Modelling the spread of post-earthquake fire in Wellington city

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ABSTRACT: Large earthquakes are often followed by fire. Sometimes, because fire suppression can be difficult after large earthquakes, it develops into conflagration that in turn can lead to very serious loss of life and property. A GIS (Geographic Information System) model containing property and valuation data is shown to be a versatile platform for modelling the spread of post-earthquake fire in the urban setting. We describe two approaches. One uses a buffering technique to define potential "burnout" zones that are sampled randomly to give estimates of losses. From repeated sampling we are able to assess the probability of exceedance of various levels of loss as a function of the number of ignitions and the spacing between buildings. The other uses a cellular automaton technique for determining both the rate and extent of fire-spread in response to a wide range of factors including wind, radiation, sparking, branding, and individual separations of buildings.

1 INTRODUCTION

Fire following earthquake is an extremely variable problem. Losses from such fires can vary from insignificant (e.g. Izmit earthquake, Turkey, 1999; ChiChi earthquake, Taiwan, 1999) to disastrous (e.g. San Francisco 1906; Tokyo 1923; Kobe, Japan, 1995). New Zealand experience mirrors that seen world-wide. There are two aspects to the variability. One is a high level of variability in the number of ignitions, and the other is a high level of variability in the extent of fire-spread from each ignition. We are developing two GIS-based models for simulating the problem. One uses a buffering technique to define potential "burnout" zones that are then sampled randomly to construct estimates of losses. It is a very quick procedure and so we are able to carry out enough simulations to gain an overview of the fire-spread problem. Both aspects can be covered, i.e. the ignitions and the spread. The second is a comprehensive model for tracking the rate and extent of fire-spread in response to a wide range of factors including wind, radiation, sparking, branding, and separations of buildings. It is more realistic than the simple model but runs much more slowly. The models are in relatively early stages of development but both are showing considerable promise.

Wellington City, which we use as an illustration, has many of the risk factors that together give a high probability of post-earthquake conflagration. It straddles one of New Zealand's most active faults and so is highly likely to experience severe ground shaking. The main access routes and water supply lines cross the fault. Much of the terrain is steep so that many access routes around the city could become blocked by landslides. Much of the inner suburban area consists of light timber-clad houses, usually of two storeys, that are close to adjoining houses. The central city is reticulated with natural gas. Wellington City thus will have 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.

2 SCOPING THE PROBLEM

Within the GIS model we have spatial and other data for all buildings in Wellington City including the footprints and estimates of the heights, the floor areas and the replacement values. In order to scope the fire problem we simply generate buffers of specified width around each building footprint, Figure 1, and then make the assumption that when the buffers from adjacent buildings touch or overlap the fire can spread from one building to another. Thus we define “burnout zones” within which fire can propagate from building to building until all have been consumed. Note that we do not make any direct allowances for biasing factors such as wind, ground slope or active suppression. The reason for not doing so is that the sizes of burnout zones then do not depend on which building within a zone is ignited first.

Figure 1. Examples of burnout zones for a mixed residential/commercial area of Wellington City. Fire is allowed to spread from one building to another when the separation is 12m or less, i.e. whenever there is contact between the 6m-wide buffer zones around adjacent buildings.

We then randomly distribute a number of ignitions amongst the buildings and, for all burnout zones that are thus ignited, accumulate the total value of the buildings destroyed. Repeating this many times enables us to estimate the probability of exceedance of various levels of loss.

As an example consider the case where any gap exceeding 12m is assumed sufficient to prevent the spread of fire from one building to another. The width of “buffer” space around each building is therefore 6m and fire-spread is possible whenever adjacent buffer zones come into contact. Figure 1 is for such a situation and shows burnout zones containing from one to many buildings.

Our estimate of the replacement value of all buildings in Wellington City is $19 billion, distributed amongst 77,000 buildings. The 12m critical separation results in the delineation of 5300 burnout zones having replacement values ranging from $0 to $170 million. We randomly distributed 1, 3, 10, 30 or 100 ignitions over the buildings accumulating the losses for each trial. This was repeated 10,000 times for each number of ignitions (Fig. 2), and the entire procedure was repeated for critical separations of 24 and 48m (Fig. 3).

