Modelling Fires Following Earthquakes in New Zealand

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ABSTRACT :

Fires following earthquakes may develop into urban conflagrations with substantial loss of life and property. Two geographic information system (GIS) models linked to property and valuation data have been developed over the last six years as tools for estimating fire losses in Wellington by GNS Science and Victoria University of Wellington. The simpler static model determines the extent of fire spread and is suitable for probabilistic loss modelling. In the second model, a dynamic cellular automaton technique determines the rate and extent of fire-spread in response to factors including wind, radiation, sparking, branding, building separations and building claddings. Estimated losses for Wellington City vary between 5% and 60% of the total building stock, depending on wind speed, compared with about 30% for shaking losses only. More detailed studies of the Wellington Central business district, pilot studies incorporating the effect of vegetation between buildings and an assessment of the suitability of the dynamic model for pure vegetation fires has also been carried out. Validation against post-earthquake fires in Napier (1931) and Kobe (1995) and a small recent fire in Wellington has been carried out with good results. The dynamic model is being further developed to include effects of ground slope and as a potential fire fighting and/or planning and training tool for the New Zealand Fire Service.

KEYWORDS: Fires following earthquake, fire, earthquake, urban, GIS, modelling

1 INTRODUCTION

Fire following earthquake is an extremely variable problem. Losses from such fires can vary from insignificant (e.g. Izmir earthquake 1999, Turkey; ChiChi earthquake 1999, Taiwan) to disastrous (e.g. San Francisco 1906, USA; Tokyo 1923, Japan). The New Zealand experience, Table 1, mirrors that seen world-wide.

Table 1: New Zealand's experience of fire losses following major earthquakes (Magnitude and Intensity are Richter and Modified Mercalli Scale respectively)

Event Name	Date	Magnitude	Intensity	Fire loss
Marlborough	16th Oct 1848	7.8	8	none
Wairarapa	21st Jan 1855	8.1	9	none
Murchison	16th Jun 1929	7.7	9	none
Hawke's Bay	3rd Feb 1931	7.8	10	conflagration
Pahiatua	5th Feb 1934	7.4	8	none
Wairarapa	24th Jun 1942	7.2	8	minor
Inangahua	23rd May 1968	7.2	10	none
Edgecumbe	2nd May 1987	6.6	9	none
Gisborne	20th Dec 2007	6.8	7	none

Wellington City, which is the focus of this study, has many of the risk factors that together give a high possibility of post-earthquake conflagrations. Wellington is located in an active tectonic environment and is subject to large earthquakes and high levels of ground shaking. A major faultline, the Wellington fault passes through the city close to the central business district and the main access routes and supply routes for water cross the main Wellington fault. The city is located in steep hills surrounding a harbour and many access routes around the city have the potential to be blocked by landslides. Much of the inner suburban area consists of light timber framed houses, usually of two storeys that have small separation distances to adjoining houses. Most have timber weatherboard cladding (Figure1). The central city is reticulated with natural gas. Most of the older houses have poor connections between floor framing and sub-floor framing that can allow differential movement resulting in damage to services, including gas and electricity.

Figure 1: Wellington Inner Suburb.

As a consequence Wellington city has many potential ignition sources after a large earthquake. Fire spread is likely to be rapid and the resources to fight fires including water supply will be limited. A magnitude 7.5 earthquake on the Wellington fault used for this study, the same as that used for previous studies into shaking losses (Cousins & Heron, 2000).

The information on conflagrations in New Zealand is sparse. Conflagrations have occurred in many New Zealand towns in the late 19th and early 20th centuries (MacLean 1992). Timber buildings with timber claddings, lack of building separation, large number of ignition sources, and lack of ability to control the fires with poor water supplies and lack of adequate fire fighting equipment resulted in large fire losses. These factors are also likely to occur post-earthquake; hence conflagrations can be expected in areas of this type of building.

Previous post-earthquake fire spread models have tended to rely on previous data to calculate rates and extent of fire spread. Due to the relatively small number of post-earthquake fire conflagrations the amount of data is small and is dominated by several events that the best data is available from. The available data is difficult to interpret as the information required relating fire spread rates, minimum firebreak sizes to building sizes and types (including cladding types) and other factors such as wind are not always available.

