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A Spatial–Temporal Stochastic Simulation of Fire Outbreaks Following Earthquake Based on GIS

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ABSTRACT: Post-earthquake fire is a dangerous secondary disaster following an earthquake, which causes severe life losses and property destruction. Similar to other natural disasters, fire outbreak following an earthquake carries its own spatial and temporal characters. In order to explore these characters, we analyzed in detail the fires caused by the Hanshin earthquake in Japan (1995). We identified the key spatial–temporal characters of the fire outbreak following an earthquake. Using this analysis methodology, we further collected and organized the records of post-earthquake fires that have occurred in the 20th century in USA, Japan, and China, and modeled fire outbreaks following an earthquake by employing a regression analysis method. Considering the stochastic characters of post-earthquake fires, we proposed a random Poisson event and Weibull distribution model in constructing the spatial–temporal probability distribution of fire outbreaks following an earthquake in urban districts. In addition, we propose a geographical information system (GIS) based stochastic simulation schema to predict the spatial–temporal process of fire outbreaks following future earthquakes. Finally, we applied our models to simulate the fire outbreaks in Xiamen city after an assumed earthquake of a

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similar magnitude as the Hanshin earthquake. Our simulation result not only exhibits the spatial–temporal characters of fire outbreaks following an earthquake, but also supplies valuable decision-making information to the planning of Xiamen city's seismic prevention and mitigation.

KEY WORDS: fire outbreaks following earthquake, regression analysis, spatial–temporal probability model, random Poisson event, Weibull distribution, Kaplan–Meier analysis, GIS.

INTRODUCTION

POST-EARTHQUAKE FIRE REFERS to fire induced by earthquakes directly or indirectly, and has been the most dangerous and frequently occurring secondary disaster following an earthquake. A large number of historical earthquake records show that fires accompanied with an earthquake could sometimes claim more life losses and property destruction than the earthquake itself [1]. For example, conflagrations resulting from the San Francisco earthquake on April 8, 1906 spread over 521 blocks, of which 508 blocks were burnt out. According to statistics after the hazard, losses from the fires were four times greater than losses from the earthquake itself. Another example is the Kanto earthquake in 1923, in which 447,000 houses were burnt and 56,000 people died in fires. Cases of post-earthquake fires even exist in recent earthquakes. For example, in the 1994 Northridge earthquake, more than 100 fires broke out and destroyed a large number of houses. The Hanshin earthquake in 1995 also resulted in 138 fires in the following 3 days, leading to $\approx$66,000 m^2 burnt regions, more than 6900 damaged houses, and more than 500 deaths. In 1999, the Kocaeli earthquake induced two massive fires at the Tupras oil refinery, burning for several days and leading to severe economic losses. In China, there are two recent typical post-earthquake fires. One is the Haicheng earthquake in 1975, which caused 60 fire outbreaks even though the prediction and emergency measures were carried out in time. The other is the Tangshan earthquake in 1976, which is one of the most calamitous earthquakes in Chinese history. Although heavy rain helped to suppress the occurrence of fires in Tangshan city itself, 36 fires broke out in Tianjin city which is about 100 km away from Tangshan city. According to incomplete statistics, economic losses caused by the fires were above a million Chinese Yuan.

The above cases indicate that post-earthquake fires could cause significant damage to human beings. With the development of social economy and human living standard, it should be noted that the losses from post-earthquake fires exhibit a rising tendency and that the causes of post-earthquake fires will become more and more complex. Therefore, to reduce the fire damage from an earthquake, it is important to be able to predict the fire outbreaks accurately and to preplan emergency measures. For this purpose, the authors made an in-depth analysis of the outbreak of urban post-earthquake fires and identified their spatial–temporal characters. Based on these characters, the authors developed spatial–temporal probability models to simulate the spatial–temporal distribution of fire outbreaks following an earthquake in urban regions. The simulation provides quantitative information for urban seismic disaster prevention and mitigation.

ANALYSIS TO THE SPATIAL–TEMPORAL CHARACTERS OF POST-EARTHQUAKE FIRES

From previous studies in history, it is well known that the process of post-earthquake fires is extremely complicated due to a large number of random factors involved. However, similar to other natural disasters, post-earthquake fires also carry their special spatial–temporal characters. In order to identify these characters, fires following Hanshin earthquake in Japan were analyzed deeply as an example.

Spatial Distribution Characters

The 5 : 46 a.m. January 17, 1995, M7.2 (JMA) Hanshin (official name: Hyogo-ken Nambu) earthquake was centered under the northern tip of Awaji Island near Kobe city, in the Kansai region of Japan [2]. The earthquake not only destroyed a large number of buildings, but also induced over 100 fires which caused severe losses. Figure 1 shows the spatial distribution of the fires in Kobe city and its adjacent cities in the period from January 17 to January 19 [3]. As clearly seen from Figure 1, the 7 JMA intensity area (gray area) was a notable long and narrow region, about 20 km long and 2 km wide. It is also clear from Figure 1 that the fire locations following the earthquake (black dots) were concentrated in this severe disaster area, implying the existence of a close relation between the spatial distribution of fires following the earthquake and the seismic intensity. Furthermore, an analysis of the fire outbreak mechanism shows that a larger seismic intensity leads to a higher risk of ignition following the earthquake because of the

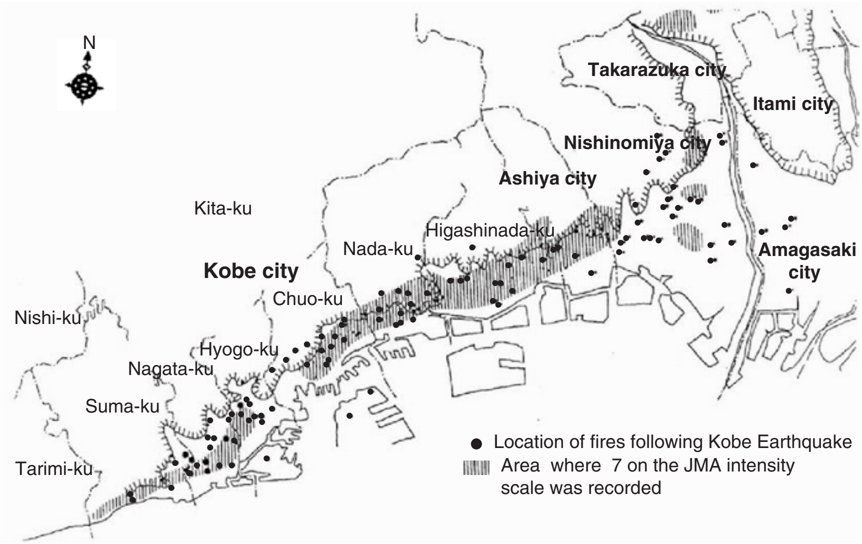


Figure 1. Spatial distribution of fires following Kobe earthquake [3].

high probability of overturn and destruction of various potential fire sources such as stoves, gas pipelines, chemical products, etc. In addition, stronger earthquakes result in more serious destruction of buildings which in turn increases the inflammable level of buildings and promotes the further spread of fires. In summary, there exists a positive correlation between the spatial distribution of fires following an earthquake and the ground parameters (i.e., seismic intensity or peak ground acceleration (PGA)) on regions.