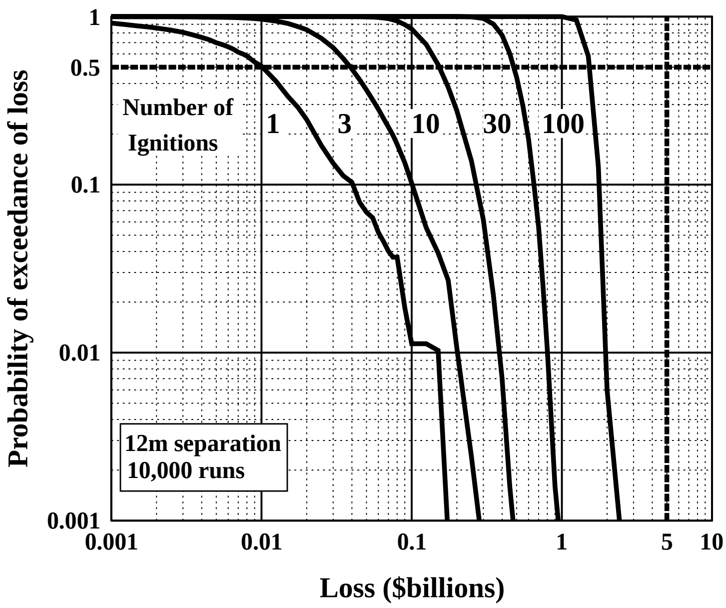

Figure 2. Probability of exceedance of various levels of loss for ignitions distributed randomly amongst the 77,000 buildings of Wellington City after they have been grouped into burnout zones defined by a critical separation of 12m. The losses are always considerably smaller than the shaking loss expected for a large earthquake on the Wellington fault ($5 billion, vertical dashed line). The horizontal dashed line is the 50th percentile loss.

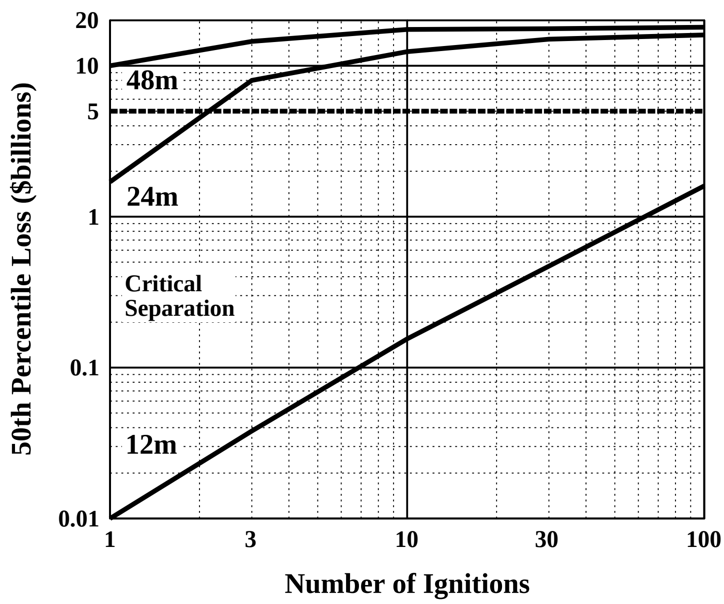

Figure 3. Effect of critical separation and the number of ignitions on the 50th percentile loss for fires affecting Wellington City. The horizontal dashed line shows the estimated loss, $5 billion, due to shaking damage in a magnitude 7.3 earthquake on the Wellington fault. Assuming 30-40 ignitions in such an earthquake the fire loss is much smaller than the shaking loss for a critical separation of 12m, but greatly exceeds the shaking loss for critical separations of 24m and above. The total replacement value for buildings in Wellington City is about $19 billion.