2 THE GEOGRAPHICAL INFORMATION SYSTEMS MODEL

In this work two models were developed and they are described in more detail in a number of publications (Cousins et al 2002, Thomas et al 2003). The models will be briefly described with more emphasis on validation exercises and the results from the models.

2.1 Description of the Static Model

The static fire-spread model uses the idea of a “critical separation”, which is defined as being the maximum distance that a fire can jump from one building to another. A Geographic Information System (GIS) buffer operation is used to identify groups of buildings that are closer together than the “critical separation”. The process uses the building footprint and draws a “buffer” of width equal to half the critical separation around each building. Where buffers touch or overlap the corresponding buildings are taken to belong to a "burn-zone", with the assumption being that whenever any building in a particular burn-zone is ignited, all buildings in that zone will be consumed. Fires do not spread from one burn-zone to another because, by definition, the distances between burn-zones are always greater than the critical separation. The size of the critical separation depends on many factors including wind speed, ground slope, or active suppression (fire fighting). Using a combination of fire physics and empirical data we have developed an approximate relationship between the critical separation and wind speed, as shown in Figure 2 (Cousins et al 2002).

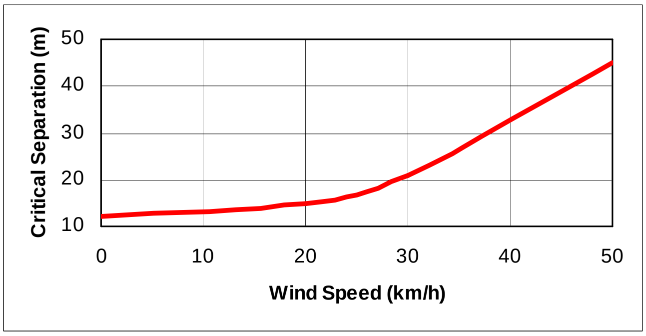

Figure 2. Effect of wind speed on maximum size of downwind gap that a fire can jump.

For gaps of up to 9m, radiation alone can be sufficient to cause spontaneous ignition. For gaps of up to about 12m a combination of radiant preheating and sparks (i.e. piloted ignition) is a likely mechanism. In windy conditions the combination of radiant preheating and sparks can cause ignition over a distance of about 20m, with the actual distance depending on the size of the fire and thus the intensity of radiation. For gaps larger than about 21m there is usually insufficient radiant preheating for piloted ignition, and 'branding' occurs. Branding occurs when there is a sufficiently strong wind to carry sizeable pieces of burning material across gaps. The static fire-spread model assumes that the fire will spread in all directions until it encounters a gap wider than the critical separation, and that the critical separation is identical in all directions regardless of the wind direction. The static model is very fast and hence is suitable for probabilistic analysis. It has been used to estimate losses due to fires after earthquakes in other parts of New Zealand as well as Wellington (Cousins & Smith 2004), and for the scenario of a repeat of the 1855, magnitude 8.2, Wairarapa earthquake (Thomas et al, 2005).

2.2 Description of the Dynamic Model

The dynamic fire-spread model uses a "cellular automaton" technique to model fire over time. A GIS program is used to divide the area of interest into a set of equal-sized square cells, and then each cell is allocated the properties of whatever fills it. For example, a cell mostly occupied by a building is deemed to be fuel and takes on the properties of the building, such as the cladding material, roof type, height, proportion of windows. A cell that lies mostly over areas with little or no fuel such as roads or parks is deemed to be empty, and thus a hindrance to the spread of fire. Spread of fire from one cell to another (represented as a change of cell state) depends on the initial state of the cell (burning or not), cell attributes (fuel or not), and a set of rules. During operation of the model the entire set of cells is scanned repeatedly, and during each scan multiple decisions are made as to whether the fire spreads from one cell to another. The time step is the interval between scans.