Temporal Distribution Characters

According to statistical data, 138 fires occurred within 3 days after the quake [4–6], and the temporal distribution of the fires is quite uneven. Figure 2 provides the data on the number of fires by hours on January 17 and the following 2 days in Kobe city [4]. The time period '5' on the horizontal axis in the figure refers to 14 min after 5 : 46 a.m. when the earthquake struck. As shown in Figure 2, from the time the earthquake occurred, the number of fires decreased gradually, from 109 fires (79%) on the day of the earthquake to 14 (10%) and 15 (11%) in the following two days, respectively. On the first day of the earthquake, it is interesting to note that about half of the fires (53) occurred within 14 min after the main shock and the other half occurred an hour

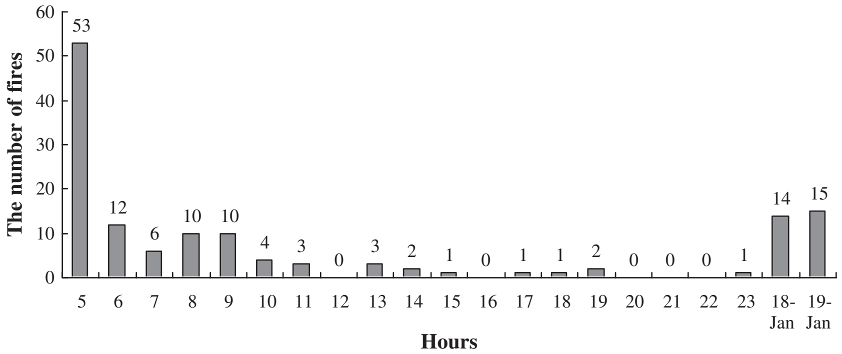


Figure 2. The number of fires by lapsed time from January 17 to 19 in Kobe city [4].

later. From this temporal pattern of fire ignitions, the phenomena aforementioned can be explained as follows. The first wave of fires was formed by a number of fires starting simultaneously just after the main shock. These fires were caused by the earthquake directly (ignition of various fire sources due to shaking). The second wave was formed by sporadic fires which were caused by restoration of electrical power, fires associated with recovery activities, and the spread of the initial fires to create additional separate fires [6]. From the above discussion, we conclude that the outbreak of post-earthquake fires is not a simple one time event, rather a special serial behavior in time order.

SPATIAL–TEMPORAL MODELING OF FIRE OUTBREAKS FOLLOWING AN EARTHQUAKE

Spatial Probability Model of Fire Outbreaks Following an Earthquake

Modeling the Outbreaks of Fire Following an Earthquake

The complication and randomness of various causes of fire outbreak following an earthquake make it difficult to perform a research on its mechanism. To date, the research on seismic ignition has remained at a relatively elementary level, and there is a lack of a matured theoretical model.

In Japan, Kawasumi was the first to study the outbreaks of fires in earthquakes [7]. Using the data of Tokyo city in the

Kanto earthquake (1923), he developed a logarithmic regression relation between fire outbreaks and the damaged buildings [8].

$$\ln \Phi = 0.684 \ln \theta - 5.807 \quad (1)$$

where, Φ is the rate of fire outbreaks in wooden buildings (%) and θ is the rate of collapsed wooden buildings (%).

Following Kawasumi's idea, Mizuno also proposed a regression model of seismic fire outbreaks [7]. Different from Kawasumi's model, after an investigation of six earthquakes since Kanto earthquake, Mizuno observed that fires occurred not only in wooden buildings but also in fireproof buildings. He suggested that the fire outbreak rate itself should be given by the number of fires per household. Based on this suggestion, he improved the logarithmic regression relation between rate of fire outbreaks per household and rate of totally collapsed households [8].

$$\ln(-\ln(1 - \Phi)) = 0.606 \ln(-\ln(1 - \theta)) - 6.149 \quad (2)$$

where, Φ is the rate of fire outbreaks per household (%) and θ is the rate of totally collapsed households (%).

Based on the statistical data of fires from selected earthquakes in the United States from 1906 to 1989, Scawthorn proposed a linear regression relation between the number of fires per 1,000,000 square foot building floor area and the PGA [2]. In HAZUS (1999), the linear regression relation was modified into a second-order formulation [9]

$$y = -0.025 + 0.592x - 0.289x^2 \quad (3)$$

where, y is the number of fire outbreaks per 1,000,000 square foot building floor area, and x is the PGA.

Among the above regression models, Kawasumi's model has the difficulty of estimating fire outbreaks in future earthquakes because it was only based on the Kanto earthquake data, which occurred almost 80 years ago when the Japanese were using old-fashioned fire appliances and solid fuels such as wood and charcoal that are scarcely used nowadays. Mizuno's regression model was based on 90 data points from 12 different earthquakes dating from 1923. However, 31 (34.4%) of the 90 data points were from the 1923 Kanto earthquake and 31 (34.4%) were from the Tango earthquake. Furthermore, 23 (74%) of the 31 data points from the Tango earthquake were from small villages of less than 500 households, while some data points from another earthquake were from large cities of more than 200,000 households. Because of the biased data selection for regression, it is questionable to apply Mizuno's model to future earthquakes. In HAZUS second-order regression formula, fire outbreak was not a monotonic function of PGA, violating the positive correlation between fire outbreaks and seismic intensity. Moreover, the regressed data were collected only from selected earthquakes that happened in the US, which limits the application of HAZUS model to Japan and China.

In order to avoid the defect of the data, we collected and compiled records of fires following earthquakes in the 20th century in the USA, Japan, and China (Table 1). Considering the different building densities in different regions, the number of fires in each record was initially normalized by building floor area, i.e., the number of fire outbreaks per 100,000 m^2 building floor area. Then, based on the fact of a positive correlation between the outbreak of fires and the ground parameters on regions, a linear regression equation was attracted between the normalized number of fire outbreaks and PGA as below:

$$\lambda = 0.0042 + 0.5985\,\mathrm{PGA} \tag{4}$$

where λ is the number of fire outbreaks per 100,000 m^2 building floor area calculated under the specific value of PGA.

Figure 3 presents the linear regressed curve between the normalized number of fire outbreaks and PGA, which reflects the fact that the number of fire outbreaks increases on increasing the PGA. On the other hand, the plot reveals that the fitting result is very satisfactory due to the scattering of empirical data.

The scattering of the data comes from the following resources:

1. Deviation on data acquisition [9]. Because of the long time-span in data collection, detailed data of fires following earthquakes cannot be attained easily. Of the collected data, some are from local fire departments and some from journals or newspapers. Therefore, it is inevitable that repetition, conflict, and deviation may exist in the data sources.
2. Uncertainty on the conversion from seismic intensity to PGA [9]. Different investigators might sometimes rate a specific area with different seismic intensity values, differing by one or two intensities. This introduced a large amount of uncertainty. The seismic intensity to the PGA conversion process also add more uncertainty to the data. For example, the same PGA values can produce different levels of damage at rock sites compared with soft soil sites, especially when liquefaction or landslides occur.

