

Precision achievable in earthquake loss modelling

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ABSTRACT: Many parts of the earthquake loss modelling process are subject to uncertainty, including such very basic inputs as the magnitude of the earthquake (for which the uncertainty is typically ± 0.3), the location of the earthquake (± 5 km?), and often the mechanism of the rupture process (strike-slip, reverse, etc). The above uncertainties alone can give rise to uncertainty factors of 2 to 3 in loss estimates, under favourable conditions, increasing to factors of 1000 to 10,000 under unfavourable conditions. Favourable conditions are high intensities and large magnitudes, unfavourable conditions are low intensities and small magnitudes. The reasons for this are explained.

In order to achieve reliable loss estimates the results of many thousands of scenarios may need to be averaged, with the input parameters being varied from one scenario to another. Use of a suitably randomised synthetic catalogue of earthquakes is one way of achieving this. Applying a 100,000-year catalogue to the whole of the present building asset of New Zealand suggests that the mean return period for a loss exceeding \$1 billion is just 60 years. The most recent earthquake capable of generating such a loss was the Hawke's Bay earthquake of 1931.

1 INTRODUCTION

A first-order earthquake loss model has been used previously to demonstrate that it should be possible to achieve a precision of about factor of 3 when estimating losses from moderate-large earthquakes affecting significant urban areas (Cousins, 2004). As a further step towards calibration the model is now compared with actual losses for the period 1990 to 2003. It is modified accordingly, and then used to estimate the return periods for \$1 billion or greater earthquake losses in New Zealand.

2 OVERVIEW OF THE FIRST-ORDER EARTHQUAKE LOSS MODEL

The main components of the loss model are an assets model, an attenuation model for earthquake shaking, and a model for damage ratio (Cousins 2004). The assets of interest here are buildings.

The assets model comprises estimated replacement values for all buildings in New Zealand, aggregated to approximately suburb-sized blocks. Within urban areas the spacing between the point locations is about 1km, increasing to 50-100km in sparsely populated rural areas. Whilst the coarseness of the data points means that the loss model has limited accuracy when modelling small-moderate earthquakes affecting rural areas, it is completely adequate for "big-picture" modelling of moderate-large earthquakes affecting towns and cities.

Ground motion in the loss model is expressed as the Modified Mercalli intensity (MMI) and is estimated using the attenuation model of Dowrick & Rhoades (1999). The impacts of microzonation are modelled as increments to the estimated "average" intensity, with the sign of the increment being governed by the type of ground (weak rock, soft soil etc), the liquefaction susceptibility of the ground, and the landslide susceptibility.

The “Loss” is obtained from:

$$\text{Loss} = D_r \times \text{Replacement Value},$$

where D_r is the vulnerability function, or “Damage Ratio”. The damage ratio is a function of the intensity of shaking and is given by:

$$D_r = \frac{\text{cost to repair}}{\text{cost to replace}}$$

For the loss model it is expressed as

$$\overline{D_r} = A \times 10^{\left(\frac{B}{\text{MMI} - C}\right)} \quad (1)$$

where $\overline{D_r}$ is the mean damage ratio, MMI the shaking intensity, and A, B and C are constants. For average houses the constants are assigned values of, respectively, 19, -12 and 4. Over the intensity range MM5.5 to MM9.5 the model then is a satisfactory representation of the damage ratio values published by Dowrick and co-workers (e.g. Dowrick 1991, Dowrick et al 2001).

Combining the two models gives a model for the attenuation of damage ratio. An illustrative example, for typical New Zealand houses, is shown in Figure 1.