Fire can spread by direct contact, spontaneous ignition, piloted ignition and branding. A combustible cell directly adjacent to a burning cell will catch fire. Combustible cells near to a burning cell may also catch fire by spontaneous or piloted ignition or branding. Spontaneous ignition and piloted ignition require 12.5kW/m^2 and 30kW/m^2 radiation respectively. The distance at which radiation is sufficient to cause spontaneous and piloted ignition was calculated assuming a 4.5m high radiator, with the radiator width being multiples of 3.0m. The separation distance is assumed to be the average distance between cells of 1.5m, 4.5m, 7.5m and so on. The level of radiation is dependent on the size of the radiator and the distance to the target but is independent of wind direction. Piloted ignition also requires sparks. Spark spread distance is a function of wind speed and direction as shown in Table 2. Branding may occur, where items large enough to sustain combustion are thrown into the air by the fire plume and spread downwind. The incidence and spread distances of branding are dependant on wind speed and direction. Branding only occurs in the model at a wind speed greater than 50 km/hr with a maximum spread distance of 45 m.

Table 2. Fire spread as a function of wind speed and direction.

Wind Speed	Calm	20 km/hr	30 km/hr	50 km/hr
Spread Distance Downwind (m)	12	15	21	45
Spread Distance Cross and Upwind (m)	12	12	12	12

3 FIRE SPREAD VIA WINDOWS AND UNPROTECTED ROOFS

Both models described previously assumed that fire would not spread to buildings with non-combustible claddings. A survey of the buildings in the Wellington Central Business District (CBD) indicated that the dominant fire-spread mechanisms between buildings with non-combustible claddings are via non-fire-rated roofs or openings in the walls (Figure 3).

Figure 3. Buildings with unprotected roof and windows on boundary

Additional rules for these modes of fire spread were developed and tested for the dynamic model to allow its use in a typical city CBD (Heron et al, 2003). It is assumed that the windows in a burning building will break due to the heat. If the windows in the target building are broken due to earthquake shaking then fire spread is six times more likely. An example of the effect of fire spread via a roof, through intact windows and then broken windows are shown in Figure 4 for one ignition.

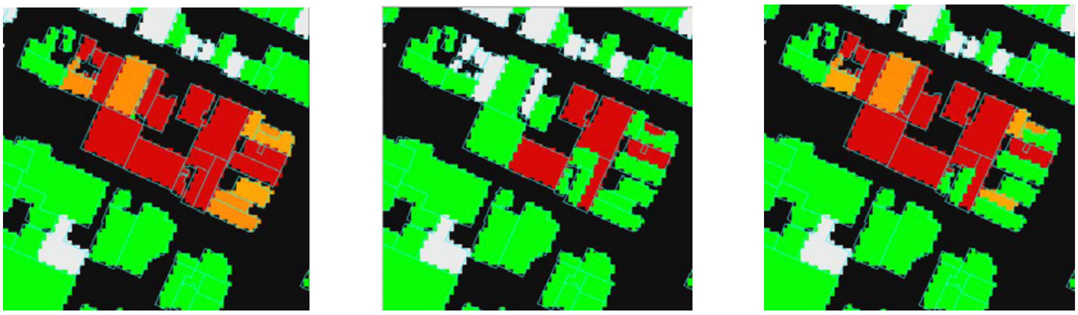

Figure 4. Effect of fire-spread for one ignition. White buildings have combustible cladding, green are non-combustible, black represents the burnt out zone. From left to right, spread by sparking and roof burn through only, including spread to buildings with intact windows and including spread to buildings with broken windows

4 EFFECTS OF VEGETATION AND MODELLING RURAL FIRES

Vegetation (between buildings and between suburbs) facilitates fire-spread. The scale of this effect is highly dependant on how dry the vegetation is and hence on recent weather conditions. Techniques were developed to incorporate vegetation into the static model (Heron et al 2003). The inclusion of vegetation data is difficult as there is no readily available data at suitable spatial resolutions. Even if available, the data is unlikely to be classified according to species and flammability. A pilot study was carried out in Karori, a suburb of Wellington. The critical separation was assumed to be 10m for buildings and 2m for trees. The critical separation is smaller for trees as they do not burn as hot as a compartment fire and they radiator is smaller. This study suggests that loss estimates including vegetation may be twice that of those made with vegetation included.

