Probabilistic estimation of fire spreading following an earthquake due to gas pipeline damage

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Abstract
Fire following earthquakes has resulted in a considerable loss of property during the history. In San Francisco earthquake (1906) the estimated loss due to a widespread fire was about 250 million dollar of its time. The case of Tokyo earthquake of 1923 was much worse where the fire-induced loss shared 77% of the total. In recent times, Loma Prieta (1989), Northridge (1994) and Kobe (1995) earthquakes are new experiences in which ignition of fire was generally because of damages in old gas networks. It is therefore justifiable to concentrate on the performance of city gas networks, among other lifelines, when assessing vulnerability of urban areas to fire following an earthquake.
From three main sources for ignition including gas leakage, damage of electrical equipments and leakage of flammable chemical substances, gas leakage is considered in this study. In fact a probabilistic model for the estimation of fire loss originated by gas pipeline damage following an earthquake can be developed using the proposed method. Linearity for correlation of loss growth on area of burned regions is assumed in the proposed model. In the so called loss model various damage scenarios and gas feeding states should be studied simultaneously. Developing the model consists of: a) assessment of damage scenarios of pipeline, b) modeling ignition of natural gas, and, c) modeling the spread of fire. New ideas are proposed in parts “a” and “b” but the method developed by Tosho is used in developing part “c”. The numerical simulation of the proposed model reads to the results which are time dependent curves illustrating how fire and the induced loss grows with time in each region after earthquake strikes. These curves can be used to determine the priority of urban areas for preventive or rescue plans. Finally, to demonstrate the applicability of the model, fire loss curves are obtained for two sample urban areas.

1- Introduction

Study on the damaging effects of earthquakes on the structure of a building has been subject of many research works in the past. Fire as an event following an earthquake can cause considerable losses and should be included in a comprehensive assessment of earthquakes damage. In fact losses due to fire following an earthquake may be ten times those due to earthquake shaking. In San Francisco earthquake (1906) fire following the earthquake affected about 28000 houses and caused a loss of 250 million $. The case of Tokyo earthquake of 1923 was much worse where the fire-induced loss shared 77% of the total [1]. In recent times, Loma Prieta (1989), Northridge (1994) and Kobe (1995) earthquakes are new experiences in which ignition of fire was generally because of damages in old gas networks.

Recent investigations illustrated three main reasons for ignition after an earthquake: gas leakage, damages in electrical equipments and leakage of flammable substances [2]. In Loma Prieta and Northridge earthquakes although the wet and stable weather was not mature for fire spreading but damages in old gas pipelines caused extensive fires.

Considerable losses due to fire following an earthquake will occur if the fire can spread. Spreading of fire depends on flammable materials, the type of ignition, direction and speed of wind and weather condition; so many of primary fire events can not spread. For example in Kobe earthquake from 181 fires only 85 cases spread and 96 cases could not go beyond a house.

Three main models should be investigated for assessing earthquake fire because of gas leakage; these models are: damage model for gas pipelines, ignition model and spreading model. In a city many fires may occur annually but only 5-10% of them cause more than 50% of total annual fire induced losses [3]. In the case of earthquake if gas leakage cause the fire, the fire spreading is much probable. Elapsed time after ignition is a most important variable for estimation of fire losses. Urban fires usually are assumed to be under control from when the extinction team arrives [4]. Modeling fire treatment includes many uncertainties in estimating the location of ignition and mechanism of spreading (conduction, convection or radiation). On the other hand finding a way for decreasing calculation time for estimation of burned areas after an earthquake is quite valuable; because less time for calculation means more time for implementation. The mentioned uncertainties and importance of time calculation cause fire modeling be implemented by using experimental relations. For example some models have been investigated for spreading fire in ships and metro lines [3].

Three types of studies are considerable about fire spreading. In this paper after a brief review of these types one of semi-empirical methods is focused on. The next part is specified to an innovative probabilistic method for ignition. Finally conjugation of proposed ignition model with fire spreading model is illustrated by a brief applied example.