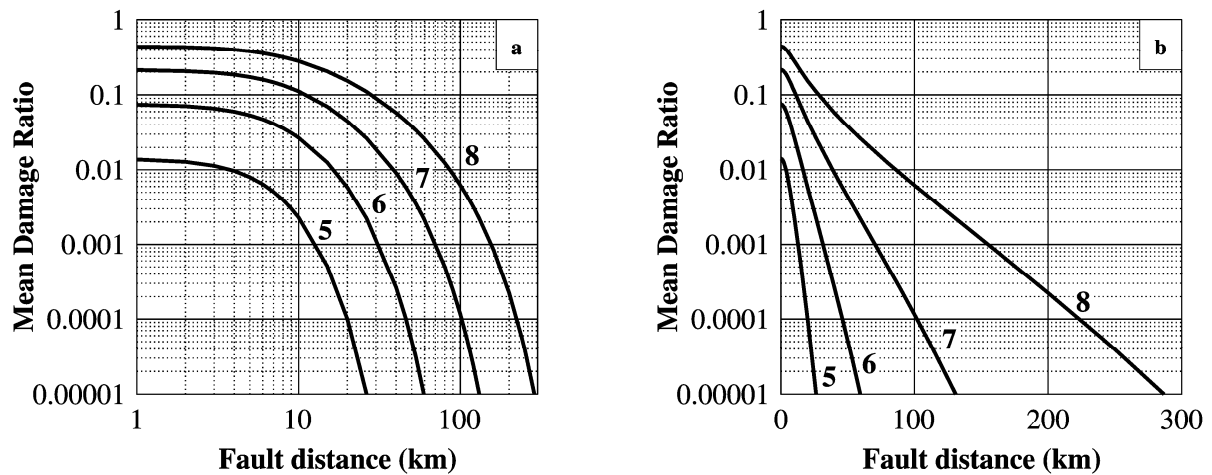


Figure 1. Attenuation of damage ratio for average New Zealand houses, for earthquakes of magnitude 5, 6, 7 and 8. Plot (a) shows that there is relatively little decrease in damage ratio within the first few km from source, while plot (b) shows that at larger distances there is almost a linear relationship between $\log(D_r)$ and distance.

3 APPLICATION TO EQC PAYOUTS

Claims data covering the 14-year period 1990-2003 were kindly made available by the EQC. In all there were approximately 20,000 valid claims, totalling a little over \$36 million, from approximately 1050 earthquakes. After (a) adding the excess of \$100 to each claim, (b) assigning \$50 to each claim that was rejected because it was less than the excess, and (c) scaling all claims to \$2004, the total damage estimate was \$49 million. From here on all damage figures are in \$2004.

Damage per earthquake ranged from \$0 to \$9.1 million with the most damaging event being the Weber earthquake of 13 May 1990. Losses were caused by earthquakes ranging in magnitude from 2.0 to 7.3.

3.1 Loss exceedance rates

Rates of “per-earthquake” loss exceedance are compared in Figure 2. In (a) the comparison is between

“actual” losses and those estimated for historical earthquakes over the 14-year period 1990-2003. Overall the agreement is good, with significant divergence for small (below about \$20,000) and large (above about \$5,000,000) losses. The divergence for large losses could simply be a result of uncertainty in the modelling, with the combined effects of variation in magnitude M (± 0.3) and between-earthquake variation in MMI (± 0.23) being illustrated. The divergence for the small losses is not attributable to uncertainty because the plotted results are effectively the averages of loss estimates for hundreds to thousands of earthquakes. Extrapolation is a potential problem area because the minimum magnitude used in the modelling was 3, and the minimum intensity was MM4.0, both well below the minima used in development of the attenuation and damage ratio models.