Table 1. Fires following earthquakes in USA, Japan, and China in the 20th Century.*

No.	City	Date	PGA (g)	Seismic intensity	Fires	Fire outbreaks per 100,000 m^2
USA						
1	Santa Rosa	1906.4.17	0.71	X	1	0.149
2	San Mateo Co	1906.4.17	0.36	VIII	1	0.151
3	Santa Clara	1906.4.17	0.44	VIII–IX	1	0.237
4	San Jose	1906.4.17	0.36	VIII	1	0.086
5	San Francisco	1906.4.17	0.44	VII–X	52	0.28
6	Oakland	1906.4.17	0.44	VII–X	2	0.065
7	Berkeley	1906.4.17	0.44	VIII–IX	1	0.172
8	Norwalk	1933.5.10	0.28	VII–VIII	1	0.054
9	Los Angeles	1933.5.10	0.15	VI–VII	3	0.011
10	Long Beach	1933.5.10	0.53	IX	19	0.28
11	San Francisco	1957.5.22	0.12	VI	0	0
12	Anchorage	1964.3.27	0.71	X	7	0.258
13	Santa Rosa	1969.10.1	0.36	VIII	1	0.065
14	Burbank	1971.2.9	0.21	VII	7	0.172
15	Glendale	1971.2.9	0.15	VI–VII	9	0.14
16	Los Angeles	1971.2.9	0.15	VI–VII	128	0.097
17	Pasadena	1971.2.9	0.21	VII	2	0.043
18	San Francisco	1971.2.9	0.53	IX	3	0.398
19	Coalinga	1983.5.2	0.36	VIII	1	0.32
20	Morgan Hill	1984.4.24	0.21	VII	4	0.43
21	San Jose	1984.4.24	0.36	VIII	5	0.022
22	Whittier Narrows	1987.10.1	0.28	VII–VIII	6	0.108
23	Daly city	1989.10.17	0.12	VI	3	0.054
24	Berkeley	1989.10.17	0.07	–	1	0.014
25	Marin Co.	1989.10.17	0.12	VI	2	0.022
26	Mountain View	1989.10.17	0.21	VII	1	0.022
27	Oakland	1989.10.17	0.07	–	0	0
28	San Francisco	1989.10.17	0.21	VII	27	0.086
29	Santa Cruz	1989.10.17	0.36	VIII	1	0.043
30	Santa Cruz Co.	1989.10.17	0.28	VII–VIII	24	0.032
JAPAN						
31	Tokyo	1923.9.1	0.8	X	163	0.102
32	Yokohama	1923.9.1	0.8	X	60	0.24
33	Fukui	1948.6.28	0.6	IX–X	24	0.618
34	Maruoka ward	1948.6.28	0.6	IX–X	4	0.91
35	Kanazu ward	1948.6.28	0.6	IX–X	3	0.976
36	Matsuoka ward	1948.6.28	0.6	IX–X	4	0.992
37	Harue ward	1948.6.28	0.6	IX–X	5	0.799
38	Morita ward	1948.6.28	0.6	IX–X	3	0.675
39	Niigata	1964.6.16	0.7	IX–X	9	0.09
40	Towada	1968.5.16	0.2	VII–VIII	9	0.6

(continued)

Table 1. Continued.

No.	City	Date	PGA (g)	Seismic intensity	Fires	Fire outbreaks per 100,000 m^2
41	Miyagi	1978.6.12	0.35	VIII–IX	12	0.072
42	Urakawa	1982.3.21	0.3	VII–VIII	2	0.08
43	Sea of Japan	1983.5.26	0.35	VIII–IX	4	0.16
44	Higshi-nada ward	1995.1.17	0.8	X–XI	28	0.368
45	Nada ward	1995.1.17	0.8	X–XI	22	0.409
46	Chuo ward	1995.1.17	0.8	X–XI	35	0.698
47	Hyogo ward	1995.1.17	0.7	IX–X	28	0.509
48	Kita ward	1995.1.17	0.3	VII–VIII	2	0.028
49	Nagata ward	1995.1.17	0.8	X–XI	27	0.505
50	Suma ward	1995.1.17	0.4	VIII–IX	20	0.301
51	Nishi ward	1995.1.17	0.3	VII–VIII	2	0.032
52	Amagasaki	1995.1.17	0.3	VII–VIII	8	0.041
53	Ashiya	1995.1.17	0.4	VIII–IX	13	0.389
54	Nishinomiya	1995.1.17	0.4	VIII–IX	41	0.256
55	Itami	1995.1.17	0.2	VII–VIII	7	0.103
56	Takarazuka	1995.1.17	0.15	VII–VIII	4	0.055
57	Kawanishi	1995.1.17	0.1	VI–VII	3	0.062
58	Akashi	1995.1.17	0.15	VII–VIII	6	0.06
CHINA						
59	Dali	1925.3.16	0.35	VIII–IX	10	0.33
60	Fengyi	1925.3.16	0.2	VII–VIII	6	0.3
61	Haicheng	1975.2.4	0.3	VIII–IX	12	0.068
62	Tangshan	1976.7.28	0.8	X–XI	5	0.125
63	Tianjin	1976.7.28	0.2	VII–VIII	38	0.317
64	Cangyuan	1988.11.6	0.2	VII–VIII	1	0.111
65	Yongsheng	1992.12.18	0.1	VI–VII	1	0.1

*Provided by Harbin Engineering Mechanic Institute of China Earthquake Bureau, and compiled by the authors.

3. Fire outbreak following an earthquake is a typical random event [2], therefore fire outbreaks are probably not related entirely to a single parameter [9], whether it is seismic intensity or PGA. Actual fires may occur for a number of reasons, including:

- Toppling over of unanchored items (this is PGA-related), causing short circuits or fuel spills. This causes fires if an ignition source (spark) is present.
- Rupture of underground gas pipelines (this is PGA-related) which provides a fuel source for ignition.

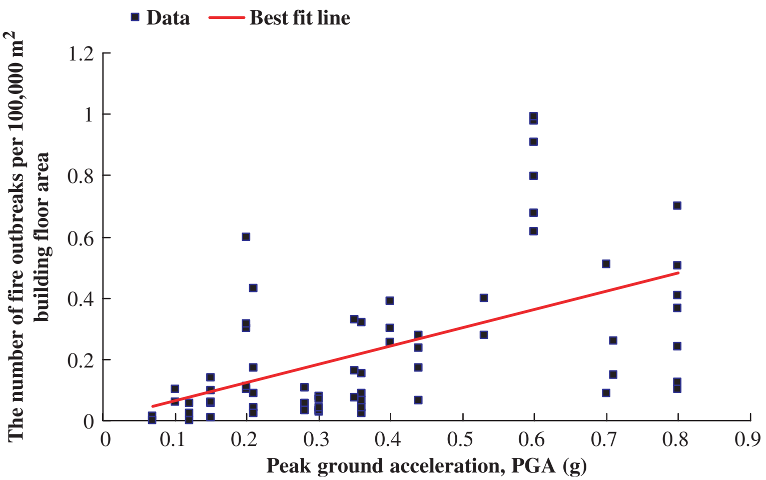


Figure 3. The linear regressed curve between normalized number of fire outbreaks and PGA.

