The Northridge, California, earthquake of 1994: fire ignition by strong shaking

M.D. Trifunac* & M.I. Todorovska

University of Southern California, Los Angeles, CA 90089-2531, USA

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The Northridge earthquake contributed unprecedented detail and quality of data on strong ground motion and on its effects on man-made structures. About 110 fires have been attributed directly to the effects of this earthquake. Two hypotheses for the principal causative agents leading to fire ignition were examined: differential motion and strains in the soil, and inertial forces. The fire-ignition frequency is described with respect to: (1) simple measures of strain in the soil (via density of water pipe breaks, \( n \)), (2) occurrence of severely damaged buildings (via density of red-tagged buildings, \( N \)), (3) site intensity of shaking, \( (I_{MM}) \), and (4) inertial forces (via peak horizontal ground velocity, \( v_n \)). It is shown that the rate of fires (per unit area) ignited by earthquake shaking can be predicted by several empirical equations of comparable accuracy and in terms of common scaling parameters of strong ground motion. © 1998 Elsevier Science Ltd. All rights reserved.

Key words: 1994 Northridge earthquake, earthquake fires, fire ignitions, damage, strong ground motion.

1 INTRODUCTION

Examples of devastating fires caused by earthquakes occurred in San Francisco during the 1906 earthquake (58 earthquake-related fires), in Tokyo following the 1923 Great Kanto earthquake (about one third of one million houses were burnt), and in Fukuji (Japan) during 1948 earthquake (2000 houses burnt). Many earthquakes have triggered fires in California (e.g., 13 fires by the 1933 Long Beach, 109 fires by the 1971 San Fernando, six fires by the 1984 Morgan Hill, 26 fires by the 1987 Whittier-Narrows, and 41 fires by the 1989 Loma Prieta earthquake). Although the fire loss has usually been small, even following numerous simultaneous ignitions, a potential for life threatening conflagrations exists during strong winds in densely built areas.

The analyses of potential risk from conflagrations consist of three parts: ignition frequency, fire-spreading models and fire suppression. The ignition rates, usually per area of built structures, are scaled empirically from peak ground acceleration, site intensity, or damage frequency of buildings. This paper presents an analysis of ignition rates of fires following the Northridge, California, earthquake of 17 January 1994 (\( M_L = 6.4 \), focus at 118°-55° West longitude, 34-21° North latitude, and at \( H = 18 \) km depth). The emphasis is placed on correlation with different characteristics of strong ground motion and its consequences, e.g., number of red-tagged buildings per unit area, \( N \), number of water pipe breaks per unit area, \( n \), and the distribution of site intensities, \( I_{MM} \), and of peak ground velocity, \( v_n \). The aim is to find the best descriptors (which can be scaled by or correlated with \( N, n, v_n, \) and \( I_{MM} \)) for the causative mechanisms and for the observed fire ignition rates. The number of fires reported for this earthquake is too small for a separate statistical analysis of the different types of fire ignition (e.g., electrical, natural gas and combustible chemicals). Also, high rise buildings are not considered in this paper.

2 THE DATA

Maps showing locations of fires caused by the Northridge earthquake were presented by the Earthquake Engineering Research Institute (EERI). Gas-related fires, responded to by the Los Angeles Fire Department (LAFD), were

*Corresponding author. Tel: 001-213-740-0570; Fax 001-213-744-1426.
summarized by Honegger (D. G. Honegger, pers. comm. 1996) and Strand (1994). While the data on gas-related fires appear to be reliable and final there will be future analyses and interpretations of other reported fires, and the total number and location of earthquake-caused fires may change. The fires presented by the EERI (1994) extended from Venice Beach along the Pacific coast to Santa Clarita in the North, and from the western edge of San Fernando Valley to Pasadena in the East. The analysis in this paper focuses on two regions, San Fernando Valley and Los Angeles, shown by rectangles in Fig. 1, and only a subset of the available fire data is used. These regions were chosen because of uniform coverage and because of availability of other supporting data and analyses (e.g., frequency of occurrence of red-tagged buildings; density of breaks in water pipes; distribution of peak velocities; and refined estimates of Modified Mercalli Intensities) which will be used in the presented analysis. In Fig. 1 the location of gas-related fires is shown by diamonds and of other than gas-related fires by triangles. The densely shaded and the hatched patches show, respectively, areas where the number of reported breaks in water pipes $n > 6$/km² and the number of red-tagged buildings $N > 5$/km². Assuming fairly uniform distribution and quality of water pipes and of buildings in the regions studied (consisting mostly of typical residential neighborhoods and wooden frame construction), large $n$ and $N$ could be used respectively as indicators of large strains in the soil and of large amplitudes of ground shaking (large Modified Mercalli Intensity, $I_{MM}$; and large horizontal peak ground velocity, $v_w$). The areas with $n > 6$/km² probably experienced some kind of nonlinear soil response, and the areas with $N > 5$/km² had high concentrations of severely damaged buildings. The lightly shaded areas in the background of Fig. 1 indicate rock and the white areas indicate sediments.