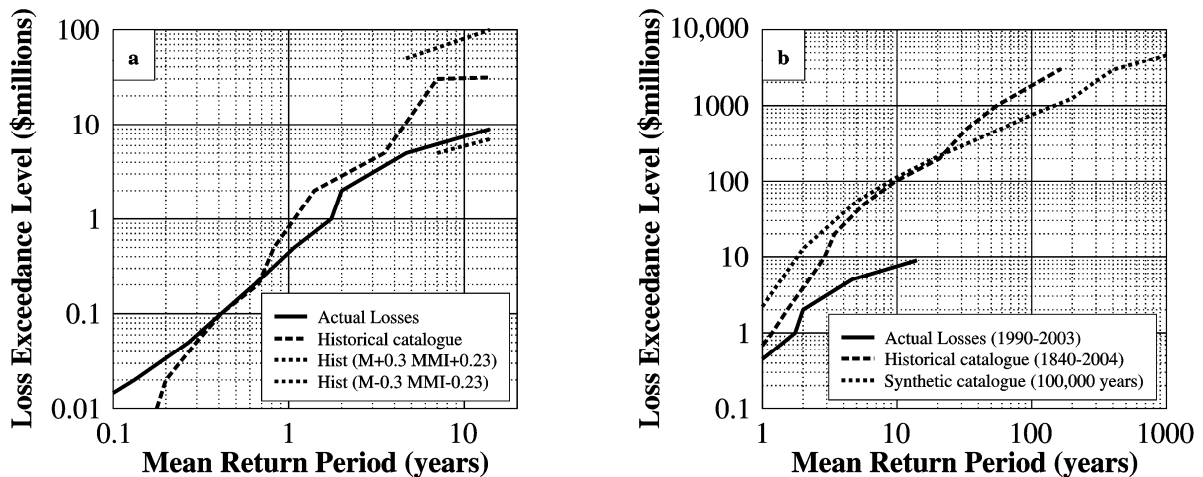


Figure 2. Rates of loss exceedance. Comparison of actual losses with estimates using various catalogues of earthquakes, comprising (a) historical earthquakes for 1990-2003, and (b) historical earthquakes for 1840-2004, and a 100,000-year long synthetic catalogue for New Zealand (Smith 2003). In (a) the dotted lines indicate the effects of uncertainty in magnitude M (± 0.3) and MMI (between-earthquake, ± 0.23) for the largest two losses.

In Figure 2(b) the comparison involves historical and synthetic catalogues much longer than 14 years. The historical catalogue covers the 165-year period from 1840 to 2004. It is known to be incomplete for earthquakes smaller than magnitude 6.5 until about 1940, hence the estimated occurrences of intensities of 7 and below in urban areas are deficient (Dowrick & Cousins 2003), and the mean return periods for losses up to about \$40 million will therefore be over-estimated. Despite this it results in loss estimates much greater than the actual losses for return periods of 1 to 14 years. This indicates that the last 14 years may well have been a period of abnormally low earthquake losses for New Zealand.

The synthetic catalogue covers a period of 100,000 years and represents the seismicity model of Stirling et al (2002). For losses above about \$400 million it gives return periods about double those based on the historical catalogue, perhaps indicating that the historical catalogue has above-average numbers of large earthquakes impacting what are now major urban areas.

3.2 Losses from individual earthquakes

Source details were able to be identified for a little over half of the earthquakes, 522, with the analysis once again being restricted to earthquakes having magnitudes of 4 or greater. As a first trial losses were estimated for the earthquakes using source details generally available within 24 hours of an earthquake, i.e. local magnitude (MI), location and depth, but no fault mechanism. The somewhat startling results are shown in Figure 3 in which the ratio of (estimated loss)/(actual loss) is plotted against the actual loss. The scatter in the ratio is very large, does not appear to have any strong link with the size of the actual loss or, as similar plots indicate, with either magnitude or focal depth.

Some improvement is obtained through the use of (a) moment magnitude (M_w) rather than MI and (b) fault mechanism. M_w values are available for about 25% of the plotted events, and at least rudimentary fault mechanisms for most. However, the results still appear far from acceptable.