- Electric power lines may be knocked down by earthquake or torn from collapsed buildings, creating potential arcing situations. This is related to the PGA, structure type, and wiring condition.
- Timing is a key factor to the number of fire outbreaks following an earthquake. There are two kinds of time factors, i.e., season and time of day. Different seasons result in different frequencies of electric and gas appliances usage in houses. Especially in winter, when electrical and gas appliances are generally used by the occupants for house heating, there would be more potential for fire outbreaks than in other seasons. The time of day when an earthquake occurs also has a significant influence on fire outbreaks following an earthquake. For example, more gas or electrical appliances are used for cooking during meal times, leading to a higher potential of fire outbreaks when an earthquake occurs at meal times than at night-time.

4. Arson [2]: intentional fire ignitions occur during the event of earthquake by people for insurance purpose. These fires from arson are sometimes mistaken as seismic fires, resulting in a higher number of fire outbreaks from earthquake.

In summary, great complexity and uncertainty are involved in modeling fire outbreaks following an earthquake. Due to various uncertainty factors, Equation (4) may not represent the collected data very well. Nevertheless, it does reflect the actual trend of fire outbreaks following an earthquake. Therefore, Equation (4) is regarded as an important equation in practical applications.

Random Poisson Event

Fire outbreaks following an earthquake are a sequence of discrete random events [10], which is usually described by the so-called Poisson model. A random event, when satisfying the following properties, can be regarded as a Poisson event [11,12].

Property 1: Stationarity

In a particular interval of Δx (e.g., time, region, or other space), the probability of events, $\lambda\ \Delta x$, is directly proportional to the length Δx and does not depend on location of this interval in the whole space, i.e., λ is a constant (λ is often named as the intensity of event occurrences).

Property 2: Independency

The numbers of event occurrences in any non-overlapping interval are independent of other intervals.

Property 3: Non-repeatability

The probability of two or more events occurring within a sufficiently small interval is essentially 0, i.e., there occurs only one event within an infinitesimal interval.

Under the above conditions, the number of events $N(\Delta x)$ in a finite interval of length Δx obeys Poisson ($\lambda\ \Delta x$) distribution:

$$P\{N(\Delta x) = n\} = \frac{(\lambda \cdot \Delta x)^n}{n!} e^{-\lambda \cdot \Delta x} \tag{5}$$

Spatial Probability Modeling

According to the principle that seismic fires must be predicted and controlled within districts [13], we suggest that the urban region should be divided into several districts based on the layout of urban streets. The district obtained through this rule has the following advantages: the area is moderate, the site conditions and structure types are comparatively consistent. Therefore, during an earthquake, the PGAs at any location of the district are approximately equal, and can be substituted with the average PGA. From Equation (4), it is clear that the intensity of fire outbreaks in such a district is constant, satisfying the first condition of the Poisson event. Furthermore, it is unquestionable that the second condition of the Poisson event can be satisfied in such a district. Moreover, it is impossible that two or more fires would occur at the same location, thus satisfying the third condition of the Poisson event. Therefore, the fire outbreak in a district is a Poisson event; and in a specific district, the probability of n fire outbreaks during t days following an earthquake can be calculated through the Poisson model as follows:

$$P\{N(s) = n\} = \frac{(\lambda_s \cdot s)^n}{n!} e^{-\lambda_s \cdot s} \tag{6}$$

where λ_s is the spatial intensity of fire outbreaks in this district which can be calculated using Equation (4) with the given averaged PGA of this district, and s is the total building floor area of this district in units of $100{,}000\,m^2$.

Noteworthily, post-earthquake fire is a pattern of spatial–temporal stochastic events, thus the data in Table 1 for regression analysis actually recorded accumulated information of fire outbreaks of regions over a time period after the earthquake. Since we normalized only the number of fire outbreaks by building floor area, the intensity from Equation (4) represents only the spatial intensity of fire outbreaks during the entire time period. As a result, the probability model from Equation (6) actually reflects only the spatial character of fire outbreaks in a district over this time period. The time period mentioned here refers to the time interval from the occurrence of the earthquake to the end of the fire outbreaks from the earthquake. According to the statistical analysis of historical seismic fires, the length of the time period is about 3 days (72 h) so that in the compilation of data in Table 1, the time interval of data has been rectified to 3 days beforehand.

Based on the above analysis, the following stochastic simulation procedure should be followed step by step to predict the number of fire outbreaks during a 3-day time period following an earthquake in urban regions.

1. Divide the urban region into several districts and predict the average PGA for each district. Subsequently, input the average PGA into Equation (4) for each district to determine the spatial intensity of fire outbreaks following an earthquake.

2. Use Equation (6) to calculate the probabilities $P(i)$ $(i = 0, 1, \ldots M)$ for each district.
3. Generate a random number μ from $[0, 1]$ interval for each district.
4. Satisfy the following inequality by adjusting the number N. Once the inequality is satisfied, N is the predicted total number of fire outbreaks during the 3-days period following an earthquake in that district.

$$\sum_{n=0}^{N-1} P(n) < \mu \leq \sum_{n=0}^{N} P(n) \tag{7}$$

TEMPORAL PROBABILITY MODEL OF FIRE OUTBREAKS AFTER AN EARTHQUAKE

General Analysis

From the analysis of historical fires following an earthquake, all of the fire outbreaks after an earthquake follow approximately the same pattern as a function of time. Most of the fire outbreaks occur during the initial hours after an earthquake. Then the number of fire outbreaks decreases monotonically as a function of time during the 3-day period after the earthquake. In particular, a large number of fire outbreaks occur within a very short period of time (30 min to 1 h) after the earthquake, and there is a sudden decrease afterward. This pattern of fire outbreaks makes it ideal to choose the Weibull distribution model, which is often applied in the time-to-event analysis, to analyze fire outbreaks in time order.

Weibull Distribution Model

A problem frequently faced by applied statisticians is the analysis of time-to-event data. Examples of such data arise in diverse fields, such as medicine, biology, public health, epidemiology, engineering, economics, and demography. According to our deep analysis, the fire outbreaks in time sequence after an earthquake follow the same characteristics as time-to-event data. Therefore, the method used to study time-to-event is also applicable to the analysis of time-dependent fire outbreaks after an earthquake. The Weibull distribution model is one of the most adopted models to carry out the time-to-event analysis. It is a versatile distribution model that can handle various characteristics of different distributions by adjusting a so-called shape parameter, β. The following section introduces the Weibull distribution model and its application in analyzing time-dependent fire outbreaks after an earthquake.