2- Models for fire spreading

Various models existing for fire spreading can be categorized as statistical methods, computational methods and semi computational methods. In statistical methods through using data gathered from previous fires, estimation for fire growth is implemented. For example in CIBSE standard energy release rate of 1000 Kw/m^2 is suggested for warehouses [5]. In computational methods the region is divided to cells and based on physical relations between the cells, the fire spreading rate can be calculated. Computational models are generally more time consuming than the other two kinds. Semi empirical models of fire spreading are the third kind. These models can be categorized in two groups: first, the models which are solely developed for fire following earthquakes and second, general models. Rathermel model [6] is developed for forest fire but it is a base for many general models. Two popular models in the first category are Hamada model (1970) and Tosho model (1995).

A comprehensive model for fire should cover two steps, include ignition and spreading. In the ignition model estimation of numbers of ignition points is important. Using existing data, HAZUS has suggested the number of ignitions as [7]:

$$Ignitions = -0.025 + (0.592PGA) - (0.289PGA^2) \qquad (1)$$

After emerging of Hamada model in 1970 it has been used vastly. HAZUS99 uses Hamada model as the fire spreading model. Of course as the time lapses, Tosho model could have a more precise estimation. The region in Hamada model is divided to square blocks and an average length is assumed for the space between buildings. Also density of buildings in each region is considered and varies between 0.1 and 0.35. Tosho method was proposed in 1997 and is used by Tokyo Fire Department [8].

An oval shape is presumed for the fire boundary in Tosho model. In the present study a better estimation for the fire boundary is proposed. The growth of the burned boundary is supposed to be in the wind direction. Then the fire spreading rate can be calculated. If this rate is shown by a scalar, the vector of fire growth for unit time can be written as:

$$V(x,y,\vec{U}) = V\left(x,y,\left|\vec{n}.\vec{U}\right|\right)\vec{n} \qquad (2)$$

Where:

$\vec{U}$: Vector of wind velocity blowing

$\vec{n}$: Boundary normal vector at the point (x,y)

$\vec{V}$: Vector of fire growth in unit time

In this study a program was developed in Mathematica which can calculate the burned boundary in each time step. Figures 1 and 2 are outputs of this program and shows the effect of the wind speed on boundary growth.

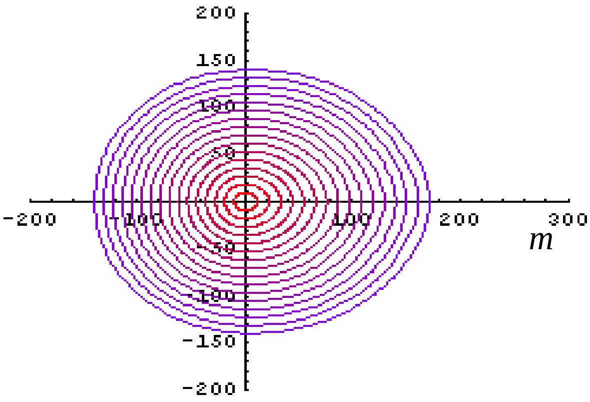

Fig 1 Fire spreading, $U = 1.2m/\sec$

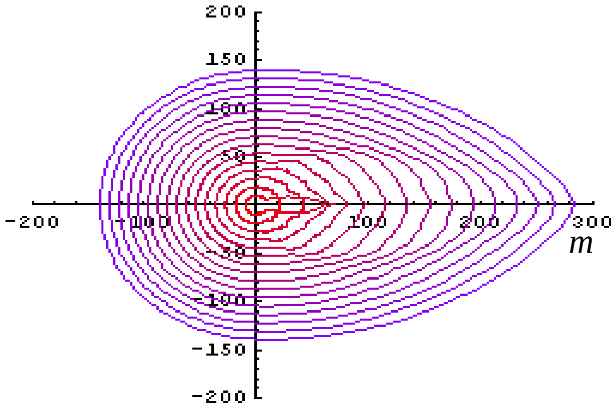

Fig 2 Fire spreading, $U = 8m/\sec$

Also in the program the effects of obstacles on the boundary can be calculated (Fig 3).