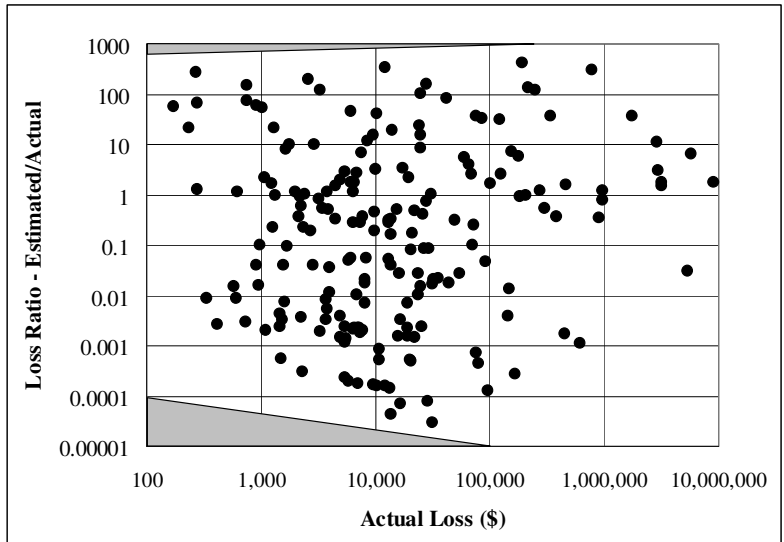


Figure 3. Comparison of estimated and actual losses for individual earthquakes (195). Events for which either of the losses is zero are not plotted (327), which means that for most of the earthquakes the ratio estimated/actual lies outside of the already wide range plotted. In most such cases the losses involved are below \$10,000. The grey triangles indicate the value range of this data and serve as a reminder not to forget it.

The key variable seems to be the “highest estimated mean intensity causing loss” (e.g. Figure 4). As an illustration of the concept consider an earthquake of magnitude 7.0. Intensity is likely to be MM10 near-source, and will decrease as the distance from source increases. At 100km it will have decreased to about MM6. If the closest buildings are 100km from the source then the highest intensity that can cause loss (to buildings) is MM6.

In Figure 4 there is reasonable agreement between the estimated and actual losses for intensities down to about MM5.7. Below 5.7 the two rapidly diverge, with the estimated losses essentially being zero for MM5 and below.

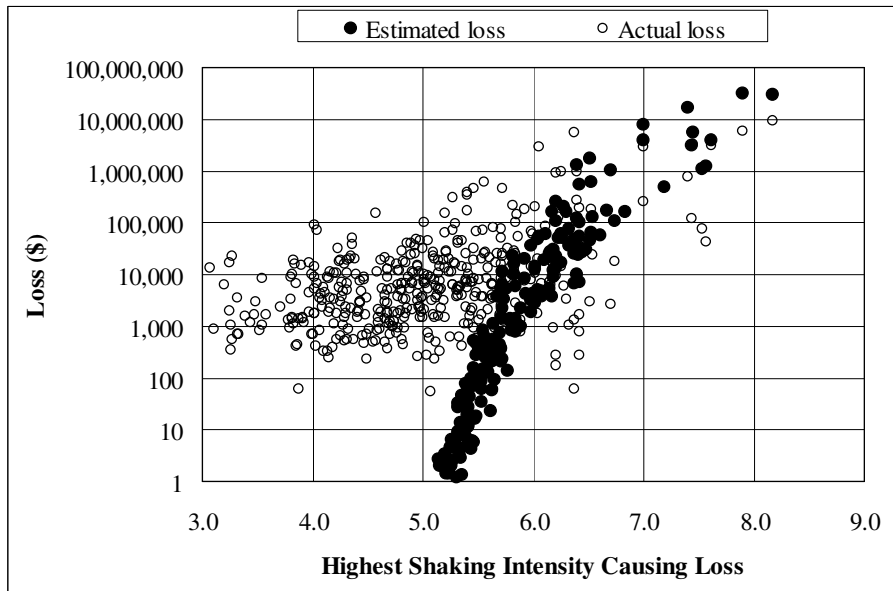


Figure 4. Relationship between losses and the highest estimated mean intensity contributing to them.

Below MM5 the actual losses are mostly fairly small, less than \$20,000, and are likely to arise from cosmetic damage to a few houses with particular weaknesses sited in places of above average shaking, i.e. small samples from the tips of fairly broad distributions. As such they will always be difficult to predict using models for mean intensities and mean damage ratios. Agreement can only be expected when the results of many trials are averaged, hence the good results of Figure 2(a). It would, however,

be desirable to achieve better individual results than those demonstrated in Figures 3 and 4. Two potential contributors to the small-intensity divergence are now discussed. One is the sensitivity to uncertainty in the basic earthquake parameters, and the other is the form of the damage ratio function.

