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A Fire Ignition Model and its Application for Estimating Loss due to Damage of the Urban Gas Network in an Earthquake

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ABSTRACT

Damage of the urban gas network due to an earthquake can cause much loss including fire-induced loss to infrastructure and loss due to interruption of gas service and repairing or replacing of network elements. In this paper, a new fire ignition model is proposed and applied to a conventional semi-probabilistic model for estimating various losses due to damage of an urban gas network in an earthquake with the aim of developing a reliable tool for better designation of resources. The suggested fire ignition model takes into account parameters such as density of gas, characteristics of gas dispersion in a city, distribution of power lines as sources of ignition, and wind speed. Because of several parameters involved, inevitably a logical combination of deterministic and probabilistic variables is applied in the loss estimation model. Economic impacts of spreading of fire, gas service suspension, and gas network damage are modeled within the same semi-probabilistic framework utilizing weight functions. Assessing different fire scenarios is possible in the model for loss estimation. The model is applied to selected examples of actual urban area earthquake scenarios and the results are discussed.

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1. INTRODUCTION

Earthquake loss estimates are forecasts of damage from future earthquakes and human and economic impacts that may arise [1]. As is asserted by FEMA [2], while loss estimation models are sophisticated, they are powerful tools for developing emergency plans and urban earthquake crisis management procedures [3, 4].

There are many studies in the field of loss estimation for buildings and lifelines. A general framework and formulation is proposed by the Pacific Earthquake Engineering Research Center (PEER) for probabilistic loss estimation. Using First Order Second Moment (FOSM) method, Baker and Connell have estimated the total uncertainty of the PEER formulation [5]. Brito and Almeida [6] developed a model for risk ranking of gas pipes using the multi-attribute utility theory. The model can be used by decision makers for prioritizing of critical sections of gas pipelines.

Estimating earthquake induced loss is a complex calculation. In the case of loss due to damage of gas network for instance, function of each lifeline member (a pipe or regulator) depends on other members, i.e., a member with no damage may stop servicing if its start and end nodes are not fed. In addition, function of a lifeline member depends on its location and age. Moreover, some events following damage of a lifeline have wide effects on societies. Thus to develop a useful tool for decision making, lifelines vulnerability should be assessed in connection with other urban elements and in a systematic approach [7]. That is why some basic models are used in this research to develop the loss estimation model. Between the models used herein, gas ignition model has been developed for the first time in this research and other models have been adopted. In fact, the presented loss estimation shows the application of the ignition model (in conjunction with other basic models). The presented loss estimation model comprises gas service failure, pipe body damage and fire due to

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gas release. The latter one needs models for ignition (developed herein) and fire spreading.

Fire following earthquake plays a remarkable role in the total loss due to an earthquake. For instance, based on a research done by San Francisco Department of Building Inspection, the fire following earthquake loss can reach $US 10.3 billion (2010) in this city. This loss is estimated to be in the range of $US 300-450 billion for Tokyo under 1923 earthquake in this city, based on a report by Risk Management Solutions [8]. In regard to loss of fire following an earthquake, gas-related damages account for 26% of fire ignitions where 56% is related to electrical damages and the rest has other causes [9]. The former source is considered in this paper.

At present the literature is under-developed regarding fire following earthquake, however significant researches have been launched in recent years. Models developed by Scawthorn have been frequently referenced in researches and technical reports in this area [10, 11]. His models consider building density, wind velocity and seismic intensity to estimate number of ignitions in an urban area. Trifunac et al. also developed empirical relations for estimating number of ignitions in urban area, considering data gathered from Northridge earthquake [12]. Moreover, HAZUS, as a well-known methodology for loss estimation, also uses empirical relations to calculate the expected number of ignitions [13]. Previous earthquakes data have been analyzed using generalized linear models with the aim of estimating location and number of ignitions due to an optional earthquake [14]. Ignitions stem from inside of structures have been estimated applying a probabilistic framework to analyze different events resulting in such ignitions by Zolfaghari et al. [15]. In contrast to the mentioned models that mostly have proposed empirical relations, an analytical approach is considered herein to develop the ignition model. This model is limited to ignition due to gas network damage and does not cover other sources of ignition.

American Lifeline Alliance (ALA) sets four design goals for a gas network. The goals are protecting public and social safety, maintaining system reliability, preventing monetary loss, and preventing environmental damage [16]. Regarding methods of measuring system performance, three general methods including graphic, localized and simulation methods are described in the above reference. In such a classification, this study uses the third method. Two approaches can be applied for seismic loss estimation including the deterministic and probabilistic methods. In the deterministic approach usually the amount of damage is measured by repair rate (repairs per unit of length or area) and the expected mean of damage is reported. Some equations for calculating repair ratio of buried pipes are presented in HAZUS [13]. Because of uncertainty existing in several parameters involved in the loss estimation process, the deterministic approach cannot be solely applied in decision making for a city [1]. The proposed method in the present paper has a probabilistic framework, although some of the applied models are deterministic.

The main contribution of this study is developing a new ignition model for the fire of a gas network following an earthquake. Parameters such as density of gas, characteristics of gas dispersion in a city, distribution of power lines as sources of ignition, and wind speed are taken into account. Then the model is applied to a semi-probabilistic combination of various types of losses and the total loss is estimated as a function of elapsed time after occurrence of an earthquake. Three types of losses are considered including losses due to spreading of fire in urban areas (an induced physical loss), gas service disruption (a direct social economic loss), and damage of network elements consisting of pipes and regulators (a direct physical loss). Although it is possible also to estimate the indirect losses using the loss types considered in this study, no estimation will be given for this type of loss since the emphasis here is only on the physical losses.

2. THE BASIC MODELS

A model to estimate loss due to gas network fire needs models for pipe failure, spread of gas, ignition of fire, and fire spreading. These are called the basic models in this study. The general characteristics of the basic models are mentioned in Table 1. These models are described in more detail in the sections followed.

2. 1. The Probabilistic Model for Gas Pipe Failure

The gas pipe network includes two parts: the underground pipes, and the pipes attached to buildings. Failure of these two parts is considered separately.