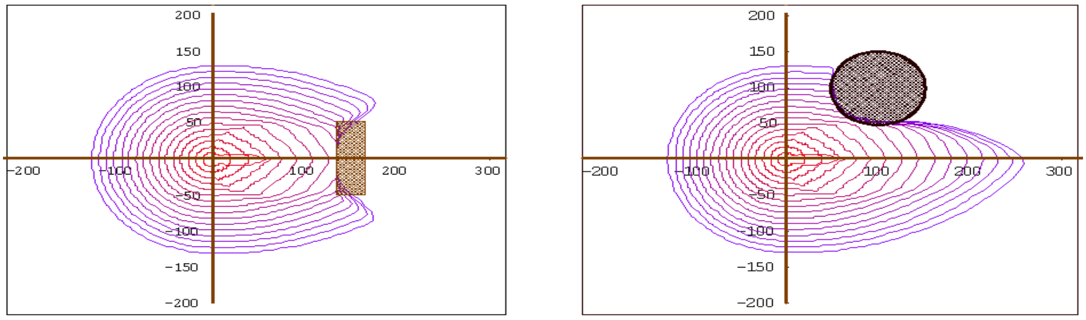

Fig 3 Effect of obstacle on the fire boundary

3- The ignition model

Ignition due to gas leakage directly depends on pipe damage, form of gas spreading and starting point of fire. In this part, first the spreading of gas is assessed and second a probabilistic model for ignition of gas due to an external factor is developed. As mentioned, HAZUS uses Eq. (1) for number of ignitions in a region. This relation solely depends on PGA. There is a deeper attention to physical properties in this paper for gas spreading and gas ignition models.

3-1-Gas spreading model

Many models have been presented for gas spreading in air. The models may have been developed for the gas exhaust of a car or gas exiting from chimney of a factory. In this study modeling of gas spreading from urban gas pipelines is intended. Gaussian model is popular and is usually used in case of gases having a similar density to air. This model is used in ALOHA software [9]. Therefore Gaussian model is suitable for spreading of city gas. In this model density distribution of gas assumed to be bell shaped in the wind direction (Fig 4).

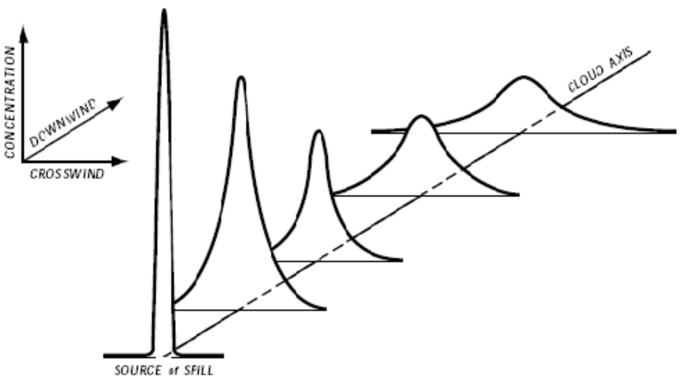

Fig 4 Gaussian distribution of gas [9]

Equation of gas density in air when wind is blowing in x direction is [10]:

$$\frac{\partial \Phi}{\partial x} + U \frac{\partial \Phi}{\partial x} = k_x \frac{\partial^2 \Phi}{\partial x^2} + k_y \frac{\partial^2 \Phi}{\partial y^2} + k_z \frac{\partial^2 \Phi}{\partial z^2} \quad (3)$$

Where:

Φ : Gas density
k : Coefficient for turbulence effects
Figure 5 shows growing of a region with a certain gas density. As the figure illustrates, the assumption of oval shapes for contours is good.