3 DISCUSSION OF THE SCOPING MODEL

Obviously we have made many assumptions and ignored some important factors in specifying the very simplistic rule that governs fire-spread in our illustration, but by choosing a wide enough range of critical separations we are able to span any realistic set of fire-spread conditions. The overall approach of defining a set of loss values by whatever rules are deemed appropriate, and then selecting from that set on a random basis to determine the probability of occurrence of various sizes of loss, is a valid way of gaining an broad understanding of a risk. In the case of post-earthquake fires one immediate aim is simply to assess whether or not such fires represent a significant problem, a task that is complicated by the very great variability of the hazard. Bearing in mind that the model is not fully developed, three tentative conclusions that can be drawn from Figures 2 and 3 are as follows.

- For small critical separations (i.e. less than about 15m) the 50th percentile loss is roughly proportional to the number of ignitions.
- The uncertainty in the loss decreases as the number of ignitions increases.
- The size of the critical separation has a dramatic and non-linear effect on the loss. If fire-spread can be halted by a 12m separation between buildings then the fire losses are not particularly serious, relatively speaking, but if a 24m separation is required then the fire losses are very serious indeed and could amount to near total destruction of the city.

To give some perspective to the fire losses, the estimated loss due to shaking damage to Wellington City's buildings in a large earthquake on the Wellington fault, which runs through the city, is in the region of $5 billion (Cousins & Heron 2000, Hopkins 1995). Based on data from post-earthquake fires in the United States an average number of about 30-40 ignitions could be expected in Wellington City following such an earthquake (Cousins et al 1991, Dowrick et al 1990, Lloydd 2001). For 30-40 ignitions Figure 3 indicates a 50th percentile loss of about $500 million for a critical separation of 12m, $15 billion for 24m and $18 billion for 48m. Respectively these losses are 10%, 300% and 360% of the shaking loss, or 2.6%, 80% and 95% of the $19 billion replacement value of all buildings.

We believe that the above conclusions will be widely applicable, though the detail of the numbers for any particular city will depend on the prevalent building separations and, even for the case of Wellington City, should be viewed with caution because the model is not yet fully developed. The estimated losses for the large critical separations are likely to be upper limits.

The scoping model gives some very interesting insights to the fire-spread problem. It is, however, just a simple static model that does not allow for biases such as wind, elevation and active suppression and, very importantly, it does not relate the critical separations to various sets of climatic and other conditions. All are essential for realistic modelling of fire-spread. A comprehensive fire-spread model that has the capacity to meet these and other needs is now described.

4 DEVELOPMENT OF A COMPREHENSIVE FIRE-SPREAD MODEL

The fire-spread model uses a "cellular automaton" spread technique in which the landscape is modeled as a regular lattice of cells, with each cell being assigned a set of states and values representing the physical environment. Spread of a factor, in our case fire, from one cell to another depends on the states, the values and a set of "rules". Possibilities can include the following: state (burning or not, if burning how fiercely), values (combustible or not), and rules (probability of ignition according to distances from burning cells, allowing for biases due to wind and elevation). The mechanics of the process is that the entire set of cells is scanned repeatedly in a raster fashion. During the scanning process cells are "activated" one at a time and whilst activated a cell's state is changed according to its current state and values, the states of surrounding cells, and the fire-spread rules. Because of the repetitive nature of the scanning process there is a built-in time step and hence it is straightforward to model time variant states such as the build-up and decline of a fire.

In our model the region is divided into 3m squares (cells). In selecting the cell size there is obviously a trade-off between detail and run-time – decreasing the cell size to 1m for instance would increase the run time by nearly a factor of ten.

4.1 *Rules for fire spread*

The fire-spread rules are obviously a critical component of the model. They have been developed from a combination of fire physics and historical data. We consider four modes of fire-spread, as follows:

- direct spread to a contiguous cell,
- radiation to a nearby cell with spontaneous ignition of the cladding,
- radiation to a nearby cell with piloted ignition of the cladding (sparking), and
- ignition by airborne flaming material (branding).

4.1.1 *Spread to contiguous cells*

Fire is assumed always to spread from a burning cell to combustible cells in contact with it. The only parameter is the time needed for the spreading from one (3m) cell to another, which we take to be 2.5 minutes based on anecdotal evidence of fire-spread rates throughout a typical New Zealand dwelling.

