the brittleness of the concrete, allowing a simple elastic analysis to be reasonably valid.

It was hoped that the analysis would explain the (good) performance of the buildings in reasonably unequivocal terms, especially invoking the positive role of the widespread use of structural walls. But this proved not to be the case. The results of the analysis were examined by comparing the theoretical applied loadings with estimated structural resistance available. Considering walls within buildings, this was done in terms of demand/capacity ratios, i.e. ratios of overturning moments to restoring moments, and ratios of applied shear forces to shear strength. As shown on Figure 5, it was found that these ratios ranged up to values $> 3$, and that many walls were predicted to fail in shear or overturning under the applied loading, whereas they clearly had not.

A lot of the mismatch between predicted and actual performance could be eliminated by assuming that the ground shaking was less than that of the hazard model, say one standard deviation less than the mean. While we have no strong motion records from that earthquake to help tune the theoretical loading, we do know from the intensity (MM10) that the shaking was very strong. A modest portion of the excess in overturning moments could be explained by the likelihood that rocking occurred, albeit without leaving any signs. Overall it must be concluded that more investigation, using more sophisticated analysis, is needed (and deserved) to explain why many of these low-tech buildings performed well beyond present-day expectation.

5 MICROZONING EFFECTS ON DAMAGE TO HOUSES IN NAPIER IN 1931

Another study of damage in this earthquake with surprising results was an investigation of the effects of ground classes on damage to houses in Napier (Dowrick et al., 1995). This was made possible by the discovery of archival records of the cost of damage to most houses in Napier, and their replacement values, in the Hawke's Bay Museum in Napier. These data were particularly pertinent because the degree of damage is most readily quantified in terms of a damage ratio,

\[ D_r = \frac{\text{Cost of damage to a house}}{\text{Replacement value of the house}} \]

The borough of Napier was microzoned according to the ground classes of the loadings code, resulting in the microzoning map shown on Figure 6, and the mean damage ratio $D_{rm}$ for one and two storey timber frame weatherboard houses were found for each of the three ground classes. The results for the single storey houses are shown on Figure 7, where it is seen that the softer or more flexible the ground, the lower the damage. It is seen from the clear separation of the confidence limits that the mean damage ratio for houses on the soft soil is statistically significantly different from those of the two stiffer ground classes.
These findings are contrary to what is commonly found for low-rise structures subjected to low to moderate strength of ground shaking. This result for the strong shaking experienced in Napier was initially surprising to some engineers, partly because comprehensive microzoning data sets from zones of very strong shaking are very rare. The result is explained by the non-linear soil behaviour that is caused by high amplitude shaking in soft soils, attenuating the short period vibrations that are responsible for most of the structural response of low-rise buildings.

6 CONCLUSIONS

Conclusions from this study are as follows:
1. The sizes and shapes of the innermost isoseismals of the 1931 Hawke's Bay earthquake are well controlled and the best defined of those for New Zealand's largest shallow earthquakes. The zone of the strongest intensity, MM10, is much shorter than the length of the fault rupture, contrary to the current assumption of strong motion attenuation models used world-wide. MM10 is probably the strongest intensity that can occur.
2. The Hawke's Bay earthquake was New Zealand's most destructive earthquake to date of property and human casualties (c.854 deaths and hospitalized injured).
3. The 80+ pre-code non-domestic buildings of brittle reinforced concrete, subjected to intensity MM10, performed surprisingly well, with only one collapse (a soft-storey building). A recent structural response study of 25 of these buildings failed to explain their good performance, predicting failure or serious damage to many of them. A further more sophisticated study is clearly warranted, so that we can benefit from understanding this important beneficial phenomenon.
4. The microzoning study of Napier that was carried out, was special in that it was very rich in high quality data in a zone of very strong shaking, in itself a rare occurrence world-wide in a built-up area. Damage levels to short-period structures (1643 single storey houses) were significantly lower on the softest of the three ground classes in the study area. This is consistent with attenuation of short period vibrations caused by non-linear behaviour of soft soil in large amplitude shaking.
5. It is remarkable that so much has been learned (so far!) from an event that occurred over 60 years before this series of studies began.

7 ACKNOWLEDGEMENTS

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8 REFERENCES


Dowrick, D.J. 1998b. Damage and intensities in the magnitude 7.8 1931 Hawke's Bay, New Zealand, earthquake, Bulletin of the New Zealand National Society for Earthquake Engineering, 31(3) 139-163.


Figure 1: Inner isoseismals of the 1931 Hawke's Bay earthquake (adapted from Dowrick, 1998b, and Dowrick & Rhoades, 2004).
Figure 2: Damage distributions for non-domestic buildings in Napier and Hastings in the 1931 Hawke's Bay earthquake. N1, N2 and N3 are the numbers of buildings of 1, 2 and 3 storeys (from Dowrick, 1998a; 2003).
Figure 3: The three-storey Empire Hotel in Napier in 1931. The brick front portion collapsed, while the rear portion of reinforced concrete was little damaged. (Reproduced by courtesy of the Alexander Turnbull Library, Wellington.)

Figure 4. Mean death rates with their 95% confidence limits in New Zealand earthquakes in the period 1840-2003 (from Dowrick & Rhoades, 2005c). While there has been zero deaths in timber houses, the confidence limits allow for the possibility of some occurring in future earthquakes.
Figure 5. Cumulative frequency plots for concrete walls of Napier and Hastings buildings, for (a) ratios of overturning moments to restoring moments, and (b) applied shear force to shear strength (extracted from van de Vorstenbosch et al., 2002).

Figure 6. Simplified ground class map for Napier (from Dowrick et al., 1995).
Figure 7. $D_m$ with its 95% confidence limits for single storey timber houses on three different ground classes in Napier in 1931. $N$ is the number of houses in each subset (from Dowrick et al., 1995).