TABLE 1. General characteristics of the basic models

Basic model	Components	Characteristic
Pipe failure (adopted from [16])	Corrosion	Probabilistic
	Equation of pipe bending due to liquefaction	Deterministic
	Mechanical properties of pipe	Probabilistic
	Amount of liquefaction settlement	Deterministic
	Occurrence of earthquake and liquefaction	Probabilistic
Gas spreading (the Gaussian model)	Density of gas in air	Deterministic
Fire ignition (developed in this study)	Minimum flammable density of gas	Deterministic
	Cause of fire	Probabilistic
Fire spreading (adapted Tosho model [16])	The Tosho model parameters	Deterministic

2. 1. 1. The Underground Gas Pipes The effect of earthquake on buried pipes can be divided into those due to wave propagation and those attributed to permanent ground deformations [17, 18]. It is perceived that pipe damage is mainly due to the latter effect in which about 80% of events appear as failure and the rest as leakage [19-22]. On the other hand, liquefaction is known to be responsible for about 88% of permanent ground deformation events in earthquakes [22]. Therefore, liquefaction is the main cause for pipe damage in potentially liquefiable areas. Numerous models have been developed for probabilistic estimation of pipe damage under earthquake. Much of these models predict number of failures in different parts of a network but some of them give the probability of failure of a certain pipe in a network. Since analysis of the network is a main step in developing the loss model, in the present study the behavior of each pipe of a network will be evaluated separately. Recently, the equally important phenomenon of corrosion has been considered when evaluating probability of seismic pipe damage. For the purpose of the present study the liquefaction-corrosion induced failure model proposed in the literature [16] was adopted as a more realistic approach. In this model, the bending angle of pipe is considered as the main parameter determining the pipe failure.

2. 1. 2. The Pipes Attached to Buildings Based on the observations and experimental research presented in the literature [23], pipes and regulators attached to a building are susceptible to failure when the building collapses. In addition, the mentioned report asserted that if the wall is not connected to a roof, court yard wall for instance, the attached pipe or regulator survives without major damage. In a certain part of a city, it is reasonable to assume that half of buildings have regulators attached to a roof-connected wall. Therefore, estimating the number of collapsed buildings in a certain earthquake in a city is essential.

Estimation of the number of the collapsed buildings can be accomplished using a damage index (DI). The DI represents the building performance against an earthquake and varies between zero and one. In this study, DI is estimated using the equation proposed by Bozorgnia and Bertero [24]. This is described as follows:

$$DI = \left[\frac{(1-\alpha)(\mu - \mu_e)}{\mu_{mon} - 1} \right] + \alpha \frac{E_H}{E_{H,mon}} \quad (1)$$

in which:

$$\mu_e = \frac{u_e}{u_y} \quad (2)$$

where α is a constant accepting values between 0 and 1 as a function of previous earthquakes, μ is displacement ductility, u_e is the maximum elastic displacement of a single degree of freedom system, u_y is maximum displacement of the building under elastic condition, μ_{mon} is monotonic displacement ductility capacity, E_H is hysteretic energy demanded by the earthquake ground motion, and $E_{H,mon}$ is the hysteretic energy dissipation capacity under a monotonically increasing deformation.

The sources of uncertainty in building failure due to earthquake include uncertainty in structural behavior and uncertainty in seismic loading. In this research the structural behavior is evaluated deterministically by assuming the exact limit of DI=0.7 being equivalent to collapse [24]. For building evaluation, first an appropriate acceleration design spectrum is selected. Then the peak ground acceleration (PGA) required for each building type in the area to assume a value of DI=0.7 is determined using Equation (1). The probability of exceeding of PGA in the study area over the PGA corresponding to DI=0.7 is considered as the probability of failure of each building type. With the buildings' collapse probability and the number of buildings known, the total number of failures can be estimated. Therefore, in the process of estimating number of collapsed buildings, here the occurrence of earthquake is considered to be probabilistic while the structural behavior is assumed to be deterministic.

2. 2. Gas Spreading Model Several models have been proposed for gas spreading in air. These models cover sources like exhaust gas of a car, gas exiting from chimney of a factory, etc. For the gas spreading from an urban gas pipelines the Gaussian model is widespread. It is usually used for the gases having similar densities as air. In this model, the density distribution of gas is assumed to be bell shaped in the wind direction [25].

Figure 1 shows growing shape of a zone with a certain gas density using the Gaussian model. Similar distances between the contours in wind direction demonstrate the fact that growth rate of the plum can be assumed to be solely dependent on wind speed. Thus, it can be assumed that a certain density of gas spreads with almost a constant speed. This important result is used in the latter sections to estimate the time needed for ignition.

2. 3. The Proposed Model for Ignition of Gas The basic idea for developing the fire ignition model in this study is the fact that adjacent excitations like sparks of power lines result in ignition of gas. This fire ignition model is developed for urban areas. In this regard, each excitation is taken as a trial having a certain probability of success. The other modeling assumptions are as follows:

- A certain 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 (including power lines), wind speed and other parameters affecting gas dispersion.

Regardless of the source of excitation, the average number of excitations in a region in a time interval (t,t+Δt) can be estimated as:

$$n = S(t)\rho_s \rho_t \Delta t \tag{3}$$

In which, *S(t)* denotes the area of flammable plume at time *t*; ρ_s is the number of excitations in unit area; and ρ_t is the number of excitations in unit time. If time *t* is divided to *m* intervals, the probability of at least one successful trial (ignition) until a certain time t_0 (t_0 is the moment in which ignition starts) is:

$$P(m < M) = 1 - \prod_{m=1}^{M} k^{S(t)\rho.\Delta t}$$
$$M = \frac{t_0}{\Delta t}, \qquad \rho = \rho_s \rho_t \tag{4}$$

where, *k* denotes the probability of an unsuccessful trial (no ignition in a trial); and Δ*t* is the elapsed time in each time interval. Because of constant characteristics in each region, *k* is constant. Therefore:

$$P(m < M) = 1 - k^{\sum_{m=1}^{M} S(m.\Delta t)\rho\Delta t} \tag{5}$$

If the shape of gas plume is approximated with an ellipse, the area of flammable gas is estimated as:

$$S(t) = \pi (V_H * V_l) t^2 \tag{6}$$

$$V^2 = V_H * V_l \tag{7}$$

$$S(t) = \pi V^2 (m.\Delta t)^2 \tag{8}$$

Thus, the number of trials until time *t* is:

$$\sum_{m=1}^{M} S(m.\Delta t)\rho.\Delta t = \pi V^2 \rho \sum_{m=1}^{M} (m.\Delta t)^2 \Delta t \tag{9}$$

$$\Delta t = \frac{t}{M} \tag{10}$$

Therefore, the probability of a successful trial (resulting in ignition) before time *t* is:

$$P(m < M) = 1 - k^{\left(\pi V^2 \rho. t^3 \frac{\sum m^2}{M^3}\right)} \tag{11}$$

In which:

$$\lambda = \frac{\sum_{m=1}^{M} m^2}{M^3} \tag{12}$$

Then the probability density function can be calculated as follows:

$$F(t) = \lim_{M \to \infty} 1 - k^{\pi V^2 \rho. t^3 \lambda} \tag{13}$$

$$\lim_{M \to \infty} \lambda = \lim_{M \to \infty} \frac{\sum_{m=1}^{M} m^2}{M^3} = \lim_{M \to \infty} \frac{(1+M)(1+2M)}{6M^2} = \frac{1}{3} \tag{14}$$

Therefore:

$$F(t) = 1 - k^{\frac{\pi V^2 \rho. t^3}{3}}$$
$$\pi V^2 \rho = \nu \tag{15}$$

Derivation of $f(t_0)$ with regards to *k* gives:

$$f(t) = -\nu \ln(k)\, t^2 k^{\frac{\nu t^3}{3}} \tag{16}$$

Figure 2 illustrates the probability density function (PDF) for ignition as a function of the elapsed time from the start of gas leakage.