The dynamic fire-spread model could be used to determine fire-spread in rural areas. A rural fire spread model could be combined with the existing model to incorporate fire-spread between built-up areas via intervening bush and scrub. The existing dynamic fire-spread model was modified and applied to the spread of rural wildfire in a pilot study (Heron et al 2003). Whilst data on New Zealand vegetation fuel characteristics are far from complete, sufficient information was available to allow a model to be tested. While preliminary tests of the influence of vegetation fuel characteristics, wind strength, and presence of barriers could be effectively modelled, the cell-based technique could not accurately model the effect of wind or slope when the direction of maximum spread was not a sub-cardinal direction. This is not a drawback with the traditional ellipse-based technique for modelling rural fire spread; however ellipse and GIS based cellular models are not compatible.

5 VALIDATION WITH OTHER URBAN FIRES

The models have been compared with fires after the 1931 Napier Earthquake, the 1995 Kobe Earthquake and a more recent fire in suburban Wellington. The comparison with this recent fire in Wellington was good. The model also showed that without the fire-fighting efforts of the New Zealand Fire Service more property would have been lost.

5.1 The 1931 Hawkes Bay (Napier) Earthquake Fires

At 10:47 am on the Tuesday 3rd of February, 1931, an earthquake of magnitude 7.8 shook the Hawke's Bay region of New Zealand (Thomas et al 2006). Two hundred and fifty-six people were killed and there was severe damage to the commercial buildings of both Napier and Hastings. Damage to housing was limited due to the resilient timber construction of most houses. Many of the commercial buildings were of un-reinforced brick masonry which performed poorly. About half of the overall loss from the earthquake was caused by fire (Figure 5). The static model compared well with the extent of fire spread with a 19.5m critical separation.

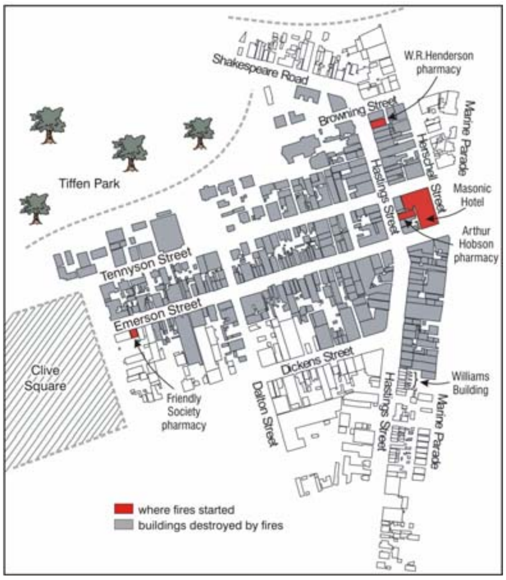

Figure 5 Map of the Napier CBD as it was in 1931, with North to the top of- the page.

A number of dynamic simulations were run using two accounts of wind changes according to Wright (2001) and Callaghan (1933). The best correlation was achieved using the account of Callaghan modified by increasing the duration of the midday northerly wind from 10 minutes to 40 minutes, as follows:

Time	Wind Direction (from)	Wind Strength
10:47 hours	270 (west)	Fresh breeze (30 km/h)
11:17	090 (east)	Strong breeze (40 km/h)
12:07	360 (north)	Fresh breeze (30 km/h)
12:57	090 (east)	Fresh breeze (30 km/h)
19:07	180 (south)	Fresh breeze (30 km/h)
00:07	360 (north)	Fresh breeze (30 km/h)

The results of one of theses simulations are shown in Figure 6. Increasing the duration of the wind from the north soon after midday caused a second fire crossing of Emerson Street, igniting the block bounded by Emerson, Hastings, Dickens and Dalton Streets at about 12:57. All buildings in this block were burning by about dusk matching some of the historical accounts.

Figure 6 Plan of Napier CBD showing the path of fire spread in the simulation

With insufficient water for fire-fighting, wind appears to have been the prime determinant of the scale of loss from the Napier fire. If the weather had been “calm” the total loss would have been much smaller than the actual loss, by about ninety percent (i.e. just two blocks at the northern end of Hastings Street would have been burned, with destruction of about 40 buildings instead of more than 400). Conversely, if the wind had been stronger than a “fresh breeze” the losses could have been somewhat greater. In the block south of Dickens Street and east of Dalton Street the fire “self-extinguished” at a group of single-storey iron-clad buildings.