4 UNCERTAINTY IN EARTHQUAKE SOURCE PARAMETERS

There is always uncertainty in reported earthquake source parameters, including in the magnitude, the location (hence uncertainty in the source-site distance) and the fault mechanism (which is often unknown). Add to this list uncertainty in attenuation modelling (± 0.2 MM “between-earthquake”, ± 0.3 “within-earthquake”) and in mean damage ratios (a factor of 2?). A few illustrative examples follow.

4.1 Uncertainty in magnitude

The uncertainty in magnitude is often given as ± 0.3 , but much larger variations can be encountered. Most attenuation modelling is based on the moment magnitude, whereas the magnitude most often given for an earthquake, particularly soon after an event when the studies needed for determining M_w have not been completed, is the local magnitude. The two can differ by 0.6 or more, particularly for earthquakes deeper than 60km.

The effect of change in magnitude can be profound, at least for the attenuation model illustrated in Figure 1. Interestingly the sensitivity of damage ratio to change in magnitude appears to depend mostly on the intensity at the location of interest (Figure 5) and is independent of the starting magnitude M . If the magnitude is small then the curves simply terminate further to the left than if the magnitude is large. For example, the highest mean intensity in an earthquake of magnitude 6.0 is MM8.5, hence the curves of Figure 5 would extend from MM5.0 to MM8.5 and no further.

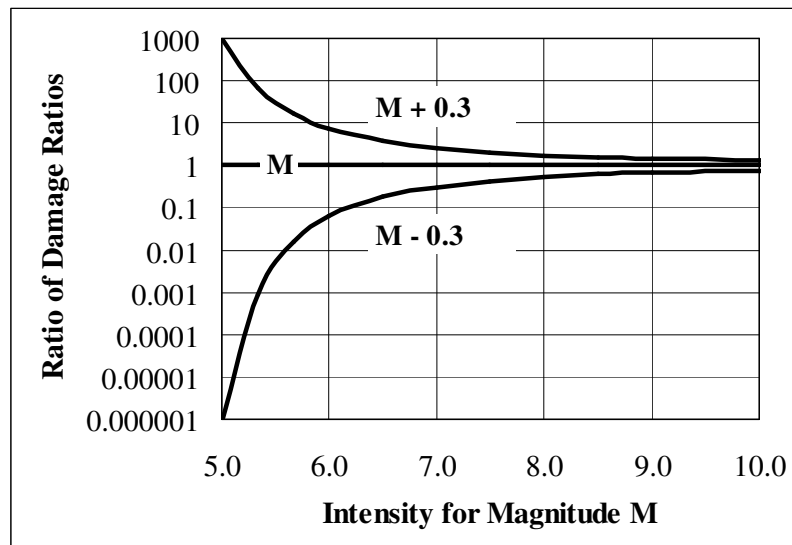


Figure 5. Effect of change in magnitude on damage ratio. If, for example, the intensity if interest is MM7.0 in an earthquake of magnitude M , changing M by ± 0.3 causes the damage ratio, at that location, to swing by about a factor of 3. If, however, the intensity of interest is MM5.0, the variation in damage ratio is orders of magnitude.

Over the period 1990-2003 many of the “highest intensities causing loss” have been smaller than MM5.0, hence fall in the regime where the effect of magnitude uncertainty is extreme. It is important to remember, however, that MM9 and greater is where the serious damage occurs. In a magnitude 7.5 earthquake centred on Christchurch, for example, the near-source intensity would exceed MM10.0, and the factorial change in damage to Christchurch’s housing on going from magnitude 7.2 to 7.8 would be about 1.6, corresponding to \$2.8 billion. Moving the epicentre 400km away decreases the intensity in central Christchurch to MM5.4 (for magnitude 7.5) and increases the factorial change in loss to 5000, corresponding to \$90,000 (i.e. a change from \$17 to \$90,000). The relatively small near-source factor of 1.6 is clearly more significant than the much larger far-field factor of 5000.