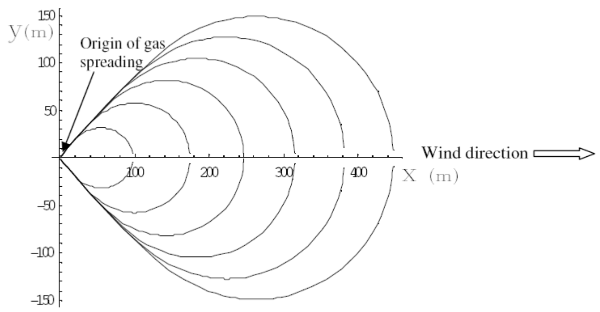

Figure 1. Growing of gas boundary with a certain density

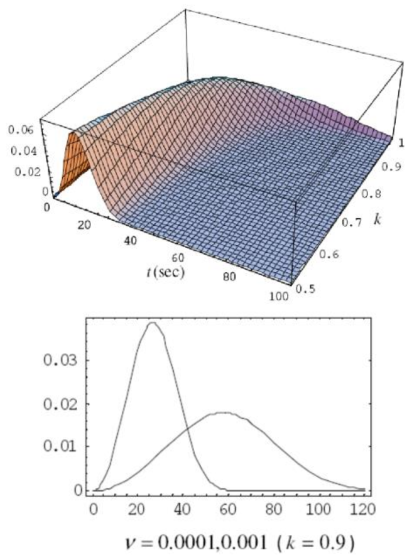

Figure 2. *f* (the probability density function) as a function of *k* (probability of no ignition) and *t* (time)

To calculate v, the minimum flammable density of gas should be known. Experiments are needed to measure this parameter. As there is a linear relation between gas density in plume and discharge of the leaked gas, it can be assumed that in a certain region v is proportional to gas discharge. Therefore, despite the need for tests, by knowing the pipe diameters and gas pressures in different regions it is possible to compare between different values of v.

In the proposed formulation, k indicates the potential of a region for ignition. k is smaller in work times (9-17 hours) than in nights. In cold and wet nights k is a minimum and it is a maximum in hot and dry days.

2. 4. Models for Fire Spreading A comprehensive model for fire should cover two events, including ignition and spreading. The various existing models for fire spreading can be categorized as statistical, semi-computational, and computational methods. In the ignition model, estimation of number of ignition points is important. The Hamada model for fire spreading [26] has been used widespreadly. For example, HAZUS uses Hamada model as its fire spreading model [21]. A more precise model, the Tosho method, was proposed in 1997 and is used by Tokyo Fire Department [16]. An oval shape is presumed for the fire boundary in the Tosho model.

In the present study the Tosho model is used to estimate the rate of fire spreading but the spread direction is determined utilizing Equation (1). In the other words, the Tosho model is adapted here to take the urban open spaces into account. In this regard, growth of the burned boundary is supposed to be in the wind direction. Use of the vector of wind velocity in the fire spreading model helps modeling of obstacles like urban open spaces be easily accomplished. Thus, the vector of fire growth in unit time can be written as Equation (17).

$$\vec{V}(x,y,\vec{\dot{U}})=V\left(x,y,\left|\vec{n}\cdot\vec{U}\right|\right)\ \vec{n} \tag{17}$$

where, $\vec{\dot{U}}$ and $\vec{U}$ denote the vectors of wind blowing velocity and displacement, respectively; $\vec{n}$ is the boundary normal vector at the point (x, y) and $\vec{V}$ is the vector of fire growth in unit time.

3. THE LOSS ESTIMATION MODEL

The semi-probabilistic models described above for gas pipe failure, gas spreading and ignition, and fire spreading are now applied to the problem of estimating loss due to earthquake damage of an urban gas network.

The diagram in Figure 3 schematically shows the suggested routine and its probabilistic components for estimating various losses due to damage of the urban gas network in a specific earthquake.

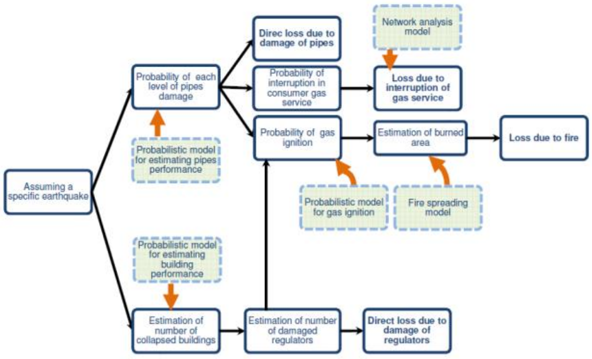

Figure 3. Proposed procedure for estimating loss

In this paper only physical losses directly related to gas network damage are considered. Thus, for example, loss due to building collapse as a direct result of an earthquake, not fire, is not modeled in the suggested method. Also indirect losses like injuries, death and psychological effects on humans are not figured out. Another important assumption is limiting the performance of the main pipes of each region only to feed (full pressure) and not feed (zero pressure) conditions, while in reality a range of different pressures in a pipe can be existing after an earthquake. In practice softwares specially developed for gas network analysis are used to estimate the working pressure at different nodes. With the help of an actual gas flow analysis, when the probability of seismic pipe failure is already calculated, the probability density function of gas pressure can be determined for the main pipe of each region. The exact analysis of gas network, that could have been done using a specialty software, was out of the scope of this research and was put aside for a later time. In the probabilistic model suggested in this work, the availability of the mentioned probability density function would result in a more accurate evaluation of the probability of feed and ignition of fire but that certainly would not alter the general aspects of the loss estimation model.

In the following sub-sections, components of the loss estimation model for calculating losses due to spread of fire in an urban area, interruption of gas service and damage of network elements, are described and then possible loss scenarios are discussed.