4.1.2 *Spread by radiation*

Each burning cell radiates heat flux across the gap between itself and nearby cells. The level of radiant heat flux incident on a nearby cell depends on the temperature and emissivity of the radiator and the radiation view factor. The view factor in the model depends on the number of contiguous cells that are alight and their arrangement.

The ignition of a heated building cell depends on whether or not the cladding material is heated sufficiently to cause either spontaneous ignition or piloted ignition. In each case the criterion is that the received radiation exceeds a critical level, which is a simplification because the level of radiation heat flux required for ignition does reduce somewhat with time.

Values reported for spontaneous ignition of timber range from 28 kW/m^2 (Drysdale 1986) to 33.5 kW/m^2 (Butcher & Parnell 1983). The value adopted for the fire-spread model is 30 kW/m^2, which also is the value used in the "deemed to satisfy" provisions of the New Zealand Building code (BIA 2000).

Similarly the value for piloted ignition varies from 10.0 kW/m^2 (long duration exposure for timber specimens in a cone calorimeter (Tewarson 1995)) to 18.0 kW/m^2 (30 minute exposure in the open as used in the "deemed to satisfy" provisions of the New Zealand Building code (BIA 2000)). The value adopted in the fire-spread model is 12.5 kW/m^2.

4.1.3 *Radiation with spontaneous ignition*

Whenever the radiation incident on a combustible cell exceeds 30kW/m^2 the cell is assumed to ignite spontaneously. Wind is assumed to have no significant effect. For simplicity in modelling the radiation from a burning cell is assumed to be "visible" through other cells that are on fire. Although this cannot be justified on a physical basis and might be expected to cause unduly rapid fire-spread across small gaps, it appears to have little effect. Theoretical modelling shows that ignition will occur when a combustible cell is 3m (1 cell spacing) from a single burning cell, 6m from two burning cells, 9m from 5 burning cells, but does not occur if the separation distance is greater than 12m (4 cell spacing).

4.1.4 *Radiation with piloted ignition (sparking)*

Fire-spread by this mode is dependent on the distance sparks can spread, on having a minimum level of incident radiation of 12.5 kW/m^2, and on a probability factor. Burning cells are assumed to produce sparks from 5 to 25 minutes after ignition, i.e. during the period of most intense combustion, and the distance the sparks can spread is dependent on both wind speed and direction. It is assumed that spread by piloted ignition occurs only downwind in a 90˚ arc and at wind speeds higher than 20 km/hr. Ignition is not guaranteed to occur – hence the model includes a probability factor that can be set by a user.

4.1.5 *Spread by flying brands*

Brands are airborne pieces of flaming material that can ignite combustible materials without any need for radiant preheating. Spread by flying brands is assumed to occur only for wind speeds higher than 30 km/hr and from 5 and 25 minutes after ignition. Brands are assumed to propagate in a 45˚ arc downwind and to spread up to 45m. As for piloted ignition there is a user-settable probability factor because a brand is able to cause ignition only if it lands on a combustible materials such as timber roof shingles or bitumen. On a sloping roof it is likely to fall off, or roll into the gutters where there is sometimes accumulated plant material that could be ignited. The likelihood of branding being a means of fire-spread is less in Wellington than regions such as southern California because the majority of roofs in Wellington are of galvanised iron.

5 DISCUSSION OF THE FIRE-SPREAD MODEL

As an illustration of the effect of wind speed the fire-spread model has been run for Wellington City with 27 randomly located ignition points. Twenty-seven was the mean number of expected ignitions based on historical data (Lloydd 2001). There were four runs each with a different wind speed but using the same set of ignition points and with the probability for spark ignition set to 1. Buildings with non-combustible claddings were assumed not to burn unless selected as one of the ignition points in which case the fire was able to spread to adjacent combustible buildings.

The estimated losses (Table 1) varied from 0.3 to 1.5% of the exposure of \$19 billion. The losses were much smaller than the 2% estimated for calm to moderate wind speeds in a previous study (Cousins 1990), but the previous study permitted fire to spread to buildings with non-combustible claddings and was based on 40 ignitions for Wellington City.

Table 1. Effect of wind speed on estimated losses from 27 ignitions.