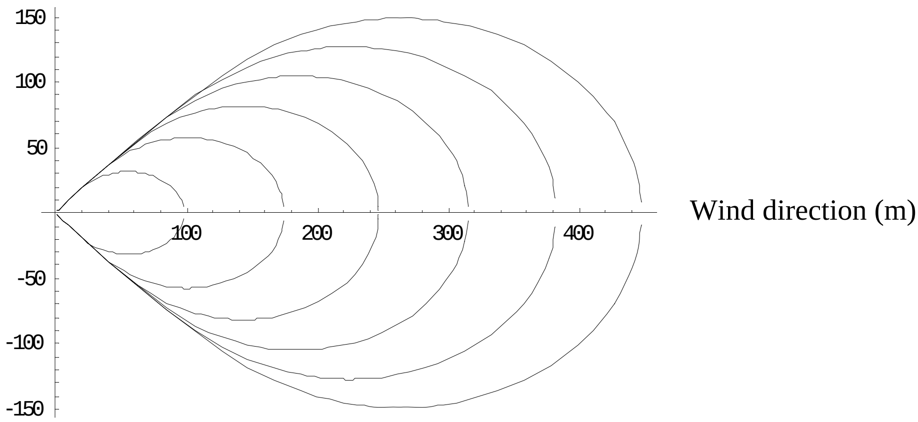

Fig 5 Growing of gas boundary with a certain density

Similar distances between the contours in wind direction demonstrates that growth rate of the plum can be assumed to be solely dependent on wind speed.
Dispersion is dominated by diffusion perpendicular to wind direction. Speed of exiting gas can affect dispersion pattern but mostly the city gas pipelines are buried so the gas speed from a broken pipe can be assumed to be zero. Moreover, the more the wind speed, the less the time for gas dispersion and the less gas density in plume. So the plume can not be flammable in higher wind speeds.
The fact that a certain density of gas disperses with almost a constant speed, is used in the following part of the paper to estimate the time needed for ignition.

3-2- The probabilistic model for ignition of gas

It is desired to develop a probabilistic model for gas ignition in this part. Assumptions for the model are as follows:

- A minimum density of gas is needed for ignition.
- In densities more than the minimum density, the probability of ignition is the same.
- Similar characteristics are assumed for gas dispersion in a certain region of a city. These characteristics are: number of excitations in unit area, and, wind speed and other parameters affecting gas dispersion.

It is assumed that ignition depends on a minimum density of gas and existence of an effective excitation in the region. Power lines are one of the excitation sources; so in the case of power lines the average number of excitations in a region depends on average density of power lines in that region.
Number of excitations in a time interval Δt is:

$$n = S(t)\rho_s \rho_t \Delta t \quad (4)$$

In which:
$S(t)$: Area of flammable plume

ρ_s : Number of excitations in unit area
ρ_t : Number of excitations in unit time

If time t is divided to m intervals, the probability of at least one successful trial (ignition) till t_0 ($t_0 < t$) is:

$$P(m < M) = 1 - \prod_{m=1}^{M} k^{S(t)\rho.\Delta t}$$
$$M = \frac{t_0}{\Delta t}, \qquad \rho = \rho_s \rho_t \tag{5}$$

Where:
k : Probability of an unsuccessful trial (no ignition in a trial)
Δt : Elapsed time in each time interval

Because of constant characteristics in each region, k is constant.
Therefore:

$$P(m < M) = 1 - k^{\sum_{m=1}^{M} S(m.\Delta t)\rho\Delta t} \tag{6}$$

If the shape of gas plume is approximated with an ellipse, the following relations can be written:

$$S(t) = \pi(V_H + V_l)t^2 \tag{7}$$
$$V = V_H + V_l \tag{8}$$
$$S(t) = \pi V(m.\Delta t)^2 \tag{9}$$
$$\sum_{m=1}^{M} S(m.\Delta t)\rho.\Delta t = \pi V\rho \sum_{m=1}^{M} (m.\Delta t)^2 \tag{10}$$
$$\Delta t = \frac{t}{M} \tag{11}$$

$$P(m < M) = 1 - k^{\left(\pi V^2 \rho.t_0^3\right)} \tag{12}$$
$$\lambda = \frac{\sum_{m=1}^{M} m^2}{M^3} \tag{13}$$

Then the probabilistic density function can be calculated as follows:

$$F(t_0) = \lim_{M\to\infty} 1 - k^{\pi V^2 \rho.t_0^3 \lambda} \tag{14}$$
$$\lim_{M\to\infty} \lambda = \lim_{M\to\infty} \frac{\sum_{m=1}^{M} m^2}{M^3} = \lim_{M\to\infty} \frac{(1+M)(1+2M)}{6M^2} = \frac{1}{3} \tag{15}$$

So:

$$F(t_0) = 1 - k^{\frac{\pi V^2 \rho.t_0^3}{3}}$$
$$\pi V^2 \rho = \nu \tag{16}$$

Derivation of $f(t_0)$ with regard to k gives;

$$f(t_0) = -\nu \ln(k) t_0^2 k^{\frac{\nu}{3} t_0^3} \quad (17)$$

Figures 6 and 7 illustrate the probability density function (PDF) for ignition depending on the elapsed time from start of gas leakage.