3 ANALYSIS

3.1 Ignition rates for general fires

We explore eight empirical scaling equations predicting the rate of fire ignition, $m$, as a function of several ground shaking and damage parameters. A subscript is added to $m$ to indicate the scaling variables for the particular equation (e.g., $I$ and $v$ refer to the site intensity, $I_{MM}$, and peak horizontal ground velocity, $v_w$; $N$ and $n$ refer to the number of red-tagged buildings and of breaks in water pipes). The unit area to measure the rates was chosen to be 25 km². The two regions studied were divided into $5 \times 5$ km² blocks, and the
fire ignitions, red-tagged buildings and water pipe breaks were counted in each block. Data from twenty blocks in the San Fernando Valley and nine blocks in the Los Angeles region were analyzed. We note that the statistics for red-tagged buildings and for water pipe breaks were derived based on a unit area of $1 \times 1$ km$^2$. Larger block size was used for this analysis because the data on fires is more sparse (75 fire ignitions occurred within the 29 blocks studied). Block size (of 25 km$^2$) was chosen to be large enough to find multiple ignition occurrences in individual blocks.

3.1.1 Rate of fire ignition vs soil strain ($m_n$)

Fires may be caused by breaks in gas lines to trailers and buildings (above ground level) or in gas lines buried in the soil (e.g. the 22 inch gas line under Balboa Boulevard). These breaks result form large strains and differential motions within soil, and between the soil and the building foundations. The geographical distribution of strains and of differential motions in the soil can be inferred from the density of observed water pipe breaks, detailed geotechnical investigations and, indirectly and roughly, from the reduction of peak amplitudes of recorded strong ground motion. Near the ground surface the strains in the soil can be computed either from peak ground velocity, $\ddot{v}_m$, or from the density of water pipe breaks, $n$. Then it becomes possible to explore whether the fire ignition rate can be correlated with the observed density of water pipe breaks. Test this hypothesis, for each of the $5 \times 5$ km$^2$ blocks, we calculated the number of water pipe breaks and the number of fire ignitions. The open circles in Fig. 2 show the data. The vertical axis shows the number of fire ignitions per block, $m_n$, and the horizontal axis shows the average number of pipe breaks, $n$, per block. The line:

$$m_n = \begin{cases} 
0 & n \leq 15 \\
-0.698 + 0.0465n & 15 < n \leq 58.1 \\
-10.89 + 0.222n & 58.1 < n < 85.1 \\
7.46 + 0.00635n & n > 85.1
\end{cases}$$

(1)

describes the trend throughout the data. The last branch, for $n > 85.1$, is not based on the data. It has been chosen to bound (approximately) the estimates of $m_n$ in the areas where large concentrations of water pipe breaks (e.g. Reseda, Granada Hills and Sherman Oaks, Fig. 1) may occur. It is seen from Fig. 2 that the correlation between $m_n$ and $n$ is not good.

3.1.2 Rate of fire ignition vs rate of red-tagged buildings ($m_n$)

Many fires result from broken gas lines in buildings that experience excessive relative deformation and damage from severely shaken gas appliances (sliding and overturning water heaters; D. G. Honegger, pers. comm. 1996), problems in the electrical distribution systems and from broken containers of flammable chemicals (e.g. the Science Building at California State University, Northridge).

Fig. 2. Rate of fire ignitions, $m_n$, vs the rate of breaks in water pipes, $n$, both per 25 km$^2$. The open circles show the data. The line shows the average trends.

Starting with data from the 1923 Kanto, Japan earthquake, the ignition frequency of fires has been correlated with the damage or destruction frequency of the buildings. If $f$ is the rate (percentage) of fire outbreaks per household and $c$ is the rate (percentage) of totally collapsed households, Mizuno showed that:

$$f = 0.0464c^{2/3}$$

(2)

For totally collapsed structures ($c = 100\%$) this equation gives rate of fire outbreaks equal to 0.01 per household ($f = 1\%$).

In the area of 725 km$^2$ considered in this study (29 blocks, each with an area of 25 km$^2$) there were approximately 1197 red-tagged buildings and 75 earthquake related fires. This gives an average rate of fire outbreaks, per red-tagged building, equal to 0.063 or 6%.

