Estimated losses due to post-earthquake fire in three New Zealand cities

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ABSTRACT: Property losses due to earthquake shaking and post-earthquake fire are estimated for three urban areas in New Zealand, i.e. Wellington City, Napier/Hastings and Dunedin. Wellington dominates the losses for both shaking and post-earthquake fire. For any given return period, the shaking losses for Wellington are estimated to be about 5 times larger than those for Napier/Hastings which in turn are about 5 times larger than those for Dunedin. The relative importance of the fire loss depends on the return period. For return periods of up to about 800 years the loss due to post-earthquake fire in Wellington is expected to be much smaller than the loss due to shaking. For a return period of about 1200 years the two losses are equal, and for return periods of 2000 years and more the fire loss greatly exceeds the shaking loss. For Napier/Hastings the fire loss equals the shaking loss at a return period of about 4000 years, and for Dunedin the fire losses are much smaller than losses due to earthquake shaking for return periods up to 100,000 years. The probabilistic method used for estimating the losses, and limitations in the modelling, are described.

1 INTRODUCTION

One of the challenges in the modelling of losses due to post-earthquake fire is in satisfactorily handling the great level of variability. Fire losses are zero for most earthquakes but, occasionally, can greatly exceed the shaking losses. A promising approach uses the “Monte Carlo” method developed by Smith (2003) for estimating losses due to earthquake shaking. The first step of the method is to generate a synthetic catalogue of earthquakes, typically 500,000 years long, which faithfully represents the seismicity model of the country or region of interest. Losses are then estimated on a scenario basis for every earthquake in the catalogue, and, because there are many of them, it is possible to account explicitly for the various uncertainties inherent in the loss-modelling process.

For shaking, a list of the processes that are subject to natural variability and hence uncertainty includes the locations and magnitudes of earthquakes on active faults, the attenuation of shaking, and the vulnerabilities of the assets at risk. For post-earthquake fire it is necessary to add variability in the rates of ignition, suppression activities, and fire-spread, all of which depend on the strength of shaking, the time of day, climate, and probably other factors as well. Hence a long catalogue of earthquakes is needed, 1,000,000 years at least, and this in turn requires that computation be efficient.

A methodology has been developed and applied to three urban areas of New Zealand, i.e. Wellington City, Napier/Hastings and Dunedin (including Mosgiel). The three areas represent a major city in a region of high seismic hazard, a medium-sized city in a region of high hazard, and a medium-sized city in a region of low hazard. Napier in particular is of interest because post-earthquake fire was a major cause of loss in the 1931 Hawke’s Bay earthquake. We estimate that the fire loss for that earthquake approximately equalled the shaking loss. One of the aims of the modelling is to determine the probability of occurrence of such a severe fire loss.
2 LOSSES DUE TO EARTHQUAKE SHAKING

In order to keep computation times reasonable the aggregated buildings model of Cousins (2004) was used for most stages of the modelling, with detailed building-by-building data being used only for delineating burn-zones (Cousins et al 2003).

Shaking losses were estimated for comparison with the fire losses. For each earthquake in the synthetic catalogue the MMI (Modified Mercalli Intensity) was estimated at each of the aggregated data locations using the attenuation model of Dowrick & Rhoades (1999). One or other of their versions, i.e. “focal mechanisms”, “main seismic region” or “deep”, was used as appropriate to the earthquake source. Losses were then computed using an average vulnerability model (Figure 1).

For any given return period (Figure 2) the shaking losses for Wellington were found to be about 5 times larger than those for Napier/Hastings which in turn were about 5 times larger than those for Dunedin.

![Figure 1. Mean damage ratios for buildings.](image)

![Figure 2. Estimated shaking losses for the three study areas. The loss is that which will be equalled or exceeded for each particular return period.](image)
3 LOSSES DUE TO POST-EARTHQUAKE FIRE

3.1 Numbers of ignitions

An “ignition” is defined as being a fire that requires Fire Service intervention. Rates of post-earthquake ignitions are highly variable, being dependant on many factors including the shaking intensity, time of day and use of building. Historical data from mostly United States earthquakes, Figure 3, illustrate the degree of variability and the relationship with shaking intensity.