4.2 Uncertainty in distance

Two distance effects are apparent in Figure 1. Near-source, i.e. within about 5km, the change in damage ratio with distance is relatively small and does not vary greatly with magnitude. In the far-field, i.e. where the intensity is about MM6.0 and the damage ratio is about 0.0001, the sensitivity to distance is larger than near-source and increases with decreasing magnitude. Table 1 gives examples of the factorial increases in damage ratio for 5km decreases in distance.

Table 1. Factor by which damage ratio increases in response to a 5km decrease in source-site distance, for various sizes of earthquake and various distances from source.

Magnitude	5	6	7	8
Factor – near source	1.8	1.4	1.2	1.17
Factor – far field	6.0	2.3	1.5	1.19

4.3 Uncertainty in mechanism

Altering the fault mechanism of an earthquake causes changes in damage ratio similar to those arising from alterations in magnitude. When the intensity is high, MM9.0 or greater, the factorial change in damage ratio due to a change in mechanism from normal to strike-slip is less than 1.4. At intensity MM6.0 the factor is 20, and at MM5.0 it is 70,000.

5 FORM OF DAMAGE RATIO FUNCTION

Some of the extreme sensitivity discussed above is due to the form of the damage ratio function. When constant “C” of Equation 1 has a value of 4 then Dr asymptotes to zero at MM4.0, which causes extreme factorial decreases in Dr in the intensity range 5.5 to 4.0. It could be argued that this is reasonable behaviour, given that the definitions of the MMI scale in that range (Smith et al, 1992) imply minimal damage, but the fact that significant numbers of damage claims arise from estimated intensities below MM5.5 suggests that modification may be desirable. It did not prove possible to induce satisfactory behaviour by modifying the constants A, B and C of Equation 1, but the expedient of replacing the B/(MMI-C) part of Equation 1 with a linear function of MMI for low intensities did appear to be satisfactory. For intensities below MM7.0 Equation 1 is replaced by

$$\overline{D_r} = (A/21) \times 10^{(D \cdot \text{MMI} - E)} \quad (2)$$

where for average houses D is 1.65 and E is 14.22.

Some effects of the model change are shown in Figures 6(a), 7 and 8. The agreement between actual and estimated losses is still far from perfect, but is better than that obtained using the original model. The introduction of the new model affects only the losses having short return periods, with the result that there are no significant changes to Figure 2(b).

6 FUTURE LOSSES

Estimated losses for all buildings in New Zealand, (a) due to earthquakes in a 100,000-year synthetic catalogue, and (b) using the 165-year historical catalogue, are now estimated using the new model for damage ratio. Uncertainty in MMI attenuation is included in the modelling. The results using the synthetic catalogue, Figure 6(b), suggest that the mean return period for a loss of \$1 billion is about 60 years.

Four of New Zealand’s historical earthquakes would be capable of causing losses of \$1 billion or more if they were to occur today. For two, Marlborough 1848 and Wairarapa 1855, the area of greatest loss was Wellington, and for the other two it was Napier. Three of the damaging earthquakes occurred in a

15-year period in the late 1800's, followed by a 68-year gap to 1931. It is now 74 years since the last billion-dollar-plus earthquake of 1931.