It is estimated that in early 1994 there were 190,000 single-family dwellings (SDFs) within 10 miles of the epicenter of the Northridge earthquake, or an average of $\sim 683$ SFD/km$^2$. This gives an average rate of 1.5 $\times 10^{-4}$ or 0.015% fire outbreaks per SFD. Kobayashi cites the following rates of fire outbreaks per household for six earthquakes in Japan: (1) 0.22 $\times 10^{-4}$ for the 1983 Nihonkai-Chubu (JMA = 5); (2) 0.37 $\times 10^{-4}$ for the 1978 Miyagiken-Oki (JMA = 5); (3) 1.26 $\times 10^{-4}$ for the 1964 Niigata (JMA = 5); (4) 1.37 $\times 10^{-4}$ for the 1986 Tokachi-Oki (JMA = 5); (5) 2.02 $\times 10^{-4}$ for the 1923 Kanto (JMA = 6); and (6) 15.5 $\times 10^{-4}$ for the 1948 Fukui earthquake (JMA = 7). The intensity is on the JMA scale (Japanese Meteorological Agency). A conversion between JMA and MMI scales is provided by Wong and Trifunac. In spite of the differences in the definitions of 'SFD' and 'household', it is seen that the data from the Northridge earthquake gives fire ignition rates which are of the same order of magnitude as those in Japan.

The spatial distribution of damaged buildings is not uniform and depends on the variations of ground shaking, and of the building stock in the area. An inference on the
distribution of fires can be approximated from the distribution of red-tagged buildings, using correlation of the two determined from observed data. The correlation is determined similarly as for ground strains (via $n$) in the previous section (Fig. 2). Fig. 3 shows the data points (the vertical axis shows the number of fire ignitions per block, $m_N$, and the horizontal axis shows the average number of red-tagged buildings per block, $N$) and the trend:

$$
N = \begin{cases} 
0 & N \leq 15 \\
-0.545 + 0.0795N & 15 < N \leq 81.7 \\
4.05 + 0.0233N & N > 81.7
\end{cases}
$$

Both $m_N$ and $N$ in eqn (3) are per 25 km$^2$. From eqn (3) the average growth of the number of fire ignitions per red-tagged building is about 0.063. This rate is higher (0.0795) for $N < 81.7 / 25$ km$^2$, and then smaller (0.0233) for $N > 81.7 / 25$ km$^2$. Value of $N = 81.7 / 25$ km$^2$ corresponds to peak horizontal ground velocity $v_m = 110$ cm/s and to $I_{MM} = 8.3$. Assuming that the average shear wave velocity in the top 30 m of soil $\bar{v} = 300$ m/s, peak ground velocity $v = 110$ cm/s corresponds to strain factor $\tilde{\varepsilon}$ $v_m/\bar{v} = 110/30000 = 0.0037$, i.e. to $\log_{10} v_m/\bar{v} = -2.4$. It was found$^{1,2}$ that soil sites with $\tilde{\varepsilon} < 360$ m/s will begin to respond nonlinearly for $\log_{10} v_m/\bar{v} \sim -2.75$, and to fail for $\log_{10} v_m/\bar{v} > -2.4$, leading to reduction and to ‘smoothing’ of high-frequency strong motion amplitudes. Then, for $N > 81.7 / 25$ km$^2$ (i.e. $v_m > 110$ cm/s and $\log_{10} v_m/\bar{v} > -2.4$) the peak horizontal acceleration and velocity of ground motion may be reduced enough to ‘slow down’

![Fig. 3. Rate of fire ignitions, $m_N$, vs the rate of red-tagged buildings, $N$, both per 25 km$^2$. The open circles show the data. The line shows the average trends.](image)

![Fig. 4. Revised distribution of intensities of shaking during the Northridge earthquake, taking into consideration the observed peak ground velocities and the distribution of red-tagged buildings (after Trifunac and Todorovska).](image)
the rate of growth of fire incidence per red-tagged building. At this stage this can only be viewed as an interesting speculation because the number of data points for \( m_4 > 6/25 \text{ km}^2 \) is not sufficient to control the trend adopted by eqn (3).

3.1.3 Rate of fire ignition vs modified mercalli intensity \( (m_i) \)

The rate of fire ignition can be correlated with the Modified Mercalli Intensity, \( I_{MM} \), using the same procedure as in the previous two sections. The intensity map of Trifunac and Todorovskaya\(^6\) was used in this paper. Their map is a revised version of the map by Dewey et al.\(^{17}\) which is based on felt reports at selected sites. Due to the relatively small number of these sites in the severely shaken area, the map by Dewey et al.\(^{17}\) did not capture all of the observed variations in the degree of damage. Trifunac and Todorovskaya\(^6\) revised this map to be more consistent with the observed rates of damage as follows. They divided the two regions (San Fernando Valley and Los Angeles, Fig. 1) into \( 1 \times 1 \text{ km}^2 \) blocks, determined the number of red-tagged buildings and assigned to each block intensity of shaking from the maps of Dewey et al.\(^{17}\). Then they determined the average trend for the number of red-tagged buildings as a function of site intensity, for the areas with relatively uniform coverage with buildings (mostly typical residential neighborhoods). Then they went back to these areas and adjusted the intensity levels based on the observed rate of red-tagged buildings and using the average trend between the two. The revised map is shown in Fig. 4.