Branding was excluded in this modelling. Branding does not require preheating of a flammable surface before ignition because the brand carries sufficient heat to allow ignition to occur at a cold surface. Branding has been observed at quite low wind speeds, 20 km/hr in Kobe, presumably in situations where large pieces of light-weight burning material are available and can be blown into the combustible interiors of damaged buildings (Hokugo, 1997). Branding could have been possible in Napier. If branding had been permitted as a spread mechanism then the increase in the strength of the easterly wind (at 11:17) that was needed to force the “Masonic” fire across Hastings Street may not have been required. Application of the models suggests that, apart from a lack of fire-fighting water, the wind was the main cause of the pattern and extent of fire spread.

5.2 The 1995 Great Hanshin (Kobe) Earthquake Fires

The model was also run to simulate two fires that occurred after the 1995 Great Hanshin (Kobe) earthquake (Kobe City Fire Dept., 1996). The results of one of these simulations for a fire situated near Mizukasa Park, Nagata Ward, Kobe City are shown in Figure 7. The overall comparison is good; however the model predicts fire spreading across streets at a later time than it actually occurred. This may be due to debris from damaged or collapsed buildings in the streets facilitating fire spread. In the model debris in streets is ignored. It should be noted that Japanese houses tend to have non-combustible claddings and fire spread occurs after damage to claddings exposing the interior whereas many New Zealand houses have combustible external claddings. It may therefore be unreasonable to expect the same model to work well for different countries. As the amount of historic data is small, calibration and validation of models of fire spread would be far more difficult and less accurate if only data from individual countries was of use.

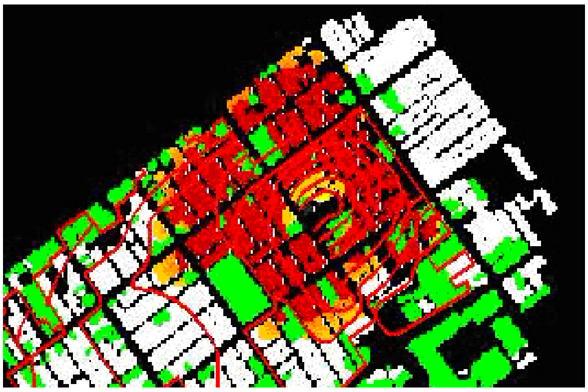

Figure 7. Comparison of fire spread using the GIS dynamic model with the fire in the vicinity of Mizukasa Park. White buildings are combustible, green is open spaces or non-combustible buildings, the contours are at one hour intervals and the red buildings show the extent of fire spread in the model.

6 RESULTS AND DISCUSSION

The static model gives two findings that may be generally applicable: - (i) the 50th percentile loss is roughly proportional to the number of ignitions and (iii) the good match with historical data as regards the extent of fire spread validates the link between critical separation and wind strength (Figure 2). The dynamic model is more comprehensive and allows for the estimation of the extent and rate of fire spread allowing for a wide range of factors such as wind speed and direction, branding, building separation, sparks and the combustibility of building claddings. This technique is more realistic, but runs more slowly.

In times when vegetation is dry and highly flammable the losses in suburban areas may double. Losses in the CBD increase significantly when fire spread via windows occurs, which more likely if windows have broken due to earthquake shaking. The effect of wind on post-earthquake fire spread is more apparent in Wellington than shown in other studies of other cities; possibly due to wider streets and larger building set-backs.

The static model tends to overestimate losses, and the dynamic model underestimates losses. The expected losses in Wellington are between US$75 and US$500 million in calm to moderate winds. In high winds when fire will spread across wider streets in outer suburbs expected losses could exceed US$4 billion. This should be compared with the expected shaking losses of US$5 billion and the total building stock of US$18 billion.

Mitigating post-earthquake fires is difficult. The probability of an earthquake, in itself a rare event, followed by fires that develop and in conjunction with very high winds, result in a low probability for a conflagration. However the consequences can be extreme. A low level of mitigation is of little use in a conflagration. This work shows that fire losses are proportional to the number of ignitions; hence the most cost-effective approach is to prevent ignitions. The majority of ignitions in previous earthquakes were due to damage to gas and electrical reticulation and appliances (Thomas 2005). Ignitions due to electrical faults can be minimised by ensuring power is shut off when an earthquake occurs and power is not re-connected until it is safe to do so.