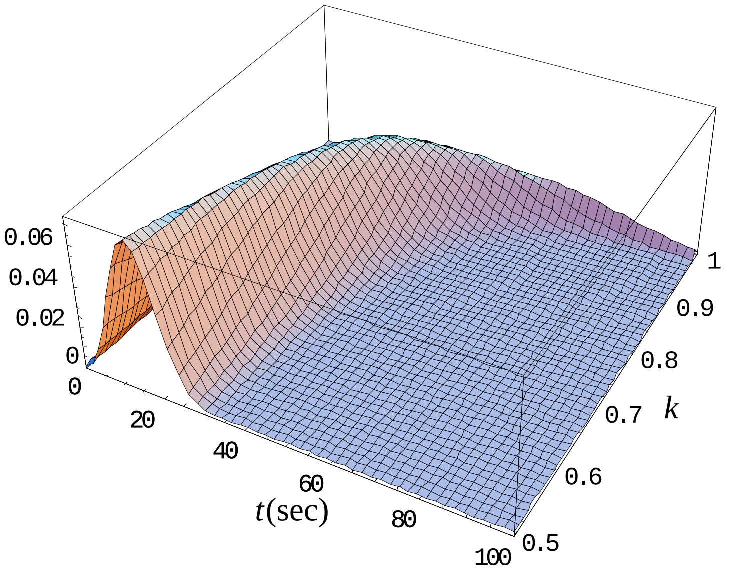

Fig 6 $f(t_0)$ as a function of k and t_0 ($\nu = 0.001$)

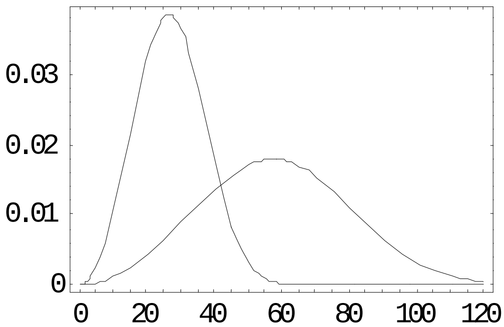

Fig 7 $f(t_0)$ for $\nu = 0.0001, 0.001$ ($k = 0.9$)

To calculate ν, the minimum flammable density of gas should be known. Experiments are needed to measure minimum flammable gas density. As there is a linear relation between gas density in plume and discharge of leaked gas, it can be assumed that in a certain region ν is proportional to gas discharge. Therefore, although tests are needed to estimate ν, knowledge of pipe diameters and gas pressure in different regions makes it possible to compare between ν's .

In the proposed formulation, k indicates the ability of a region for ignition. In work times (9-15 hours), k is smaller than in nights. In cold and wet nights k is minimum and it is maximum in hot and dry days.

4- Using ignition and fire spreading model for estimating losses

Calculating probability of ignition and estimating burned boundaries are two main steps for estimation of losses due to fire following an earthquake.

Although the value of burned asset (direct and indirect) should be known but a physical analysis is considered in this paper.

For a region if the total value of assets is val , the following relation can be written for the average loss due to fire following an earthquake:

$$l_F(t) = p_p \int f_{Ig}(t_{Ig}).val.A_F(t - t_{Ig}).dt_{Ig} \quad (18)$$

In which:

$l_F(t)$: Average loss due to fire till t

p_p : Probability of existence of flammable plume

f_{Ig} : Probability density function for ignition

$A_F(t)$: Burned area till t

f_{Ig} and A_F have been developed in the previous part. As was mentioned, weather condition, land use and damage mode of pipe affect f_{Ig}. In the case of A_F, wind speed, building materials, building distance and widths of roads are important parameters.