The Weibull probability density function (pdf) can be expressed as [14]:

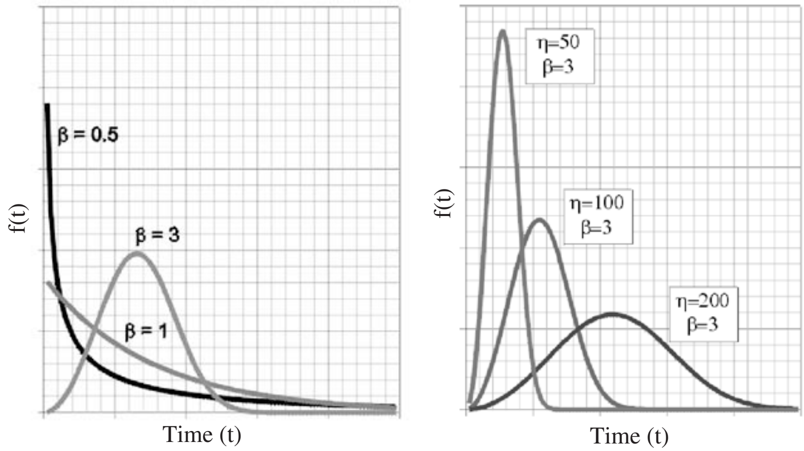
$$f(t) = \frac{\beta}{\eta}\left(\frac{t-\gamma}{\eta}\right)^{\beta-1} \mathrm{e}^{-((t-\gamma)/\eta)^{\beta}} \tag{8}$$

where β is the shape parameter, η the scale parameter, and γ the location parameter.

Since the fires after an earthquake always occur at $t=0$ (i.e., seismic time), it is obvious that location parameter γ in the Weibull pdf should take the value of zero. Therefore, time-dependent fire outbreaks depend only on two parameters in the Weibull probability model.

$$f(t) = \frac{\beta}{\eta}\left(\frac{t}{\eta}\right)^{\beta-1} \mathrm{e}^{-(t/\eta)^{\beta}} \tag{9}$$

Figure 4 shows the plots of the Weibull pdf as a function of β and η respectively. Figure 4(a) shows that the parameter β controls the shape of the pdf curve. For $0<\beta\leq 1$, $f(t)$ decreases monotonically and is convex with increasing t. For the special case of $\beta=1$, $f(t)$ becomes an exponential distribution. For $\beta>1$, $f(t)$ increases initially and then decreases with increasing t, leading to a peak in pdf curve. Considering the fact that the fire outbreaks after an earthquake show an initial sharp drop and a gradual decrease afterward, $0<\beta<1$ should be adopted in the Weibull probability model to describe the fire outbreaks. Figure 4(b) shows that the effect of η on the distribution is to change the time scale: increasing the η value while fixing β only has the effect of stretching out the pdf curve. Since the total area under a pdf curve needs to be normalized to unity, the maxima of the pdf curve should decrease with increasing η. As discussed in the last section, the typical time period of fire occurrence after an earthquake is 3 days (72 h). Therefore, an η value should be assigned to the Weibull probability model to correspond to a 72 h time period of fire outbreaks.



(a) With $0 < \beta < 1$, $\beta = 1$ and $\beta > 1$ (b) With varying values of η

Figure 4. Weibull pdf plots with varying values of β and η [14].

Estimation of Parameters

In order to obtain the numerical values of the two parameters in the Weilbull distribution, we collected and studied the recorders of fire outbreaks at different times during the January 17 to 19 period after the Hanshin earthquake in Kobe city and adjacent areas in Hyogo and Osaka Prefectures (Table 2) [15]. Meanwhile, the Kaplan–Meier survival analysis, which is a popular method of estimating time-to-event models, was applied in the parameter estimation of the Weibull distribution [14]. It is based on estimating conditional probabilities at each time point when an event occurs and taking the product limit of those probabilities to estimate the survival rate at each point of time. Through this method, parameters β and η of the Weibull distribution for each record were calculated and listed in Table 3. By analyzing the data in Table 3, some key results can be summarized as follows: (1) as expected, most of the estimated shape parameters fall in the range of 0–1. The exceptions that are bold in the table may result from the stochastic character of fire outbreaks; (2) different areas, no matter if it is the ward or city, all have relatively unanimous shape parameters. From these shape parameters, we deduce a median value of 0.67 after excluding exceptional values; and (3) scale parameters also have relatively unanimous values. The exception of scale parameters may come from the difference of an effective period of fire outbreaks. For example,

Table 2. Fire-outbreaks in time order in Kobe city and adjacent areas in Hyogo and Osaka prefectures for January 17–19 after Hanshin earthquake (1995, JAPAN) [15].

Name of ward and city	1/17 –6 : 00	1/17 –9 : 00	1/17 –12 : 00	1/17 –24 : 00	1/17 total	1/18 total	1/19 total	1/17–19 total
Higashi-nada ward	10	4	0	3	17	2	4	23
Nada ward	13	2	1	1	17	2	0	19
Chuo ward	8	7	2	3	20	3	3	26
Hyogo ward	11	3	2	3	17	4	3	24
Nagata ward	12	2	2	1	17	1	4	22
Suma ward	4	7	2	0	16	2	1	16
Tarumi ward	0	4	1	1	6	0	0	6
Kita ward	0	0	0	1	1	0	0	1
Nishi ward	1	0	0	0	1	0	0	1
Kobe city total	59	29	10	11	109	14	15	138
Ashiya city	4	5	0	0	9	2	2	13
Nishinomiya city	11	13	2	4	30	2	3	35
Takarazuka city	2	0	1	1	4	0	0	4
Itami city	2	5	0	0	7	0	0	7
Kawanishi city	1	2	0	0	3	1	0	4
Amagasaki city	3	3	1	1	8	0	1	9
Akashi city	0	1	4	1	6	1	0	7
Awaji city	1	1	0	1	2	1	0	3
Hyogo Pref. total	83	59	18	18	178	21	21	220
Osaka city	7	6	1	2	16	2	2	20
Toyonaka city	2	3	0	1	6	1	2	9
Suita city	1	1	0	0	2	1	0	3
Takatsuki city	1	0	0	0	1	0	0	1
Sakai city	1	0	0	0	1	1	1	3
Takaishi city	0	0	0	0	0	0	0	0
Osaka Pref. total	12	10	1	3	26	5	5	36
Total	95	69	19	21	204	26	26	256

Nada ward in Kobe city has a small scale parameter of 4.6 due to no fire outbreaks on January 19 (the third day after earthquake). Similarly, a small scale parameter of 6.47 also appears in Takarazuka city due to the absence of fire outbreaks on January 19. Therefore, the effective time period of fire outbreaks after an earthquake controls the scale parameter value.

In summary, with respect to the shape parameter β, we believe that the shape parameter should take a value in the range of 0.6–0.8, allowing a variation to account for the different local fire-resistant

Table 3. Estimation of parameters of Weibull distribution for fire-outbreaks in time order by using Kaplan–Meier method.

Name of ward and city	Scale parameter (η)	Shape parameter (β)
Higashi-nada ward	12.97	0.62
Nada ward	4.60	0.65
Chuo ward	12.90	0.69
Hyogo ward	12.98	0.65
Nagata ward	8.22	0.58
Suma ward	16.11	0.68
Tarumi ward	**7.85**	**1.47**
Kita ward	–	–
Nishi ward	–	–
Kobe city	10.23	0.64
Ashiya city	13.27	0.64
Nishinomiya city	9.55	0.70
Takarazuka city	6.47	0.86
Itami city	**3.5**	**2.6**
Kawanishi city	10.39	0.73
Amagasaki city	8.89	0.69
Akashi city	**14.46**	**1.21**
Awaji city	12.32	0.69
Hyogo Pref.	10.09	0.66
Osaka city	10.83	0.67
Toyonaka city	18.79	0.71
Suita city	12.32	0.69
Takatsuki city	–	–
Sakai city	12.48	0.78
Takaishi city	–	–
Osaka Pref.	13.61	0.66
Total	10.54	0.66

'–' means no estimated value.

capacity in different countries or in different regions of the same country. In this study, the median value '0.7' was chosen for shape parameter β. On the other hand, it has been mentioned that the effective time period of fire outbreaks after an earthquake is about 3 days (i.e., 72 h). Therefore, we can assume that the possibility of fire outbreak after 3 days following an earthquake is very small. According to the Weibull distribution model, this assumption can be expressed as Equation (10) and the scale parameter η can be calculated easily from this equation.

$$R(t \geq 72) = \mathrm{e}^{-(72/\eta)^{\beta}} = \sigma \tag{10}$$

where σ represents a small probability value. In this study, $\alpha = 0.05$ was assumed and the scale parameter η was derived to be 15 h.