The data points for \( m_i \) vs the average of \( I_{MM} \) are shown by the 8 open circles in Fig. 5. For convenience, \( I_{MM} \) is treated as a ‘continuous real variable’ in defining the average intensity levels for given \( m_i \). Linear regression analysis gives:

\[
m_i = -37.94 + 5.37 I_{MM}, \quad I_{MM} \geq 7.07
\]

This trend is shown by the weak line in Fig. 5.

Fig. 6 shows the data on fire outbreaks per SFD (left scale) vs Modified Mercalli Intensity (bottom scale) for the Northridge earthquake (open circles) and for eight other California earthquakes\(^{18}\). The coordinates of the data points for the Northridge earthquake in this plot were determined from the data on the rate of fire ignitions \( (m_4) \) per \( 25 \text{ km}^2 \) vs \( I_{MM} \) (Fig. 5) as follows. The points in Fig. 6 correspond to \( m_4 = 1, 2, 3, 4, 5, 6 \) and \( 8 \) per \( 25 \text{ km}^2 \). The x-coordinate is the average value of \( I_{MM} \) for the \( 5 \times 5 \text{ km}^2 \) blocks with \( m_4 = 1, 2, 3, 4, 5, 6 \) and 8 fire ignitions. The y-coordinate is the value of \( m_i \) divided by the average number of SFDs in \( 25 \text{ km}^2 \text{ area} \) (total of \( \sim 190,000 \text{ SFDs} \) within 10 miles radius from the epicenter implies average of \( 683 \text{ SFDs/km} \), or \( 17,075 \text{ SFDs per} \) \( 25 \text{ km}^2 \)). The eight other California earthquakes\(^{18}\) are as follows: 1906 San Francisco (F), 1925 Santa Barbara (B), 1933 Long Beach (L), 1957 San Francisco (G), 1969 Santa Rosa (R), 1971 San Fernando (S), 1983 Coalinga (C) and 1984 Morgan Hill earthquake (M). Multiple entries for the same event, e.g. six S data points for the 1971 San Fernando earthquake, describe the fire ignition rates in different areas of the Los Angeles Metropolitan area (Los Angeles County, \( I_{MM} = 6 \); Pasadena, \( I_{MM} = 6 \); Glendale, \( I_{MM} = 6/5 \); Los Angeles City, \( I_{MM} = 7 \); Burbank, \( I_{MM} = 7 \); and San Fernando, \( I_{MM} = 9 \)).

For comparison, data points are shown for the five Japanese earthquakes\(^4\) (full circles) cited in the previous section: (1983 Nihonkai-Chubu, 1978 Miyagi-Oked, 1964 Niigata, 1968 Tokachi-Oki and 1923 Kanto earthquake). The data point for the 1948 Fukui earthquake, \( 1.55 \times 10^{-3} \) fire outbreaks per household, has \( JMA = 7 \), and falls outside the limits of this plot. The rate of fire outbreaks for the Japanese data is per ‘household’ (right scale) and the intensity of shaking is on the JMA scale (top scale). The conversion between the JMA and MMI (\( = I_{MM} \)) scale is as per Wong and Trifunac\(^{16}\).

The Northridge earthquake data in Fig. 6 suggest that in the Los Angeles area fires start to occur at \( I_{MM} = 7^+ \). The Japanese data for the Nihonkai-Chubu, Miyagi-Oked, Niigata, and Tokachi-Oki earthquakes suggest that fires begin to occur at \( JMA = 5 \). The conversion from JMA to \( I_{MM} \) shows that \( JMA = 5 \) corresponds to \( I_{MM} = 7.8 \). The other California data suggest that fires begin to occur for \( I_{MM} > 6 \).