3. 1. Spread of Fire in an Urban Area When calculating loss due to fire in city regions, parameters like gas leakage, possibility of gas ignition and rate of spreading have the main role. While the value of burned asset (direct and indirect) should be known beforehand but to keep the generality of the model, only a physical analysis is considered in this paper. If the total value of assets in a region is *val*, the following relation can be written for the average loss due to fire following an earthquake [27]:

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

In which, $l_F(t)$ is the average loss due to fire until time t; p_p is the probability of existence of flammable plume; f_{Ig} denotes the probability density function for gas ignition; $A_F(t)$ denotes burned area until t, and t_{Ig} is the time of ignition.

3. 2. Interruption of Gas Service To emphasize the importance of this kind of loss, it should be mentioned that various industries including heavy sectors are consumers of gas service. For these consumers disruption of energy can cause a considerable amount of loss.

In this paper l_{ss} shows loss due to interruption of gas service. l_{ss} is a function of time, i.e., the more the time to reconnect gas service, the more the loss for consumers. Thus, l_{ss} not only depends on earthquake intensity but also on ability of technical teams to repair and return the gas system again to work.

In this study, the probability of interruption of gas service to a region has been calculated using the Fault Tree method. In this method gas network is modeled as nodes and connecting links. The set of links (pipes) with their malfunction causing interruption of gas flow in a region is called the Minimal Cut Set. Having the probability of pipes damage in an earthquake and the Minimal Cut Sets of a region, the probability of occurrence of a set of pipe damages causing cut-off in a region can be calculated. Details of the method are available elsewhere [28-30].

3. 3. Damage of Network Elements As experiences with previous earthquakes show, because of pipes being in huge numbers, these components are the most vulnerable elements in an urban gas network. This kind of loss can be divided into two types: damage of buried main pipes of each region, and damage of consumer pipes and/or regulators attached to buildings. This fact was explained in sections 2.1.1 and 2.2.2.

For the buried pipes, different probabilistic methods have been developed for estimating their performance subjected to earthquake [31]. HAZUS has suggested a probabilistic based formula for estimating number of damaged pipes for each level of damage [21]. The main ingredients of the HAZUS formula are peak ground velocity and displacement. In this study probability of underground pipe damage is calculated using the HAZUS procedure.

Regulators damage, as the main reason for fire in a gas network, is mostly due to collapse of the nearby building. Thus, to estimate the number of damaged regulators, the number of collapsed buildings must be estimated. Such estimation has normally to be applied to large areas with huge numbers of buildings. For this reason, the Damage Index (DI) has been used as an effective tool to calculate the amount of earthquake damage in a building, as mentioned in section 2.2.2. Therefore, damage of regulators will need two prerequisites; first, regulator must be attached to a building (not to an independent wall), and second, building's DI must be larger than a certain threshold, say, 0.7. If there is no information about regulators' location, it can be assumed that half of regulators are attached to buildings and the other half to court walls across the street [23].

In this paper l_{MR} is defined as the replacing cost of main pipes of a region, l_{1CD} is the cost of finding, repairing/replacing damaged regulators as well as testing and making regulators ready to use and l_{2CD} is cost of finding, repairing/replacing damaged consumer pipes plus testing and making consumer pipes ready to use.

As regulator damage depends on incidence of building collapse, the mean of l_{1CD} is:

$$\bar{l}_{1CD} = \sum_n p_i m_i \times l_{1CD} \qquad (19)$$

In which, n= Number of building types; m_i= Number of building in type i; p_i= Probability of collapse of a building in type i.

As it is assumed that in half of the buildings regulator is attached to a roof-connected wall, the number of collapsed buildings resulting in collapse of regulators will be $0.5\sum p_i m_i$.

3. 4. Loss Scenarios and Mean of Loss To estimate each loss numerically and calculate its contribution to the total loss in a region, in this section possible scenarios and related assumptions for various losses are discussed.

3. 4. 1. Possible Events Immediately after an earthquake, for the main pipe of a region one of two conditions can be presumed: connected or interrupted. If the start or end nodes of a link (region main pipe) are being fed, the link is in connected condition. Then events *I* to *IV* and their sub-events in the order of criticalness may occur as follows:

I: Breakage of a region main pipe

- Gas service in the region is interrupted
- Main pipe of the region must be replaced
- Fire is probable in an area near the main pipe
- Consumer pipes and regulators may become damaged

II: Gas leakage from a region main pipe

- Main pipe of the region must be replaced; thus interruption in the region gas service will occur
- Fire is probable in an area near the main pipe
- As consumer pipes are being fed, ignition of fire is probable due to damage of consumer pipes and/or regulators

- Consumer pipes and regulators may become damaged

III: No damage in a region main pipe

- As consumer pipes are being fed, fire is probable due to damage of consumer pipes and/or regulators
- Consumer pipes and regulators may become damaged

IV: Disconnection of a region main pipe

- The gas service in the region is interrupted
- Region main pipe may break or leak
- Consumer pipes and regulators may become damaged

Based on the mentioned events, three forms of losses can be defined which are called $\bar{l}_I$, $\bar{l}_{II}$ and $\bar{l}_{III}$, noting that fire is improbable in event *IV*.

3. 4. 2. Estimating Mean of Loss For loss estimation, the events and sub-events described in the previous section are utilized through their expected loss and probability of occurrence.

Parameters to be used are as follows:

$l_F^{\mathrm{Re}}(t)$: Loss due to fire in a region when time t has elapsed

l_{CD} : Mean of loss in a region due to damage of consumers pipe and regulators

l_{MR} : Loss due to replacing main pipe of a region

l_{SS} : Loss due to interruption in gas service

$l_i^F(t)$: Fire loss in event i (i=*I, II, III*)

$l_{II}^j(t)$: Loss in event *II* when sub-event "j" has happened (j=a, b, c defined in Figure 4)

$l_i(t)$: Loss function in event i (i=*I, II, III*)

$f_{Ig,MR}(t)$: Probability density function for ignition due to main pipe's break

$f_{Ig,CR}(t)$: Probability density function for ignition due to regulator's break

$f_{II,I}(t)$: Probability density function for change of event *II* to *I*

$F_{II,I}(t)$: Cumulative distribution function for change of event *II* to *I*

p_p : Probability of existence of the flammable volume of gas

n : Number of building types

m_i : Number of buildings in the ith type ($1 \le i \le n$)

p_i : Probability of collapse for buildings in the ith type ($1 \le i \le n$)

p_j : Probability of occurrence of event j (j=*I, II, III, IV*)

For simplicity, it is assumed that rate of fire spreading and value of burned assets are uniformly distributed in the region under study. Of course any other assumption is also possible and applicable in the model. Repair activities after an earthquake have not been considered in the proposed model (see definition of l_{MR}, l_{1CD}, and l_{2CD} in Sec. 3.3). In event *I*, fire can occur only adjacent to the main pipe of the region. Thus the expression related to fire loss inside the region vanishes in this event. If fire starts near the main pipe of a region at time t_{Ig}, $l_F^{\mathrm{Re}}(t-t_{Ig})$ shows fire loss at time t. Thus mean of loss in event *I* is:

$$\bar{l}_I(t) = l_I^S + l_I^F \tag{20}$$

In which:

$$l_I^S = l_{MR} + l_{CD} + l_{SS} \tag{21}$$

$$l_I^F(t) = p_p \int_{t_{Ig}=0}^{t} f_{Ig,MR}(t_{Ig}) l_F^{\mathrm{Re}}(t-t_{Ig}) dt_{Ig} \tag{22}$$

As defined previously, p_p is the probability of existence of the flammable plum of gas. This parameter depends on weather conditions like wind speed and humidity [27].