In the following, losses are estimated for an example region using some assumptive properties for that region. The values are as in Tables 1 and 2.

Table 1 Characteristics of the region being calculated for fire spread

Parameter	a	d	b'	c'	b_w	f_b	v_m	v_c	v_{nn}	v_{nc}	v_{cc}
Quantity	12	2	Var	0.8	10	4	25	30	24	24	20

Percentage of inflammable regions: 5%

In Table 1:

a : The average Length of buildings (m)

d : Spacing between buildings (door to door) in meters

b': The ratio of non-damaged fire resistant structures

c': The ratio of fire resistant structures

V_m : Fire speed inside fire resistant buildings

V_c : Fire speed inside collapsed buildings

V_{nn} : Fire speed from non-collapsed to non-collapsed buildings

V_{nc} : Fire speed from non-collapsed to collapsed buildings

V_{cn} : Fire speed from collapsed to non-collapsed buildings

V_{cc} : Fire speed from collapsed to collapsed buildings

Table 2 Parameters of ignition PDF

	$v(m^2/\min^2)$	k
Main pipe	0.0036	0.999

Using these data, the probability density function for time of ignition is shown in Fig. 8.

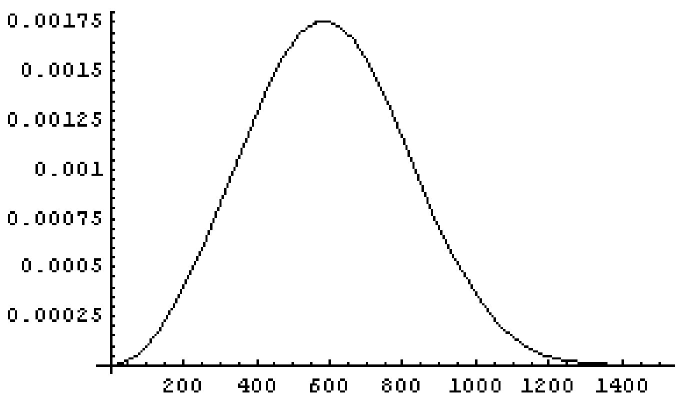

Fig 8 PDF for ignition time

Probability of existence of flammable plume depends on weather condition. For this region p_p is assumed to be 0.75.

Using Tosho method $A_F(t)$ is calculated and shown in Fig. 9.

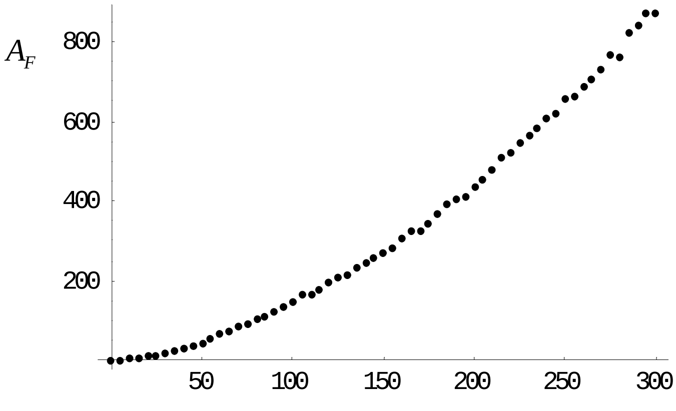

Fig 9 Growth of A_F in time

Having A_F and f_{Ig}, $l_F(t)$ can be calculated. Estimation for the example region is as follows:

$$l_F(t) = p_p * val * \begin{cases} 0.01757t^2 - 0.06133t & 0 \le t \le 20\,\text{min} \quad (R^2 = 0.97) \\ 0.01210t^2 + 0.0067t - 21.0955 & 20\,\text{min} \le t \quad (R^2 = 0.95) \end{cases} \tag{19}$$

Conclusions

In this paper a model for ignition and spreading of fire following an earthquake was proposed. Using such a model developing a method for estimating losses due to fire following an earthquake is possible. The model for gas ignition was proposed in a probabilistic form. In addition, a method of modeling was investigated for ignition. Some modifications were applied to Tosho method for using it as a fire spreading model. Finally application of the proposed model was illustrated via an example.

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