![Figure 3](image)

Figure 3. Effect of shaking intensity on rates of ignition. The top right data point is from the Hawke’s Bay, New Zealand, Earthquake of 1931 (estimate by authors). All of the others are from United States earthquakes from 1906 to 1989 (HAZUS 1997). The sloping dotted line is an approximate upper bound to the data, and the sloping solid line is the mean line used below in fire loss modelling.

Not included in the data are the many instances of zero ignition rate, which makes it difficult to derive an ignition rate model from the data alone. A reasonable expectation, however, is that nearly all occurrences of MM6.0 will not be accompanied by ignition, whereas the majority of occurrences of MM11.0 will be, and there will be some kind of steadily increasing trend between the two. A model that qualitatively matches that expectation and the data of Figure 3 is a linear relationship between the mean ignition rate, \( N \), (in ignitions per millions of \( m^2 \) of floor area) and shaking intensity, viz.

\[
N = \text{MMI} - 8.5,
\]

where the ignition rate is normally distributed about \( N \) and has a standard deviation of 1.0. Hence, for example, when the intensity is MM8.0 the mean rate of ignitions is -0.5, for which no real ignitions eventuate (Figure 4). Real ignitions occur only for positive rates, i.e. +0.5 (which accompanies 12% of occurrences of M8.0), +1.0 (7%), +1.5 (3%), +2.0 (1%) and +2.5 (0.3%). Most occurrences of MM8.0 are not accompanied by real ignition (Figure 5).

![Figure 4](image)

Figure 4. Assumed normal distribution of ignition rates at a shaking intensity of MM8.0. The black bars indicate rates of ignition that are positive and which, therefore, result in actual ignitions, whereas the white bars indicate rates that are zero or negative and which are not accompanied by ignition.
Figure 5. Probability that various shaking intensities will be accompanied by ignition. Twenty-three percent of occurrences of MM8.0, for example, are accompanied by ignition, whereas seventy-seven percent are not.

3.2 Active suppression

Some post-earthquake fires will be suppressed by the Fire Service, the actual number depending on the availability of water, ease of access to the fire sites, and many other factors. The ability of the Fire Service to control multiple fires will almost certainly decrease as the shaking intensity increases. In the absence of real data we adopted the relationship outlined below in Table 1.

Table 1. Numbers of fires able to be controlled by the Fire Service at various shaking intensities.

<table>
<thead>
<tr>
<th>Urban Area</th>
<th>MMI ≤ 8.0</th>
<th>8.0 &lt; MMI &lt; 11.0</th>
<th>MMI ≥ 11.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wellington</td>
<td>10</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Napier/Hastings</td>
<td>5</td>
<td>Numbers decrease linearly with increasing intensity</td>
<td>0</td>
</tr>
<tr>
<td>Dunedin</td>
<td>5</td>
<td></td>
<td>0</td>
</tr>
</tbody>
</table>

For modelling purposes we also assume that all suppressed fires will destroy the building of origin, with a loss of $300,000, but will not spread beyond the building of origin.

All fires not suppressed are assumed to spread, with numbers as in Figure 6. Governed by the relative levels of seismic hazard and property, Wellington is expected to have many more spreading post-earthquake fires than Napier/Hastings, which is expected to have many more than Dunedin.

Figure 6. Numbers of spreading fires for various return periods of earthquake.
3.3 Spreading fires and wind

For modelling the losses from spreading fires we used a static “burn-zone” model that has been developed for Wellington (Cousins et al 2003, Thomas et al 2002). The model relies on the specification of a “critical separation”, which is the maximum distance that a fire can jump from one building to another. To define the “burn-zones” we draw buffers with width equal to half the critical separation around the footprint of every building in the urban area, and then group together those buildings whose buffers touch or overlap. By definition, all buildings within a given burn-zone will be burned whenever any building within that zone is ignited, and fire cannot spread from one burn-zone to another. Fire losses are determined by randomly distributing ignitions amongst the buildings of the city and then summing the losses over the burn-zones so selected. Repeating this process many times enables the derivation of relationships like, for example, that between critical separation and loss.