Gas ignitions can be minimised by ensuring appliances are well secured preventing damage to connections. Ensuring buildings are secure on their foundations avoids rupture or damage to gas and electrical connections and also reduces the risk of shaking damage (Irvine & Thomas, 2008).

7 CONCLUSIONS

The GIS model with linked database containing materiality, cost information and other details is a suitable tool for determining post earthquake fire spread. Two modelling techniques using this database have been used, one static and one dynamic. Both correlate well with the New Zealand experience following the magnitude 7.8, 1931, Hawkes Bay earthquake. The dynamic model gives a good correlation with both the extent and timing of fire spread. Preventing ignitions is seen as the most cost-effective mitigation measure, particularly when combined with measures that also reduce shaking losses.

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REFERENCES

Callaghan, F.R. (1933). "The Hawke's Bay earthquake - General Description", *New Zealand Journal of Science and Technology*, **15(1)**.

Conly, G., (1980). The Shock of '31. The Hawke's Bay Earthquake, A.H. & A.W. Reed Ltd, Wellington, Sydney, London, Auckland.

Cousins, W.J. and Smith, W.D. (2004). Estimated Losses due to Post-Earthquake fire in three New Zealand cities, Proc. *New Zealand Society for Earthquake Engineering Annual Conference*, Rotorua.

Cousins, W.J. et al, (2002). Estimating risks from fire following earthquake, Institute of Geological and Nuclear Sciences client report 2002/60, Lower Hutt, New Zealand.

Cousins, W.J., and Heron, D.A. (2000). Integrated risk assessment model for Wellington City Council - Phase 2, Client Report 1998/135, Institute of Geological & Nuclear Sciences, Lower Hutt.

Heron, D.W, Cousins, W.J, Lukovic, B, Thomas G.C, and Schmid, W. (2003). *Modelling Fire Spread in and around Urban Centres*, Institute of Geological and Nuclear Sciences, Client Report 2003/96, Wellington.

Hokugo, A., (1997). The Performance of Fire Protection of Buildings against the Fires Following the Great Hanshin-Awaji Earthquake, *Fire Safety Science - Proceedings of the Fifth International Symposium*, International Association for Fire Safety Science.

Irvine, J. D and Thomas, G.C. (2008), Adequacy of existing House Foundations to resist earthquakes: the Cost-befit of Upgrading. *Bulletin of the New Zealand Society for Earthquake Engineering*, **41(1)**.

Kobe City Fire Dept. (1996). Research on Earthquake Fires in Kobe, November 1996, Kobe City Institute for Disaster Prevention and Safety and Tokyo Horei Publishers, Kobe, (In Japanese).

McLean G. (1992). New Zealand Tragedies, Fires and Firefighting, Grantham House, Wellington.

Thomas G.C, Cousins, W.J, Lloydd, D.A, Heron, D.W. and Mazzoni, S. (2003). "Post-earthquake fire spread between buildings, Estimating and costing extent in Wellington", *Fire Safety Science - Proceedings of the Seventh International Symposium*, International Association for Fire Safety Science.

Thomas, G.C, Cousins, W.J, Heron, D.W, Lukovic, B and Schmid, W. (2006). Post-Earthquake Fire Spread between Buildings – Correlation with 1931 Napier Earthquake, Proc. *New Zealand Society for Earthquake Engineering Annual Conference*, Napier.

Thomas, G.C. (2005), Fire-Fighting and Rescue Operations after Earthquakes – Lessons from Japan, *Proc. New Zealand Society for Earthquake Engineering Annual Conference*, Wairakei, March, 2005.

Thomas, G.C., Cousins, W.J. and Heron, D.W. (2005). Post-earthquake fire and the 1855 Wairarapa Earthquake. *Proceedings*, *Wairarapa Sesquicentennial Symposium*, Te Papa, Wellington.

Wright, M. (2001). Quake – Hawke's Bay 1931, Reed Publishing (NZ) Ltd., Auckland.