In event *II*, one of the three sub-events is possible at time t. This fact is described in Figure 4. Therefore mean of loss in event *II* is:

$$\bar{l}_{II}(t) = p_p(1-F_{II,I}(t))l_{II}^a(t) + p_p(F_{II,I}(t))l_{II}^b(t) + (1-p_p)l_{II}^c(t) \tag{23}$$

In which:

$$l_{II}^a(t) = \int_{T=0}^{t} f_{Ig,CR}(t) l_F^{\mathrm{Re}}(t-T)dT + l_{CD} + l_{MR} + l_{SS} \tag{24}$$

$$l_{II}^b(t) = \int_{t_{II}=0}^{t}\left(f_{II,I}(t_{II})\left[p_p \sum_{i=1}^{n}(p_i m_i)\int_0^{t_{II}} f_{Ig,CR}(\bar{t}_{II}) l_F^{\mathrm{Re}}(t-\bar{t}_{II})d\bar{t}_{II} + l_I^F(t-t_{II})\right]\right)dt_{II} + l_{CD} + l_{MR} + l_{SS} \tag{25}$$

$$l_{II}^c(t) = l_{CD} + l_{MR} + l_{SS} \tag{26}$$

The parameters of the above formula are defined at the beginning of this section. In all sub-events of event *II*, the loss includes l_{CD} and l_{MR}. Since interruption in gas service is also not avoidable, the term l_{SS} also appears in loss formula in the three mentioned sub-events. If weather conditions are not suitable to form the flammable volume of gas, ignition will not be probable in event *II*.

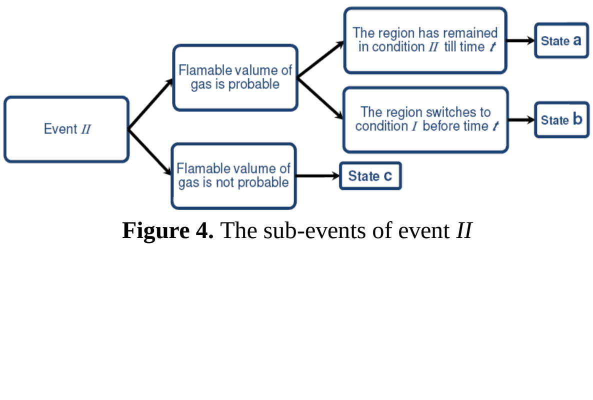

Figure 4. The sub-events of event *II*

Sub-event "c" refers to this situation. In sub-event "c" loss is solely limited to l_{CD} , l_{MR} and l_{SS}. If fire occurs in event *II*, the region will switch to event *I*. Fire is probable inside the region because regulators are being fed, before fire is initiated at the main pipe. $\bar{t}_{II}$ is time of initiation of fire in the region; thus at time *t*, l_F^{Re} would have time $t-\bar{t}_{II}$ to cause loss. When gathering of the flammable volume of gas from the main pipe of a region is probable but no fire has been initiated from this pipe, region's condition will be similar to event *III*. In this situation, regulators are being fed and fire is probable inside the region.

In event *III* consumer pipes and regulators will be damaged but main pipe of the region will not. In this event two types of losses including loss due to damage of consumer pipes and regulators and loss due to fire initiated from regulators are expected. Therefore regulators have the main role for the extent of loss in this case. The *i*th damaged regulator after time *t* causes $loss(t\text{-}T_i)$. T_i is the time between the regulator being damaged and ignition of fire.

As noted earlier, failure of regulators is assumed to be solely because of building collapse. In this study the effect of failure of a building on failure of the adjacent building is neglected; therefore there is no cross-correlation in buildings collapse. With such an assumption, failures of regulators will also be independent of each other. Therefore, the total loss due to regulators damage is calculated as follows:

$$\bar{l}_{III}(t)=E\left[loss(t-T)\right]\sum_{i=1}^{n}p_i m_i \qquad (27)$$

The term *loss(t-T)* has two components as loss due to fire and loss due to damage of regulator itself. Therefore mean of loss in event *III* is as follows:

$$\bar{l}_{III}(t)=E\left[l_F^{\mathrm{Re}}(t)\right]\sum_{i=1}^{n}p_i m_i + l_{CD} \qquad (28)$$

$$E\left[l_F^{\mathrm{Re}}(t)\right]=p_p\int_{T=0}^{t}f_{Ig,CR}(t)\,l_F^{\mathrm{Re}}(t-T)\,dT \qquad (29)$$

In event *IV* no fire is probable neither from main pipe of the region nor from regulators. Thus mean of loss in this event is:

$$\bar{l}_{IV}(t)=l_{SS}(t)+(p_I+p_{II})l_{MR}+l_{CD} \qquad (30)$$

Finally, based on the discussed events, mean of loss for a region when an earthquake occurs is as follows:

$$\begin{aligned}\bar{L}(t)&=p_{IV}\,l_{IV}(t)\\&+[(1-p_{IV})(p_I l_I(t)+p_{II}l_{II}(t)+p_{III}l_{III}(t))]\end{aligned} \qquad (31)$$

In which:
p_I, p_{II}, p_{III} and p_{IV} are probabilities of occurrence of events *I* to *IV*, respectively, calculated using the model described in Sec. 2.1 for pipe damage; $\bar{L}(t)$ is the mean of total loss due to gas network damage for a region when an earthquake occurs.

Using Equation (31), it would be possible to calculate the proportion of each type of loss in the total loss.