Because of the many differences in use of ‘one household’ (Kobayashi\(^4\)) vs ‘SFD’, uncertainties in the intensity levels, and variable densities of ‘households’ and ‘SFDs’, the rate of fire outbreaks in Japan cannot be compared directly to our present interpretation for the 1994 Northridge earthquake. However, an approximate straight-line fit through the data of Kobayashi\(^4\) and conversion from JMA to MMI intensity scales shows that these two data sets result in essentially the same estimates of the intensity where fires begin to occur.
It is seen that our interpretation of the Northridge data is consistent with the previous estimates, but that the trend is 'steeper' relative to $I_{MM}$. We interpret this to be the result of using the revised (more accurate) estimates of site intensity$^6$ for the Northridge earthquake. In this paper we use an average estimate of 683 $\times$ 25 = 17075 SFDs/25 km$^2$. This gives the number of fires ignited by an earthquake, per SFD, as:

$$m_{SFD} = -0.0021 + 0.0003I_{MM}$$  \hspace{1cm} (5)

It is seen that $m_{SFD} = m_r/17075$. The Dames and Moore report$^{18}$ is based on Single Family Equivalent Dwelling (SFED), which corresponds to 1500 ft$^2$ area per SFED. Assuming that SFD~SFED, and combining all the California data shown in Fig. 6 with the Northridge data, gives:

$$m_{SFD} = -0.00073 + 0.000125I_{MM}$$  \hspace{1cm} (6)

Before interpreting the differences between the trends in eqns (5) and (6) it would be necessary to revise the analyses of the previous earthquakes using more detailed maps of site intensity. This probably cannot be done because the detail in the information on these events does not approach that of the 1994 Northridge earthquake. Therefore, it seems prudent to use the trends for fire ignition based on Northridge data in future fire hazard analyses, particularly for levels of shaking larger than $I_{MM} = VIII$.

### 3.1.4 Rate of fire ignition vs peak velocity ($m_r$)

As already stated many fires caused by earthquakes can be associated with gas leaks, severed electrical lines and spills of flammable chemicals. The frequency of these problems can be assumed to be proportional to the level of shaking within the structures and to the degree of damage in the structures. We found that the number of damaged buildings (i.e. red-tagged buildings) during the Northridge earthquake can be related to the peak velocity of ground motion, $v_m$. It is reasonable to suppose that the rate of fires ignited due to earthquake shaking is also related to the peak ground velocity.

We calculated the average velocity within each of the 29 blocks, and then correlated those values with the number of fires in the same areas. Fig. 7 shows $m_r$ vs peak ground velocity (shown by open circles). A parabolic regression through these points gives:

$$m_r = \begin{cases} 
-2.31 + 0.0421v_m + 0.000314v_m^2 & ; \quad v_m > 41.7 \\
0 & ; \quad v_m \leq 41.7 
\end{cases}$$  \hspace{1cm} (7)

This trend is shown by the weak solid line in Fig. 7. Eqn (7) should not be used beyond $v_m = 120$ cm/s, because of the lack of data on $m_r$, vs $v_m$ for high velocities. However, this should not pose serious problems, since the highest...
ground velocity recorded so far in California\(^19\) is about 160 cm/s.

### 3.1.5 Rate of fire ignition vs modified mercalli intensity via \(N\) and \(n\) (\(m_{Nf}\) and \(m_{af}\))

Eqsns (1) and (3) presented empirical trends for prediction of the rate of fire ignitions when \(n\) and \(N\) are known. These equations are useful for better understanding of the causal relationships that exist (or do not exist) between the chosen scaling variables. As can be seen from Figs 2 and 3, the correlation between \(m_N\) and \(N\) is strong, while between \(n\) and \(n\) is weak.

For probabilistic seismic hazard mapping and for earthquake scenario analyses neither \(n\) or \(N\) are available a priori and must be estimated via other empirical relationships. Such relationships developed for the Northridge data\(^6,7\) are:

\[
\log_{10} N = -4.09 + 0.547I_{MM} \quad (8)
\]

\[
\log_{10} n = -1.08 + 0.0079I_{MM} + 0.0229I_{MM}^2 \quad (9)
\]

The rates of fire ignition, \(m_{Nf}\) and \(m_{af}\) are determined as follows. For a given site intensity, \(I_{MM}\), first \(N\) and \(n\) are computed via eqns (8) and (9), and then eqns (3) and (1) are used to estimate \(m_{Nf}\) and \(m_{af}\). The results of this procedure are shown in Fig. 5 by solid and broken lines. It is seen that the agreement with the data and with the trend described by \(m_1\) is good.