In principle the critical separation could depend on many factors, including wind speed, season, and ground slope. Wind is very important because strong winds can carry sparks and burning brands over considerable distances. The relationship between wind speed and critical separation (Figure 7) has been derived from a combination of fire physics and historical data (Cousins et al, 2002). Under calm conditions, when radiation is the only fire-spread mechanism available, the greatest gap that a fire can jump is about 12m. For moderate to fresh breeze conditions (20 to 30 km/h) the dominant spread mechanism is piloted ignition, which involves radiant pre-heating followed by contact with wind-blown sparks. Gaps of up to 24m can by crossed by this method. For larger gaps, winds at speed sufficient to carry burning brands are required, i.e. near gale (50km/h) and stronger.

A problem with using the static fire-spread model is that it contains an implicit assumption that the size of the critical separation is the same for all directions of spread. This assumption is likely to be valid for calm to light wind conditions when radiation is the main contributing factor to ignition across a gap. As appears to have been the case for the post-earthquake conflagration in Napier in 1931, it may also be nearly true for “fresh-breeze” conditions (Heron et al, 2003). Relatively rapid and frequent changes in wind direction, as a result of eddying and swirling, is a realistic expectation for a significant proportion of the time, but not necessarily always. We have, therefore, imposed random reductions in the sizes of the “fresh-breeze” burn zones (i.e. critical separation of 20m), down to a minimum of 50% of the initial size.

Under high wind conditions, “near gale” and stronger, we would expect the influence of the prevailing wind to overshadow any deviations in direction due to eddying and swirling, in which case the assumption of uniform spread would nearly always be invalid. We have handled this situation by randomly decreasing the sizes of the selected burn-zones down to 10% of the initial sizes, based on the assumptions that the ignition points have been randomly placed in the burn-zones and that only property down-wind of the ignition points will be burned.

Detailed burn-zone distributions have been estimated for Wellington only. Assuming that all three study areas have similar building-type distributions to Wellington, and given that Napier/Hastings and Dunedin both are about half as large as Wellington, the Wellington distributions have been halved for application to the other two study areas.

![Figure 7. Effect of wind speed on critical separation for fire spread.](image-url)
4 SUMMARY OF PROCEDURE

For each significant earthquake in the synthetic catalogue (i.e. one giving an intensity of at least MM6 somewhere in a study area) the procedure followed was to:

- Estimate the shaking loss.
- Estimate the numbers of ignitions using floor area data from the aggregated buildings model.
- Allow for active suppression.
- Select a wind speed using recorded wind run data as a guide (NIWA 2003).
- Specify the critical separation (Figure 7), and thence the burn-zone distribution.
- Randomly distribute ignitions amongst the buildings, accumulate the losses, repeat 100 times, calculate the mean loss.

5 TREATMENT OF VARIABILITY

Natural variability and hence uncertainty are always present when earthquake losses are being modelled. Because we based our modelling on a catalogue containing millions of earthquakes we were able to address explicitly many of the most important sources of uncertainty. In most cases the procedure involved generating a random number at the point of uncertainty and using it to select from a distribution of values. The forms of distribution used were either normal, for ground motion parameters, lognormal, for damage ratios, or based on recorded data, for wind speeds. The parameters handled in this manner were as follows: characteristic magnitudes and locations of earthquakes, shaking attenuation (including both between-earthquake and within-earthquake variability), damage ratio (using a standard deviation of 0.3 in the logarithm to base 10 of the mean damage ratio), numbers of ignitions, wind speed, and placement of ignition points.

Three of the sources of uncertainty were investigated in a brief sensitivity study, i.e. the uncertainty in the mean numbers of ignitions, in the capacity of the Fire Service to suppress multiple fires, and in the spread of fire under high wind conditions.

6 RESULTS AND DISCUSSION

For any return period, the estimated losses due to post-earthquake fire in Wellington were about five times greater than in Napier/Hastings, and more than two orders greater than in Dunedin (Figure 8).