Loss in a region includes l_{CD} in all cases, which is related to the number of damaged regulators and consumer pipes. As mentioned previously, number of damaged regulators in a region can be estimated as $0.5\sum p_i m_i$. On the other hand, number of damaged pipes can be estimated with *Repair Rate* defined in reference [22] as "repairs per 1000 feet or repairs per km". Thus the share of l_{CD} in Equation (31) is:

$$Rl_{CD}=l\times\sum p_i m_i l_{1CD}+R.R\times pl\times l_{2CD} \qquad (32)$$

In which:
Rl_{CD}: Share of l_{CD} in the region's total loss
R.R: Repair rate;
pl: Total length of pipes in the region;

l_{MR} appears when computing loss for all events except event *III*. Using Equation (31) the proportion of l_{MR} in the total loss is:

$$Rl_{MR}=(p_I+p_{II})l_{MR} \qquad (33)$$

l_{SS} appears in events *I*, *II* and *IV*. Its proportion in the total loss is:

$$Rl_{SS}=[p_{IV}+(1-p_{IV})(p_I+p_{II})]l_{SS} \qquad (34)$$

Loss due to fire depends on time; in fact the fire loss in each region is an increasing value with time (Equations (35-37)).

$$Rl_I^F=[(1-p_{IV})p_I]l_I^F(t) \qquad (35)$$

$$Rl_{II}^F=[(1-p_{IV})p_{II}]l_{II}^F(t) \qquad (36)$$

$$Rl_{III}^F=[(1-p_{IV})p_{III}]l_{III}^F(t) \qquad (37)$$

There are a few suggested equations for fire spread rate. In this paper, fire spread rate is evaluated by the Tosho method [16]. In this method more parameters are considered in comparison with the previous methods like Hamada method which is used in HAZUS. The area of the burned zones is estimated with the method suggested in the literature [23]. In this method the direction of fire spreading is determined considering wind direction and the form of the fire boundary in each time step.

4. EXAMPLE OF APPLICATION

In this section estimation of loss for an example network in earthquake is considered. Each region in the example network is assessed separately and rate of growth of loss functions is calculated. This in turn results in the ability to compare various types of losses in different regions and to compute the total loss.

4. 1. Basic Data As shown in Figure 5, the example network has 13 regions. Each region is defined as the area being fed from a certain main pipe. Dashed lines in Figure 5 show regions attributed to each main pipe. Each region is named using start and end node numbers. For example in region 1-2 start node of the main pipe is 1 and end node is 2. A number of properties are assumed to be identical in all regions; they are: probability of occurrence of the flammable volume of gas (p_p), wind speed, and, humidity. p_p is assumed to be 0.75 or example regions. It means weather condition is such that in 75 percent of days occurrence of the flammable volume of gas is probable.

Humidity and wind speed are supposed to be 35% and 3*m/s*, respectively. For earthquake scenario the design earthquake is considered, i.e., the earthquake with occurrence time of 475 years. As this is the standard earthquake of any seismic design code, for numerical analysis the design spectral values corresponding to the fundamental periods of the buildings are used. For calculating the fire loss, it is assumed that there is a linear relation between the amount of loss and the amount of burned area in a region. This is equivalent to assume a uniform distribution of assets in a region. Moreover, the regions are divided into two groups differing only in the fire spreading properties. Group A consists of the regions 3-6, 4-5, 5-7, 6-7, 6-9, 7-8, and 8-9, and Group B includes the regions 1-2, 1-3, 1-4, 2-5, 2-8, and 3-4. Properties of the regions are as follows.

a) Gas ignition

Gas ignition characteristics for use in the model developed in this study, Sec. 2.3, are presented in Table 2.

b) Fire spreading

Fire spreading properties corresponding to the Tosho method are given in Table 3.

In Table 3:

a: Plan dimension of the building,

d: Spacing between buildings (door to door),

b': Ratio of non-damaged fire resistant structures to the total number of structures,

c': 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.

c) Building types

A type number is assigned to buildings with each structural system as presented in Table 4.

The buildings with the structural systems introduced in Table 4 are assumed to be distributed at identical percentages in all regions, as given in Table 5. Moreover, the collapse probability of each building type is calculated using the method described in Sec. 2.1.2 and presented in Table 5.

Using the method presented in Sec. 3.3, number of collapsed buildings will be 0.29N, where N is the total number of buildings.

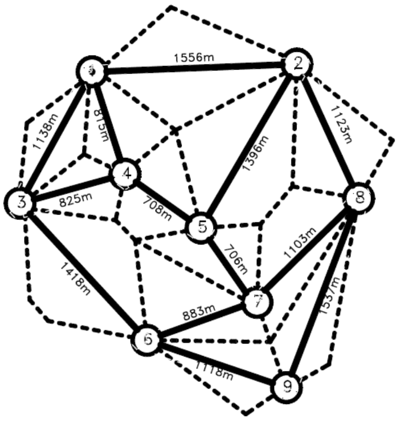

Figure 5. Example network and its regions

TABLE 2. Gas ignition characteristics

Parameters of the probability density function	v (m^2/min^2)	k
Breakage of main pipes	0.0036	0.999
Leakage of main pipes	0.0018	0.999
Regulators	0.0018	0.999

TABLE 3. Values of the parameters of the fire spreading model (units: m. & sec.)

Parameters		a	d	b'	c'	b_w	f_b	v_m	v_c	v_{nn}	v_{nc}	v_{cc}
Group A		12	2	Var.	0.8	10	4	25	30	24	24	20
Group B	**30% of regions**	12	2	Var.	0.8	10	4	33	35	31	31	22
	70% of regions							15	19	15	15	12

TABLE 4. Type number of buildings with each structural system

Structural system	Number of stories							
	1	2	3	4	5	6	7	8
Non seismic resistant	1	1	-	-	-	-	-	-
Seismic resistant concrete structure	2	4	6	8	10	12	14	15
Seismic resistant steel structure	3	5	7	9	11	13	-	-

TABLE 5. Percentage and collapse probability of each building type

Type of building	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Percentage in every region	8	5	4	15	12	18	10	9	7	4	2	3	1	1	1
Probability of collapse (%)	100	4	15	46	75	49	61	54	75	63	77	80	73	69	70

4. 2. Probabilities of Pipe Events Regarding pipe events mentioned in Sec. 3.4.1, corrosion rate and liquefaction effects are considered and probabilities of break and leakage of pipes are calculated using the method presented in reference [16].

In this method the fragility curves of buried pipes are calculated considering corrosion rate, pipe diameter, soil properties and the site's seismic risk. In this example it is assumed that these probabilities are known. Pipe diameters are given in Figure 6 and probability of pipes failure in Table 6.

Now, the probability of a pipe being fed or not can be calculated using the fault tree method. For instance, the probabilities of selected regions not being fed are presented in Figure 7. Using Table 6 and data similar to Figure 7, probabilities of events I to IV of Sec. 3.4.1 can be calculated.