Wind speed (km/h)	0	20	30	50
Number of buildings burned	235	263	272	1122
Area burnt (1000 m^2)	37	39	39	97
Loss (\$millions)	66	73	74	286

The effect of allowing for piloted (spark) ignition of buildings in the downwind direction is apparently not very great for low to moderate wind speeds as shown by the relatively small increase in total loss from the calm to the 30 km/h scenarios. In contrast the combined effect of sparking and branding at a wind speed of 50 km/h is quite large. Note, however, that all of the wind-affected results depend very much on the probabilities of ignition assigned to the sparking and branding modes of fire-spread. In our model we assume that branding occurs only at wind speeds greater than 30 km/h. In Kobe 20 instances of branding were reported even though the wind speed did not exceed 22 km/hr (Hokugo 1997). More development and calibration of the model are clearly needed in this area.

The low level of loss in calm conditions may be attributed to the relatively large road widths in Wellington (McIndoe 2001). In the outer suburbs road reserves are of the order of 20m wide, with town planning requirements prohibiting building within 3.0m of the front boundary. This creates an "across-road" gap of 26m between buildings. In the inner suburbs the road reserves are smaller, but timber buildings (mostly dwellings) tend to be built back from the boundaries and the separation distances across streets are rarely less than 15m, which in the model prevents fire-spread except in the downwind direction.

At this point it is relevant to refer back to Figure 3 which shows that once fires are able to cross a gap of about 24m then fire losses for Wellington City become severe.

Some important factors are not yet accommodated in the model. Neither ground slope nor vegetation is considered. Both could either enhance or hinder fire-spread depending on particular conditions. Fire-spread between buildings with non-combustible cladding has been ignored in the above trials, but will occur in some situations particularly when the cladding is damaged. In addition many large buildings are interconnected with others and the closures in penetrations may not be secure after an earthquake.

6 FUTURE DEVELOPMENT OF THE MODELS

Both fire-spread models are at an early stage of development. Future plans include:

- improved modelling of building height and ground slope,
- allowing for enhanced spread between damaged buildings,
- finer-resolution modelling in high-value areas,
- accounting for vegetation – both large blocks of sometimes highly combustible scrub/trees between suburbs and small plantings of shrubs and trees between individual buildings,
- carrying out a variety of sensitivity studies,
- calibration against known conflagrations (especially the Napier conflagration of 1931), and
- estimating impacts on people.

7 CONCLUSIONS

A GIS system with linked database containing building-specific data such as footprints, materiality, replacement values and other details shows great promise as a tool for modelling the spread of post-earthquake fire. Two modelling techniques using the system are being developed.

A simple buffering technique for defining potential "burnout" zones provides an overview of potential losses and gives three findings that may be generally applicable, i.e.

- the 50^{th} percentile loss is roughly proportional to the number of ignitions,
- the uncertainty in the loss decreases as the number of ignitions is increased, and
- the loss depends in a highly non-linear manner on the size of gap that fires can jump.

Estimated fire losses have been compared with shaking losses for a large earthquake impacting Wellington City. Assuming 30-40 ignitions in such an earthquake the fire loss is about 10% of the shaking loss when a building separation of 12m is sufficient to prevent fire spread, but greatly exceeds the shaking loss when separations of 24m and above are necessary. This may be a consequence of the prevalent road widths in Wellington.

A “cellular automaton” technique supports a comprehensive model that allows for estimation of the rate and extent of fire-spread as determined by a factors such as wind speed and direction, branding, building separation and the combustibility of cladding materials. The comprehensive model is more realistic than the simple buffering one but runs much more slowly.

The effect of wind on fire-spread is markedly non-linear. In part this could be due to the wide “across-street” separation between buildings in some parts of Wellington.

The “buffer” model has application in scoping the extent of the fire-spread problem and in quickly assessing the effectiveness of large-scale mitigation measures. It can also be used to identify those parts of a city where conflagration could be a problem and where more detailed modelling should be undertaken. The comprehensive model has application in detailed investigation of mitigation measures and for response planning during fire emergencies.

8 ACKNOWLEDGEMENTS

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