![Figure 8. Estimated post-earthquake fire losses for Wellington City, Napier/Hastings and Dunedin.](image-url)
The exposures in Wellington, Napier/Hastings and Dunedin were, respectively, $24.6 billion, $10.1 billion and $12.4 billion.

The curves of Figure 8 have an interesting and relatively abrupt transition from a state of steady increase with return period to a state of rapid increase. This could be interpreted as a change from non-spreading to spreading fires. For short return periods the shaking intensities are relatively low, there are few ignitions, and all are suppressed by the Fire Service. Under such conditions there is likely to be a steady increase in the numbers of ignitions, and hence losses, with increasing intensity. At some point the return period is reached where the numbers of ignitions exceed the capacity of the Fire Service, spreading fires occur, and the losses escalate.

The relative importance of post-earthquake fire can be assessed by comparison of fire losses with shaking losses (Figure 9). For Wellington, the average fire loss (solid heavy line) is much smaller than the shaking loss for return periods of up to about 800 years. The two losses are equal for a 1200-year return period, and for return periods above 2000 years the fire losses dominate. This, at least qualitatively, matches the worldwide historical experience that losses due to post-earthquake fire are usually much smaller than losses due to shaking but, rarely, can greatly exceed the shaking losses.

A similar pattern was obtained for Napier, with the fire and shaking losses reaching equality at a return period of about 4000 years. Thus the 1931 earthquake and fire could be regarded as a 4000-year event. For Dunedin there were no spreading fires for return periods below 4000 years, and the point of equality between fire and shaking losses was 100,000 years.

The broken lines in Figure 9 illustrate the sensitivity of the fire losses to variation in the numbers of spreading fires. Varying the numbers of fires by about ±8 leads to a threefold variation in the return period for any given loss level. To provide some perspective to the losses, there are on average 19 spreading fires at a return period of 1000 years, the average cost of each is $150 million, and the cost of each additional spreading fire is $300 million.

Figure 9. Comparison of shaking and post-earthquake fire losses for Wellington. The total replacement value of the buildings is about $25 billion. The labels “high”, “medium” and “low” refer to the numbers of spreading fires. “Medium” is the base case arising from the numbers of ignitions and numbers of suppressions derived in Sections 3.1 and 3.2 above (see Figure 6), “High” represents the base case plus 8 ignitions, and “Low” the base case minus 8 ignitions.

7 CONCLUDING REMARKS

The above work demonstrates a methodology that shows great promise for probabilistic evaluation of losses due to post-earthquake fire. Some significant areas of uncertainty remain, however, and while the results displayed in Figures 8 and 9 are our best estimates at present, they can be expected to change in the future as the modelling is further developed. Significant features that are yet to be
incorporated into the modelling are as follows:

- **Vegetation.** Under some conditions, at the end of a hot, dry spell of weather for example, vegetation between houses could be sufficiently flammable to enhance the spread of fire and so increase the fire losses.

- **Ground slope.** It is well known that fires spread more rapidly up-slope than either down- or cross-slope, which might lead to increased fire losses.

- **Fire resistant claddings.** Modelling carried out for the case of Wellington City indicates that such claddings could approximately halve losses from post-earthquake fire (Cousins et al, 2003).

In particular the large variation is fire loss due to variation in the mean numbers of ignitions should be noted. Because there is very little data available, the model that we adopted was based largely on our judgement and, therefore, could well change in the future when more data become available.

Perhaps the most important finding is the potential cost of each post-earthquake fire. At the 1000-year level of return period each spreading fire could cost, on average, $150 million. The desirability of either preventing post-earthquake ignitions, or immediately making strenuous efforts to suppress them, is clear.

8 **ACKNOWLEDGEMENTS**

The work reported above has been heavily dependent on models developed by or jointly with others, particularly Dave Heron of GNS and Geoff Thomas of Victoria University. Helpful advice has been received from reviewers Noel Trustrum and Nick Perrin. Funding was provided by PartnerRe Insurance, the New Zealand Fire Service Commission, and the Foundation for Research Science and Technology (Contract CO5X0209). Their support is appreciated.

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