4. 3. Estimating Losses in Each Region Among losses defined in Sec. 3.4.2, l_{1CD} and l_{MR} can be estimated using equations suggested by ALA [22]. In this example it is arbitrarily assumed that pipe damage in regions 1-2, 1-3, 1-4, and 3-4 is due to the permanent ground displacement and in other regions due to the earthquake wave propagation. With the number of collapsed buildings estimated as in Table 5, $\bar{l}_{1CD}$ can be calculated using Equation (19). On the other hand, in this example l_{SS} is not estimated and just its proportion in the total loss is presumed to be a constant.

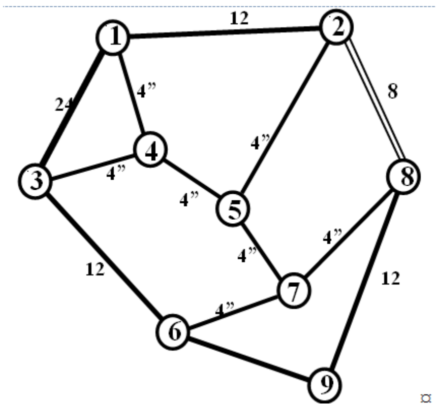

Figure 6. Diameters of pipes in the example network

TABLE 6. Probabilities of failure of the pipes

Pipe	Year 0-5	Year 5-10	Year 10-15	Year 15-20	Year 20-25	Year 25-30
	Probability of failure (%)					
1-2	0.79	5.17	12.28	20.51	28.75	36.42
1-3	0.09	0.92	2.73	5.15	9.07	13.30
1-4	7.0	9.91	14.05	19.92	28.23	40.0
2-5	4.0	8.4	10.6	12.8	15.0	17.0
2-8	2.0	3.6	5.2	6.8	8.4	10.0
3-4	7.0	9.91	14.05	19.92	28.23	40.0
3-6	1.0	2.4	3.8	5.2	6.6	8.0
4-5	7.0	9.91	14.05	19.92	28.23	40.0
5-7	4.0	8.4	10.6	12.8	15.0	17.0
6-7	4.0	8.4	10.6	12.8	15.0	17.0
6-9	1.0	2.4	3.8	5.2	6.6	8.0
7-8	4.0	8.4	10.6	12.8	15.0	17.0
8-9	1.0	2.4	3.8	5.2	6.6	8.0

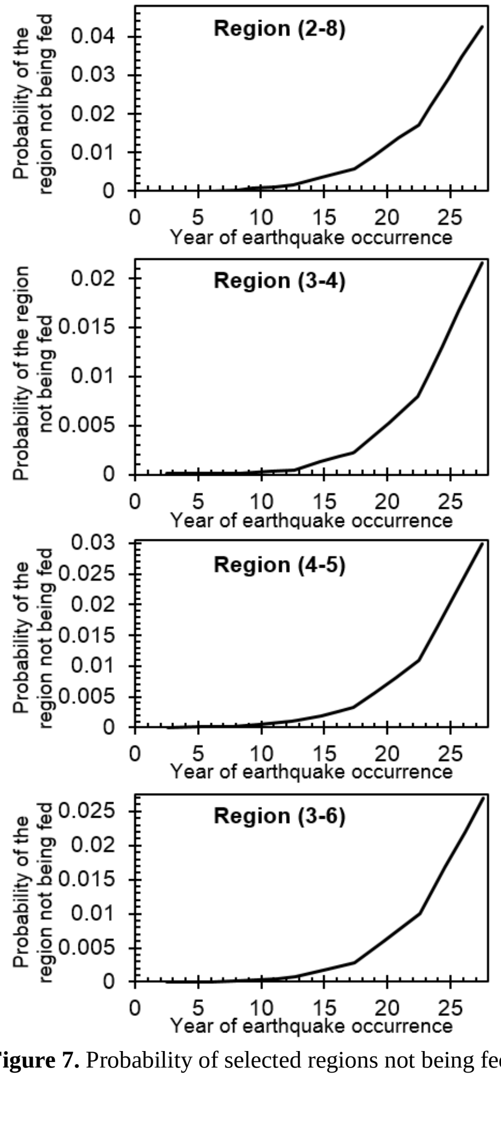

Figure 7. Probability of selected regions not being fed

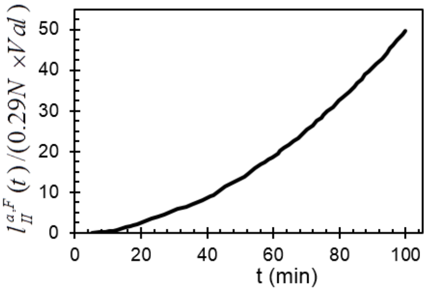

Figure 8. Fire loss for Group A regions under sub-event "a" of event II (see Figure 4)

To calculate the fire losses, using the Tosho method [16] a time-dependent function to estimate burned zones is obtained. As in this example a linear relation between the area of burned zones and the fire loss is assumed, the fire loss in each event can be estimated using the equations of Sec. 3.4.2. For instance, Figure 8 illustrates fire loss for Group A regions when the sub-event "a" of the event II, defined in Figure 4, occurs.

4. 4. The Total Loss To evaluate the proportions of various losses mentioned in Sec. 3, the total loss in a region is written as follows:

$$\bar{l}(t) = \sum p_i m_i \times l_{1CD} + a \times l_{2CD} + b \times l_{MR} + c \times l_{SS} + d \times Val \times l_I^F(t) + e \times Val \times l_{II}^F(t) + f \times Val \times l_{III}^F(t) \quad (38)$$

In Equation (38), coefficients *a* to *f* show proportion of each loss at time *t* in a region and *Val* is value of assets per unit area of the burned zone. The coefficients can be calculated using Equations (32) to (37). For instance, Table 7 presents the coefficients calculated for the region 1-2 for a 30 year interval. In this table, area of the region is 72.6 ha, length of the 4" main pipe is 11,118 m, number of families in the first year is 430, and number of buildings in the first year is 134.

In Table 7 it can be concluded that because of liquefaction, the proportion of loss due to pipe damage is relatively large for region 1-2. Similarly, the loss due to gas service disruption is also considerable. Figure 9 illustrates mean of the fire loss 60 minutes after earthquake for a 30 year period. This figure can be used to compare between various regions regarding fire loss.

As seen in Figure 10, the fire loss is negligible in the early minutes after earthquake but it follows a linear and then a parabolic pattern afterwards. Figures like Figure 10 can be helpful for preparing a dispatching plan for fire fighters beforehand.

It can be concluded from Figure 10 that among all regions, region 4-5 is the most vulnerable region to fire and region 1-2 is the next one. In region 4-5 number of buildings is nearly 30 percent less than region 1-3.