Temporal Probability Modeling

From the above analysis, time-dependent fire outbreaks after an earthquake can be described by the Weibull probability model. Thus, the probability density of one fire outbreak at t h after an earthquake can be calculated using Equation (11):

$$f(t) = \frac{0.7}{15}\left(\frac{t}{15}\right)^{-0.3} \mathrm{e}^{-(t/15)^{0.7}} \tag{11}$$

Based on this probability model, the stochastic simulation of fire outbreaks during a 3-day (72 h) period after an earthquake can be implemented from the following procedure:

1. Construct the Weibull distribution function of fire outbreaks after an earthquake using Equation (12).

$$F(t) = 1 - \mathrm{e}^{-(t/15)^{0.7}} \quad t \geq 0 \tag{12}$$

2. Generate N (the total number of fire outbreaks in each district from the spatial stochastic simulation) random numbers $\mu_1, \mu_2, \ldots, \mu_N$ in the interval of $[0, 1]$ to calculate random variables $t_1, t_2, \ldots, t_N$ using Equation (13), which was inverted from Equation (12).

$$t_i = 15(-\ln \mu_i)^{1/0.7} \quad t_i \geq 0 \tag{13}$$

   where t_i is the lapsed time of fire outbreaks after an earthquake.
3. Order the time variables $t_1, t_2, \ldots, t_N$ and record them into the timetable of fire outbreaks.
4. Simulate the dynamic process of fire outbreaks following an earthquake in each district by creating one fire outbreak at each time (t_i) queried from the timetable.

A SPATIAL–TEMPORAL STOCHASTIC SIMULATION SCHEMA FOR FIRE OUTBREAKS FOLLOWING AN EARTHQUAKE

Computer simulation of disasters has become an important method to predict the occurrence, recur the process, and estimate the losses associated with a disaster. As for post-earthquake fires, we proposed a GIS-based simulation schema to predict the spatial–temporal process of fire outbreaks following an earthquake in urban regions. Figure 5 presents the flow chart of schema with a detailed procedure described as follows:

1. Divide the urban region into small districts according to the layout of streets.
2. Build a local empirical seismic intensity attenuation model based on the statistical materials of local earthquakes in history [16,17]. Then input the three parameters of epicenter, seismic magnitude, and fault angle, into the model to calculate the averaged seismic intensity for each district.
3. Convert the seismic intensity into PGA for each district. Then input the PGA into the model of fire outbreaks following an earthquake to determine the spatial intensity of fire outbreaks (λ_s) for each district.
4. Compute the total floor area of buildings for each district; and input the λ_s, area, and a random number into the spatial Poisson probability model to calculate the total number (N) of fire outbreaks during the 3-day period after the earthquake in each district.
5. Generate N random numbers for each district and input them into the temporal Weibull probability model to create the timetable of fire outbreaks in each district.
6. Start the stochastic simulation with the seismic time as the time origin and 1 h as time increment. Each time the system increases the simulation time increment, the statistics to the number (n) of fire outbreaks in each district within the current simulation time-slice will be carried out and recorded. Subsequently, these outbreaks of fires will spread when fire-fighting through fire-spread and fire-suppression simulation. The system will process the above operations repeatedly until the end of the simulation time ($t = 72$ h). At the end of the simulation, the fire-burnt area and corresponding losses will be estimated. (Note: the study of fire-spread and fire-suppression simulation will be carried out by the authors.)
7. Because of the stochastic character of post-earthquake fire events, each simulation result is just a stochastic sample of the models' output [18]. Thus, independent simulation should be implemented many times to give a comprehensive statistical result. The final statistical result includes the spatial distribution map, temporal statistical chart of potential fire outbreaks during 3 days following an earthquake, statistical fire-burnt area, and the corresponding losses due to fire-spread.

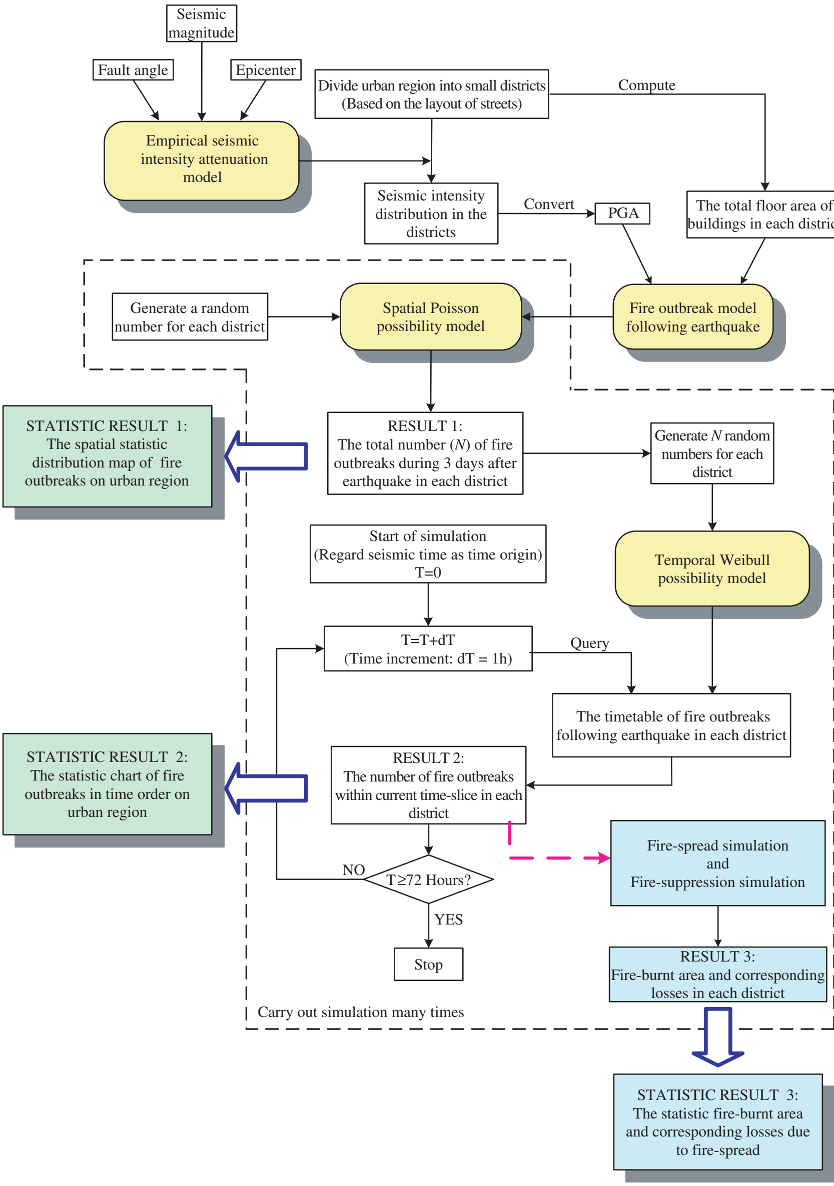


Figure 5. The flow chart of stochastic simulation to spatial–temporal distribution of urban post-earthquake fires.