### 3.1.6 Rate of fire ignition vs peak velocity via \(N\) and \(n\) (\(m_{Nv}\) and \(m_{av}\))

The procedure for computing \(m_{Nf}\) and \(m_{af}\), described in the previous section, can be repeated for peak velocity in place of site intensity, and rates of fire ignition \(m_{Nv}\), and \(m_{av}\), can be computed. The equations relating \(N\) and \(n\) to the peak velocity, \(v_m\), are:

\[
\log_{10} N = (v_m - 64)/94 \quad (10)
\]

and

\[
-3.5 \leq \log_{10} \bar{v} \leq -2.35 \quad (11)
\]

where \(\bar{v}\) is the average shear wave velocity in the top 30 m of soil. In the examples in this paper, the average estimate \(\bar{v} = 300 \text{ m/s}\) is used. Then eqns (3) and (1) are used to compute \(m_{Nv}\) and \(m_{av}\). The results are shown in Fig. 7 by the broken lines. It is seen from Fig. 7 that the agreement between the equations for \(m_v\), \(m_{Nv}\), and \(m_{av}\) is fair to good.

### 3.1.7 Residuals for the models

Next, the relative success of the eight models, presented in the preceding text, in predicting the fire ignition rates observed during the Northridge earthquake is analyzed. For each of the eight models and for each of the twenty nine \(5 \times 5\) km\(^2\) blocks studied the residuals between the predicted rates, \(m\), and the observed rates, \(m_{o}\), are calculated. Then, the mean of the residuals, \(\mu\), and the standard deviation, \(\sigma\), are computed for each model as follows:

\[
\mu = \frac{1}{75} \sum_{j=1}^{29} (m_{o,j} - m_j) \quad (12)
\]

\[
\sigma = \left[ \frac{1}{75} \sum_{j=1}^{29} (m_{o,j} - \mu - m_j)^2 \right]^{1/2} \quad (13)
\]

and the results are summarized in Table 1. It is seen that, except for \(m_v\), the standard deviation of all residuals is less than 1.6. The standard deviation is the smallest for \(m_{Nv}\), which starts with eqn (8) and then uses eqn (3).

It is also examined in how many of the 29 blocks \(|m_{o} - m_j| < 1\) and \(|m_{o} - m_j| < 0.5\). The results, in percentages, are shown in the last two columns of Table 1. It is seen that, in this regard, the model \(m_1\) is superior to model \(m_v\), while model \(m_{Nv}\), is slightly better than \(m_{Nf}\). Fig. 8(a) and (b) present the 'scatter' diagrams for \(m_v\) vs \(m_{Nf}\) and \(m_{Nv}\), and give a visual impression of the quality of fit.

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![Fig. 7. Rate of fire ignitions, \(m_v\), per 25 km\(^2\) vs horizontal peak ground velocity, \(v_m\). The open circles show the data, and the weak solid line shows the trend. The two broken lines show the rates \(m_{Nf}\) and \(m_{av}\) computed via the rate of red-tagged buildings and the rate of water pipe breaks.](image)
Table 1. Comparison of relative performance of different fire ignition models

<table>
<thead>
<tr>
<th>Scaling model</th>
<th>$\mu$</th>
<th>$\sigma$</th>
<th>% times $m_o - m &lt; 1$</th>
<th>% times $m_o - m &lt; 0.5$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$m_n$ eqn (1)</td>
<td>0.3</td>
<td>2.7</td>
<td>31</td>
<td>21</td>
</tr>
<tr>
<td>$m_{31}$ eqn (3)</td>
<td>0.0</td>
<td>1.4</td>
<td>76</td>
<td>52</td>
</tr>
<tr>
<td>$m_{41}$ eqn (4)</td>
<td>0.0</td>
<td>1.3</td>
<td>72</td>
<td>38</td>
</tr>
<tr>
<td>$m_n$, eqn (7)</td>
<td>0.1</td>
<td>1.5</td>
<td>55</td>
<td>28</td>
</tr>
<tr>
<td>$m_{34}$, eqn (8) $\rightarrow$ eqn (3)</td>
<td>-0.2</td>
<td>1.1</td>
<td>69</td>
<td>48</td>
</tr>
<tr>
<td>$m_{34}$, eqn (9) $\rightarrow$ eqn (1)</td>
<td>0.0</td>
<td>1.6</td>
<td>69</td>
<td>45</td>
</tr>
<tr>
<td>$m_{34}$, eqn (10) $\rightarrow$ eqn (3)</td>
<td>-0.2</td>
<td>1.4</td>
<td>76</td>
<td>48</td>
</tr>
<tr>
<td>$M_{34}$, eqn (11) $\rightarrow$ eqn (1)</td>
<td>0.4</td>
<td>1.6</td>
<td>66</td>
<td>52</td>
</tr>
</tbody>
</table>

- $m_o$ — observed fire ignition rate, per 25 km$^2$
- $m$ — predicted fire ignition rate, per 25 km$^2$
- $\mu$ — mean of residuals
- $\sigma$ — standard deviation of residuals.