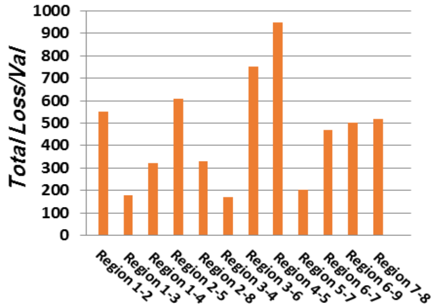

Figure 9. Fire loss in different regions, 60 minutes after earthquake

TABLE 7. Coefficients $a - f$ for the region 1-2 (see Equation (38))

Year of earthquake occurrence from the construction date	1-5	5-10	10-15	15-20	20-25	25-30
a	22	26	30	33	37	41
b	0.01	0.06	0.15	0.26	0.36	0.46
c	0.01	0.065	0.153	0.256	0.359	0.455
d	0.008	0.052	0.123	0.205	0.288	0.364
e	0.002	0.013	0.031	0.051	0.072	0.091
f	0.99	0.935	0.847	0.744	0.641	0.545

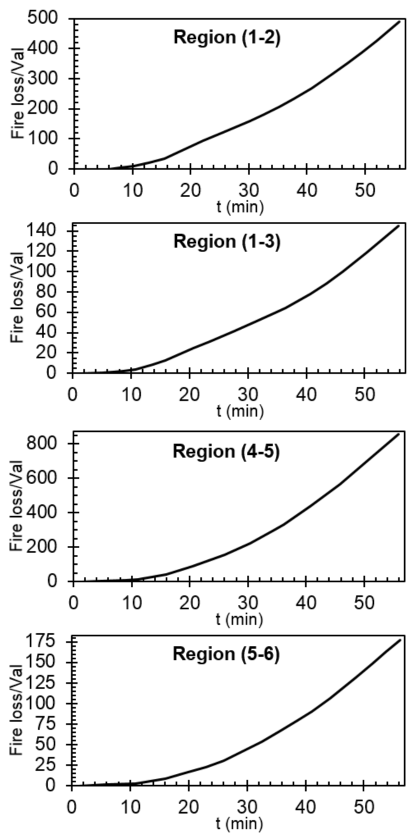

Figure 10. The fire loss vs. time for selected regions

However, the larger probability of damage of the main pipe in region 4-5 and this region being in Group A, have caused the amount of fire loss in region 4-5 being more than 60% larger than 1-2 after one hour.

The obtained charts show estimation of various losses in each region in detail, allowing comparison between different regions. In addition, prioritizing and scheduling of emergency actions after an earthquake can be accomplished using these charts. Also, effective remedies for reducing amount of loss in each region may be developed by studying relations between network characteristics and losses. These characteristics include shape of the network, rate of degradation of pipe strength and size, building properties, weather condition, etc.

As is more evident with the above example, in the loss estimation model used in this study, the effects of corrosion, liquefaction, building collapse, gas leakage, and fire ignition and spreading are properly taken into account. Among the mentioned parameters, corrosion is a factor resulting in an increased level of loss through increasing the probability of pipe failure. The probability of failure in the pipes subjected to corrosion is a continuously increasing quantity with time. Therefore the model proposed here can trace the growth of different loss probabilities in each region and relate them to the corrosion rate. Using this information, a network repair policy can be devised and prioritized. On the other hand, type and arrangement of buildings in a city affect not only the failure level of regulators but also the gas dispersion and rate of fire spreading. The presented analysis can be useful in designing an appropriate urban planning scheme to minimize probable fire losses due to earthquake. Such a scheme can include criteria for minimum open spaces or mean of building to building distances.

5. CONCLUSIONS

A fire ignition model was developed and applied to the problem of loss estimation due to damage of the urban gas network in earthquakes in this study. The proposed model takes into account essential factors including density of gas, characteristics of gas dispersion in a city, distribution of power lines as sources of ignition, and wind speed. In the loss estimation procedure, the probable events instantly after an earthquake in regions of city are closely considered.

The loss estimation model evaluated in this study needs some basic models including a probabilistic model of pipe damage due to an earthquake, a model for initiating gas ignition and a fire spreading model. The advantage of the developed fire ignition model in comparison to the other models is its benefit from more physical parameters. This helped this study achieve a comprehensive formulation for loss and combine various losses in a semi-probabilistic framework which cover all probable scenarios.

The loss diagrams calculated for each region in the example network illustrate how losses increase with time. A comparison between regions regarding each loss is also possible. Results of similar studies using the proposed semi-probabilistic model can help decision makers choose effective and efficient ways for reducing amount of loss in each region. Moreover, these results can be used to plan urban emergency activities after an earthquake. Further development of this model to enhance its accuracy and applicability seems to be necessary. This can include tasks such as accomplishing gas flow analysis within the model using the relevant specialty softwares as a part of loss estimation process, and developing a model for repair and maintenance of gas network after an earthquake.

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A Fire Ignition Model and its Application for Estimating Loss due to Damage of the Urban Gas Network in an Earthquake

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چکیده

خسارات وارد شده به شبکه گاز شهری در یک زلزله می‌تواند زیان‌های زیادی از جمله خسارت ناشی از آتش‌سوزی در شبکه زیر ساخت، و خسارت ناشی از قطع خدمات رسانی، تعمیر و تعویض اعضای شبکه، را در بر داشته باشد. در این مقاله یک مدل آتش‌سوزی پیشنهاد شده است. مدل پیشنهادی در یک مدل نیمه احتمالاتی مرسوم برای برآورد خسارت‌های مختلف ناشی از آسیب دیدن شبکه گاز شهری، به کار برده شده است. هدف از این کار توسعه یک ابزار قابل اعتماد جهت تخصیص بهتر منابع می‌باشد. در مدل آتش‌سوزی پیشنهادی اثر عواملی همچون چگالی گاز، خصوصیات گاز منتشر شده در شهر، توزیع خطوط اصلی به عنوان منابع اشتعال، و سرعت باد، در نظر گرفته شده است. به دلیل وجود چندین عامل مرتبط به هم، در مدل برآورد خسارت ترکیبی از متغییرهای احتمالاتی و تعینی به کار برده شده است. اثرات اقتصادی گسترش آتش، قطع خدمات گاز، و خسارت به شبکه گاز، نیز با استفاده از مدل با ساختار نیمه احتمالاتی مشابه و با استفاده از توابع وزنی، شبیه سازی شده است. ارزیابی سناریوهای مختلف آتش‌سوزی در مدل برآورد خسارت امکان‌پذیر می‌باشد. از مدل پیشنهادی در مثال‌های واقعی از سناریوهای زلزله در ناحیه شهری استفاده شده است و نتایج آن مورد بررسی قرار گرفته است.

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