CASE STUDY

Description of Studied Region

The studied region is Xiamen city, which is in the southeast coast of the Fujian province in China. It covers a land area of 1565.09 km^2 and a sea area of $\approx$300 km^2. Xiamen city is one of the five special municipalities of China with a prosperous economy and dense population, and has been an important coastal city in southern China. On the other hand, Xiamen is a city frequently attacked by natural hazards, especially earthquakes. According to historical records, the city has been attacked several times by strong earthquakes that caused severe destruction to the city. Therefore, the protection against earthquake has become the primary goal and formed the core of urban disaster prevention and mitigation planning of Xiamen city. Post-earthquake fire, as the most serious secondary disaster of earthquake, is inevitably at the top of the list of prevented disasters.

Assumption of Earthquake Occurrence

In order to predict the spatial–temporal process of fire outbreaks following a future earthquake, a shallow-focus earthquake is assumed to occur near Xiamen city.

The simulation seismic parameters are:

1. Epicenter: $118^\circ\ 10'\ 15''$E, $24^\circ\ 36'\ 10''$N
2. Seismic magnitude: 7.2
3. Fault angle: 60°

PGA Distribution in Districts

Based on the statistics of local historical earthquakes, the empirical seismic intensity attenuation elliptic model suitable for Xiamen city is provided as follows by the China Earthquake Bureau.

Along major-axis:

$$I_a = 3.6345 + 1.6124M - 1.7106\ln(D + 20) \tag{14}$$

Along minor-axis:

$$I_b = 2.7030 + 1.5779M - 1.5470\ln(D + 14) \tag{15}$$

where I is the seismic intensity, M the seismic magnitude, and D the distance to the Epicenter (km).

Using Equations (14) and (15), the average seismic intensities in all districts can be calculated and further converted into the average PGA. Table 4 is a conversion table from Chinese seismic intensity to PGA [16,17]. Figure 6 presents the PGA distribution in the districts of Xiamen city.

Table 4. Chinese seismic intensity to PGA conversion Table [16,17].

Seismic intensity	V	VI	VII	VIII	IX	X	XI
PGA (m/s^2)	0.31	0.63	1.25	2.50	5.00	10.00	>10.00
Normalized PGA(g)	0.03	0.06	0.13	0.25	0.51	1.02	>1.02

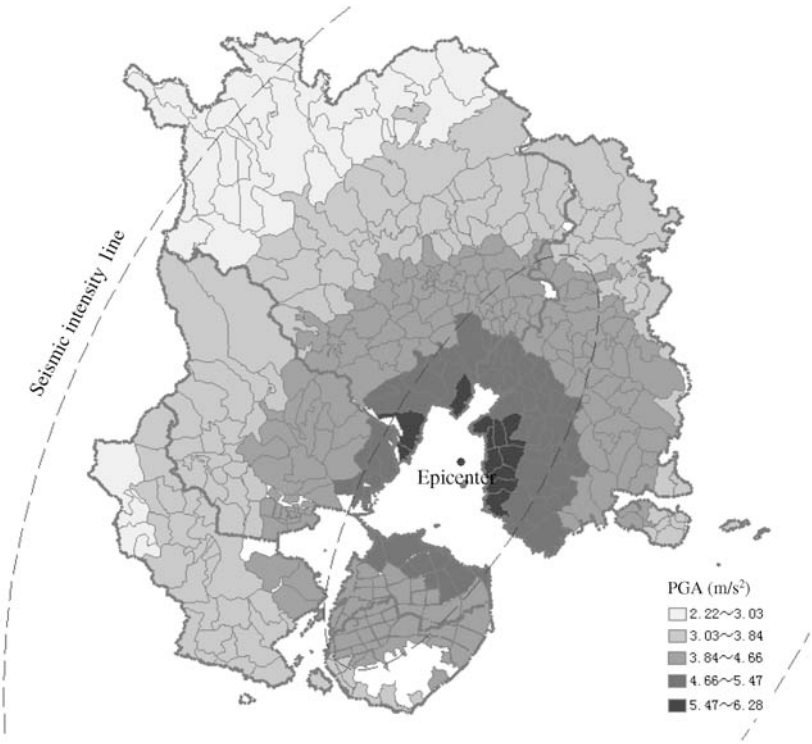


Figure 6. The PGA distribution in districts of Xiamen city after assumed earthquake.

Results of One Stochastic Simulation

Using the spatial Poisson probability model and the temporal Weibull distribution model, we performed one stochastic simulation for Xiamen city and obtained two simulation results on the distribution, in both space and time, of the fire outbreaks during a 3-day period after the assumed earthquake (Figures 7 and 8).

Statistic Results of 1000 Independent Stochastic Simulations

In order to investigate the statistical distribution of fire outbreaks in space and time, 1000 independent stochastic simulations were carried out to ensure statistical accuracy. After simulations, we found a normal distribution of fire outbreaks in both space and time. Thus, the mean

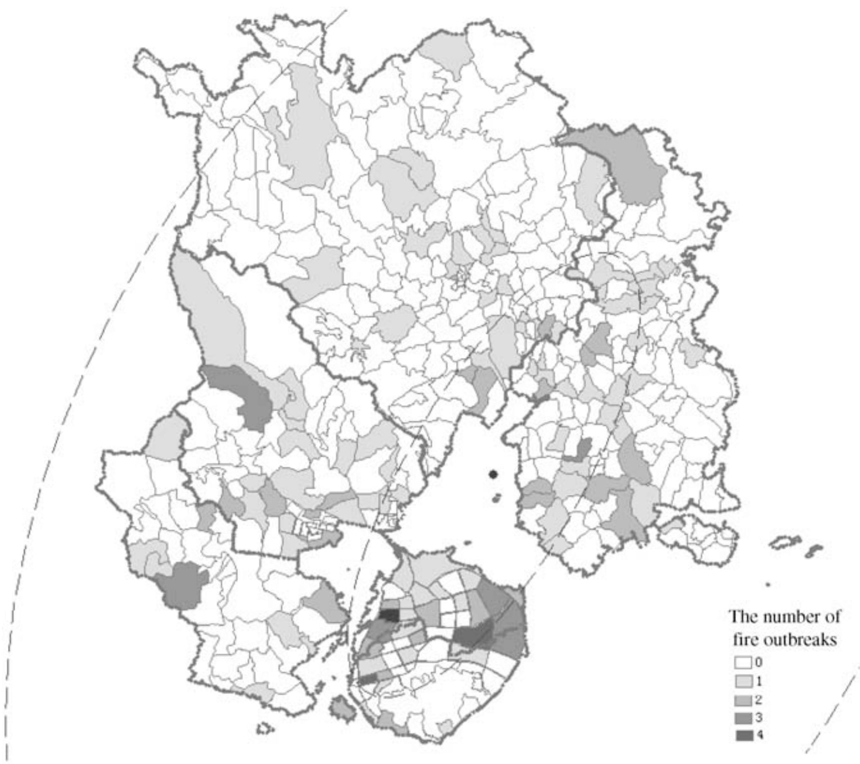


Figure 7. The spatial distribution of fire outbreaks during 3 days after assumed earthquake (one stochastic simulated result).