### 3.2 Gas related fires

The Los Angeles Fire Department (LAFD) reported 38 gas-related fires as being caused by the Northridge earthquake$^9$ (D. G. Honegger, pers. comm. 1996) (24 fires occurred in SFDs, five in apartment buildings, six in mobile homes, and three in businesses). Two fires occurred between the street line and the gas meter (one block wall fell on a meter and one large main ruptured in the street). In the mobile homes the units fell off their supports (due to large inertial forces or differential motions) severing the gas line$^9$. From the 38 reported fires that occurred in the San Fernando Valley and Los Angeles regions, we used 32 for further analysis.

The data was analyzed as follows. For each of these fires a $1 \times 1$ km$^2$ area was defined which contained the fire, and the number of breaks in the water pipes, $n$, and the number of red-tagged buildings, $N$, were determined. There were no fire ignitions closer than 1 km from each other. The results are summarized in Table 2 and Table 3. The fist line of the Tables 2 and 3 lists respectively values of $n$ and $N$ per km$^2$. The following rows, for each $n$ and $N$, show: (1) the number of $1 \times 1$ km$^2$ blocks where a fire occurred; (2) the number of $1 \times 1$ km$^2$ blocks where a fire occurred which has been attributed to strain and differential motion (Table 3) or to a broken gas line at water heater or appliance (Table 2), (3) the total number of $1 \times 1$ km$^2$ in the sample, and (4) the probability that at least one gas related fire per km$^2$ area will be ignited given that there were $n$ water pipe breaks or $N$ red-tagged buildings per km$^2$ area at that location ($P(m_G > 0|n)$ and $P(m_G > 0|N)$).

The histograms were evaluated by dividing the number of blocks where there was a fire by the total number of blocks with the corresponding observed values of $n$ and $N$.

The histograms in Fig. 9 show how many of the 32 fires occurred in a block with (a) $n = 0, 1, 2, \ldots$ pipe breaks, and (b) $N = 0, 1, 2, \ldots$ red-tagged buildings. The highlighted areas show those fires that might have occurred mainly because of (a) large strains in the soil (11 out of 32 fires), and (b) a broken gas line at a water heater or a gas appliance (17 out of 32; i.e. due to large inertial forces). The relationship between the shaded and white areas as $n$ and $N$ increase could be used to test the hypothesis that the gas related fires are primarily started due to large strains in the soil or due to large inertia forces. The histograms do not show a clear trend that the percentage of shaded area increases or decrease as $n$ and $N$ increase, and so the hypotheses cannot be verified.

![Fig. 8](image-url)  
(a) Observed ($m_n$) vs computed ($m_{31}$) fire ignition rate for the $I_{31} \rightarrow N \rightarrow m_{31}$ model.  
(b) Observed ($m_n$) vs computed ($m_{31}$) fire ignition rate for the $V_n \rightarrow N \rightarrow m_{31}$ model.
Table 2. Frequency of occurrence and probability of occurrence of at least one fire ignition (per km$^2$), given the number of breaks in water pipes (per km$^2$), $n$

<table>
<thead>
<tr>
<th>$n$/km$^2$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of occurrence of at least one fire ignition per km$^2$</td>
<td>2</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fires caused by strain and differential motion (?)</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of 1 km$^2$ blocks with observed $n$</td>
<td>223</td>
<td>126</td>
<td>74</td>
<td>67</td>
<td>49</td>
<td>19</td>
<td>23</td>
<td>15</td>
<td>19</td>
<td>6</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>$P$</td>
<td>0.00897</td>
<td>0.0476</td>
<td>0.0676</td>
<td>0.0597</td>
<td>0.0816</td>
<td>0.158</td>
<td>0.0435</td>
<td>0.0666</td>
<td>0.105</td>
<td>0.167</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

$\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\hline
Frequency of occurrence of at least one fire ignition per km$^2$ & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
Fires caused by strain and differential motion (?) & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 & 1 \\
Number of 1 km$^2$ blocks with observed $n$ & 1 & 5 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 & 2 \\
$P$ & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 & 0.0200 \\
\hline
\end{array}$

Fig. 10(a) and (b) shows the conditional probabilities $P(m_c > 0|n)$ and $P(m_c > 0|N)$ vs $n$ and $N$. The open circles correspond to the data points and the line shows the trend. It is seen that the data is not sufficient to define the trend for $P > 0.2$ (shown by a dashed line).

4 DISCUSSION AND CONCLUSIONS

One of the purposes of this analysis has been to find whether the rate of fire ignitions, per 25 km$^2$, is better correlated with one or another characteristic of ground shaking and damage in populated areas. Correlation with intensity of shaking, $I_{MM}$, peak horizontal ground velocity, $V_{sh}$, rate of occurrence of red-tagged buildings, $N$, and of breaks in water pipes, $n$, was considered. The analysis showed that the correlation with $N$ is 'better' than the correlation with $n$. The interpretation is that the prevailing cause for the fires were the large inertia forces rather than the large strains in the soil. Detailed and systematic documentation of the most probable causes for ignition of fires for future earthquakes should be systematically documented to find out whether the results for the Northridge earthquake apply in general.