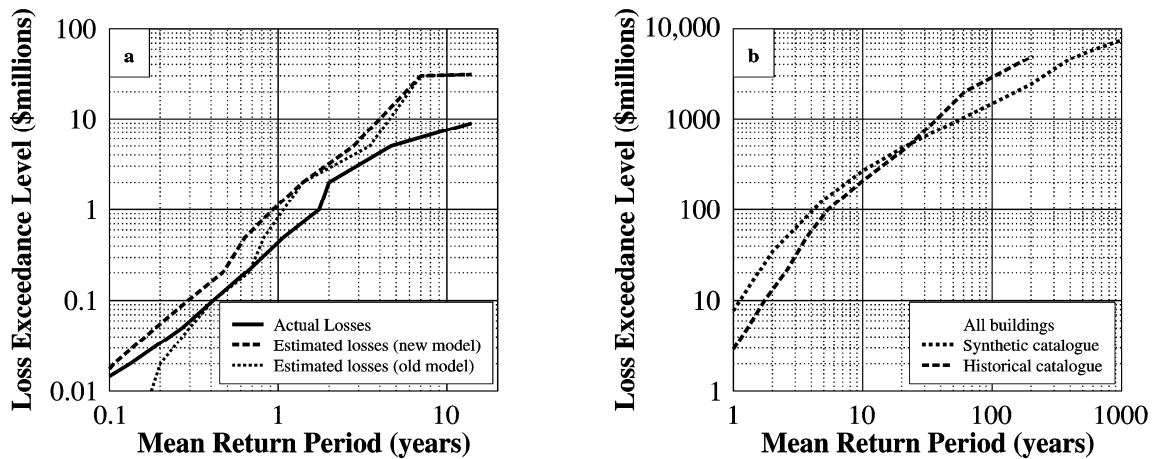


Figure 6. Rates of loss exceedance for estimated losses, (a) to houses from historical earthquakes for the period 1990-2003, (b) to all buildings from 100,000-year synthetic and 165-year historical catalogues. MMI uncertainty is included in the modelling for (b).

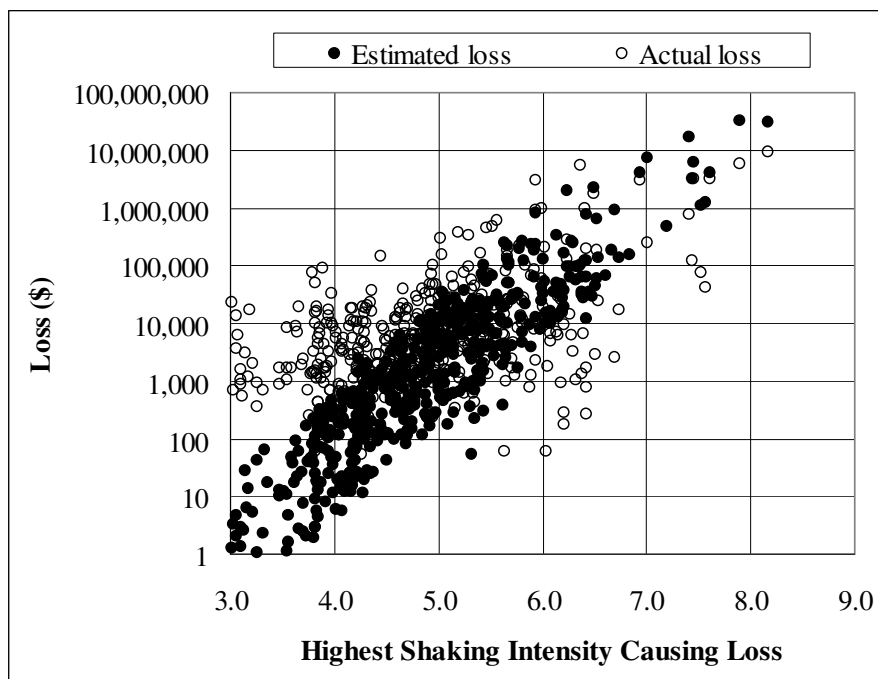


Figure 7. Comparison of estimated and actual losses

Table 2. Estimated losses for historical earthquakes impacting the current New Zealand building stock.