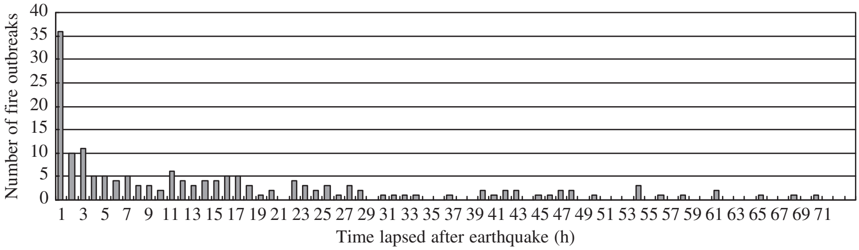


Figure 8. The number of fire outbreaks in time order during 3 days after assumed earthquake (one stochastic simulated result).

number of fire outbreaks in each district ($\bar{N}_{d_i}$) and each hour after the earthquake ($\bar{N}_{t_i}$) are calculated using the following equations [18]:

$$\bar{N}_{d_i} = \frac{\sum_{k=1}^{n} N_{d_i}(k)}{n} \quad \bar{N}_{t_i} = \frac{\sum_{k=1}^{n} N_{t_i}(k)}{n} \tag{16}$$

where d_i is a specific district and t_i is a specific hour after an earthquake; n is the total number of stochastic simulations. The results of the calculation are presented in Figures 9 and 10, respectively.

CONCLUSIONS

Post-earthquake fire is one of the most frequently occurring urban disasters whose potential destruction has been intensely studied by experts. We studied the specific case of fire outbreaks following an earthquake, and obtained the following results regarding the spatial–temporal stochastic process of fire outbreaks.

1. The spatial–temporal characters of fire outbreaks following an earthquake were presented by analyzing the classical case of fires in the Hanshin earthquake in Japan.
2. A positive correlation between the number of fire outbreaks per 100,000 m^2 building floor area and PGA was formulated through a linear regression based on collected data from the USA, Japan, and China. We discussed in detail the key problems in the scattering of regressed data.
3. In order to reflect the stochastic character of fire outbreaks following an earthquake in space, the random Poisson event model was introduced to establish the spatial probability distribution of fire outbreaks.

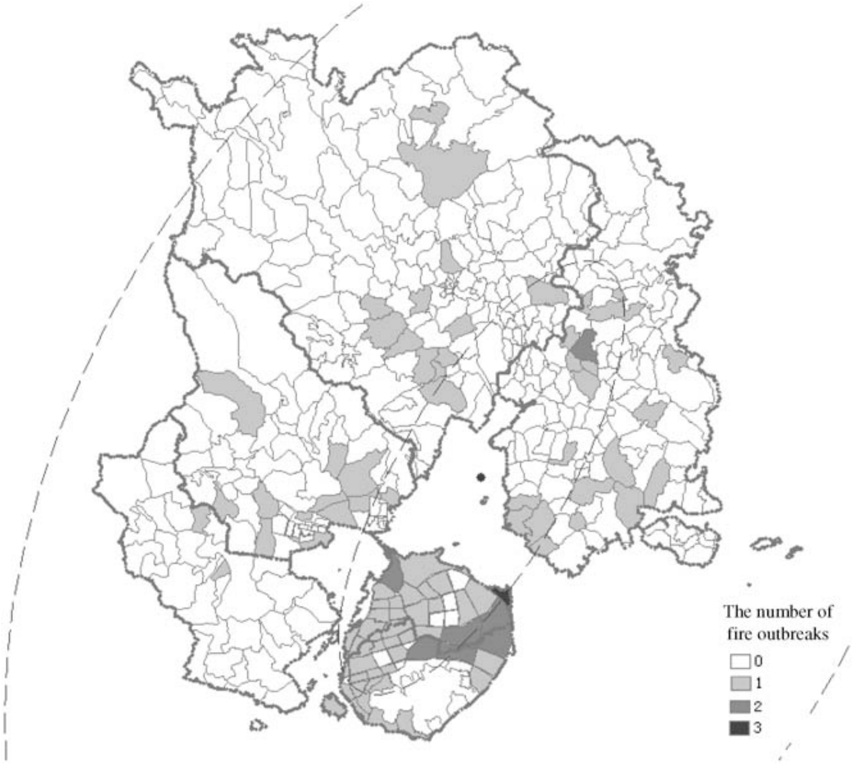


Figure 9. *The mean number of fire outbreaks in districts after 1000 simulations.*

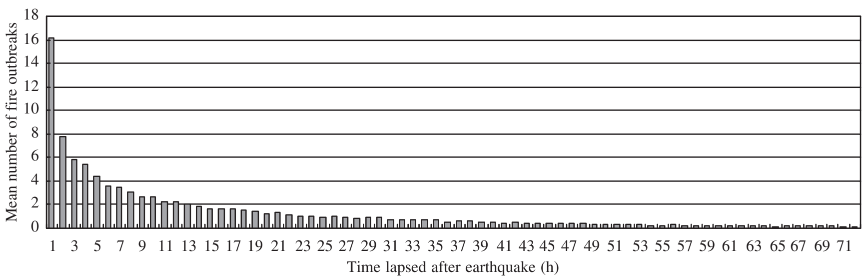


Figure 10. *The mean number of fire outbreaks in time order after 1000 simulations.*

4. With respect to the time-dependent stochastic character of fire outbreaks following an earthquake, the Weibull distribution model was employed to establish the temporal probability distribution of fire outbreaks.

5. Based on the above models, we proposed a stochastic computer simulation schema and applied it to a case study of a simulated earthquake in Xiamen city. The result shows that the simulation schema is suitable for the prediction of the spatial–temporal dynamic process of fire outbreaks following an earthquake.

There are several unresolved issues remaining for future studies:

1. In modeling the number of fire outbreaks following an earthquake, only one factor (PGA) was considered in the formulation. However, the number of fire outbreaks should also depend on other factors, especially on the timing of the earthquake occurrence. Thus further studies should integrate into the model of the correlation between the fire outbreaks and the seismic timing.
2. Although the model in this article can well predict the total number and temporal distribution of fire outbreaks in a district, a prediction of the ignition sites within the district cannot be made due to the complexity of various building's ignition threshold and its inherent stochastic character. Therefore, modeling the probability of a single building's ignition after an earthquake should be another key subject for future study.
3. In order to make an entire assessment of the losses resulting from post-earthquake fires, the models of fire spread and fire suppression should be studied successively after the prediction of the outbreaks.

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