Several one-dimensional correlations were presented, i.e. it was assumed that the rate of fire ignitions depends mostly on one scaling variable ($I_{MM}$, $V_{sh}$, $N$ or $n$). In reality the rate of fire outbreaks depends on more than one of these variables and should be scaled via multi-dimensional regression analyses. However, such analyses would require detailed data with more specific attributes. It is not surprising that one of the 'best' scaling models in this paper, $m_{\text{sh}}/n_{\text{sh}}$, is based on site intensity, $I_{MM}$, which can be viewed as a weighted parameter that reflects several different characteristics of strong ground motion.

As the data on fire outbreaks was sparse larger block size ($5 \times 5$ km$^2$) had to be used in this analysis than in our previous analyses of the occurrence of red-tagged buildings and of breaks in water pipes. The larger block size averaged fluctuations in $N$ and $n$ and made it possible in the sample to have blocks with more than one fire outbreak, so that a regression analysis could be carried out.

In Japan for smaller intensities of shaking ($JMA < 5$, $I_{MM} < 8$) a significant number ($\sim 50$ percent) of fires in households are extinguished by the inhabitants immediately. For large levels of shaking this success rate diminishes, and for very strong shaking ($JMA = 7$, $I_{MM} = 12$) it becomes

Table 3. Frequency of occurrence and probability of occurrence of at least one fire ignition (per km$^2$), given the number of red-tagged buildings (per km$^2$), $N$

<table>
<thead>
<tr>
<th>$N$/km$^2$</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency of fire ignition per km$^2$</td>
<td>6</td>
<td>7</td>
<td>4</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Fires caused by broken gas line at water heater or appliance</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of 1 km$^2$ blocks with observed $N$</td>
<td>558</td>
<td>154</td>
<td>72</td>
<td>54</td>
<td>35</td>
<td>19</td>
<td>11</td>
<td>12</td>
<td>5</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>$P$</td>
<td>0.0168</td>
<td>0.0522</td>
<td>0.0555</td>
<td>0.0294</td>
<td>0.0571</td>
<td>0.1180</td>
<td>0.0909</td>
<td>0.1060</td>
<td>0.0400</td>
<td>0.1870</td>
<td>0.2000</td>
<td>0.2000</td>
<td>0.2000</td>
<td>0.2000</td>
</tr>
</tbody>
</table>

$\begin{array}{|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|c|}
\hline
\hline
Frequency of fire ignition per km$^2$ & 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 \\
Fires caused by broken gas line at water heater or appliance | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 \\
Number of 1 km$^2$ blocks with observed $N$ & 3 | 2 | 5 | 2 | 1 | 1 | 2 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 \\
$P$ & 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 | 0.0200 |
\hline
\end{array}$
negligible\textsuperscript{4}. Similar trends are likely in southern California and may help explain why \( m_n \) is essentially zero for \( I_{MM} \leq 7 \) (Fig. 6) for Northridge data and for \( I_{MM} < 6 \) for other earthquakes in California.

Fire ignition rates should be documented to determine the relative occurrence of gas, electrical, chemical and other types of fires. This would assist in the development of prediction equations based on correlations with a combination of scaling parameters that include coefficients proportional to the relative participation of the various fire ignition mechanisms. It was not possible to apply this approach in this analysis because of the small number of data points for the Northridge earthquake.

The equations for prediction of fire ignition rates, \( m_n \), presented in this paper can be used to predict the rate for a future scenario earthquake or for an assembly of earthquakes, within the framework of probabilistic seismic hazard analyses\textsuperscript{29}. These equations are, however, specific for typical residential areas of the two regions studied (prevailing construction type, age and density of buildings). Application to other regions would require appropriate adjustments.

Fig. 9. (a) Number of fires which occurred in 1 km\(^2\) blocks with \( n \) breaks in the water pipe system. The contribution from fires which may have been caused by large strain in soil and by differential motions is highlighted by a hatched pattern. (b) Number of fires which occurred in 1 km\(^2\) blocks with \( N \) red-tagged buildings. The contribution from fires which appear to have been caused by broken gas lines at water heaters are highlighted by a hatched pattern.

Fig. 10. Conditional probability that at least one gas related fire per km\(^2\) area will be ignited given that there were (a) \( n \) breaks in water pipes per km\(^2\) or (b) \( N \) red-tagged buildings per km\(^2\) at that location.

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REFERENCES