Earthquake Name	Magnitude	House Loss (\$billions)	Comm/Ind (\$billions)	All Buildings (\$billions)
Wairarapa 1855	8.1	3.5	2.0	5.5
Hawke's Bay 1931	7.8	1.6	1.0	2.6
Marlborough 1848	7.8	1.4	1.0	2.4
Central Hawke's Bay 1863	7.5	0.8	0.5	1.3

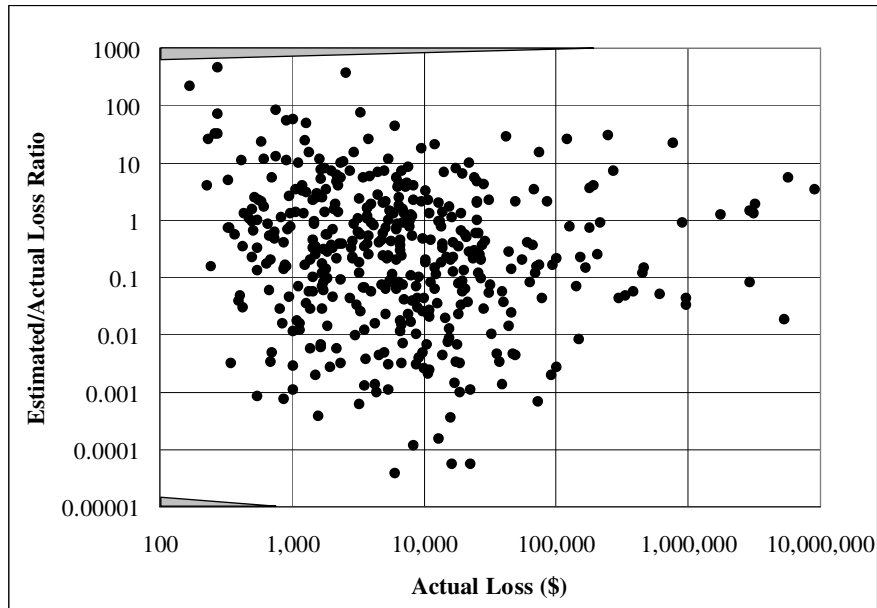


Figure 8. Comparison of estimated and actual losses for individual earthquakes (420). Events for which either of the losses is zero are not plotted (102).

7 ACKNOWLEDGEMENTS

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REFERENCES:

- Cousins, W.J. 2004. Towards a first-order earthquake loss model for New Zealand. *Proceedings, 2004 Conference of the New Zealand Society for Earthquake Engineering*, 19-21 March 2004, Rotorua. New Zealand Society for Earthquake Engineering, Paper No. 029.
- Dowrick, D.J. 1991. Damage costs to houses and farms as a function of intensity in the 1987 Edgecumbe earthquake, *Earthquake Engineering and Structural Dynamics*, 20 455-469.
- Dowrick, D.J. & Cousins, W.J. 2003. Historical incidence of Modified Mercalli intensity in New Zealand and comparison with hazard models”, *Bulletin of the New Zealand Society for Earthquake Engineering*, 36(1) 1-24.
- Dowrick, D.J. & Rhoades, D.A. 1999. Attenuation of Modified Mercalli intensity in New Zealand earthquakes”, *Bulletin of the New Zealand Society for Earthquake Engineering*, 32(2) 55-89.
- Dowrick, D.J., Rhoades, D.A. & Davenport, P.D. 2001. Damage ratios for domestic property in the magnitude 7.2 1968 Inangahua, New Zealand, earthquake, *Bulletin of the New Zealand Society for Earthquake Engineering*, 34(3) 191-213.
- Smith, E.G.C., Andrews, A.L., Davis, R.O., Dowrick, D.J., King, A.B., Lowry, M.A. and Wood, P.R. 1992. A revision of the Modified Mercalli intensity scale. *Bulletin of the New Zealand National Society for Earthquake Engineering*, 25(4) 345-357.
- Smith, W.D. 2003. Earthquake hazard and risk assessment in New Zealand by Monte Carlo methods. *Seismological Research Letters*, 74(3) 298-304.
- Stirling M.W., McVerry G.H. & Berryman K.R. 2002. A new seismic hazard model for New Zealand. *Bulletin of the Seismological Society of America* 92,1878-1903.