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Further Development in Predicting Post-Earthquake Fire Ignition Hazard

Pegah Farshadmanesh, Jamshid Mohammadi, Mehdi Modares

***Abstract*—**In nearly all earthquakes of the past century that resulted in moderate to significant damage, the occurrence of post-earthquake fire ignition (PEFI) has imposed a serious hazard and caused severe damage, especially in urban areas. In order to reduce the loss of life and property caused by post-earthquake fires, there is a crucial need for predictive models to estimate the PEFI risk. The parameters affecting PEFI risk can be categorized as: 1) factors influencing fire ignition in normal (non-earthquake) condition, including floor area, building category, ignitability, type of appliance, and prevention devices, and 2) earthquake related factors contributing to the PEFI risk, including building vulnerability and earthquake characteristics such as intensity, peak ground acceleration, and peak ground velocity. State-of-the-art statistical PEFI risk models are solely based on limited available earthquake data, and therefore they cannot predict the PEFI risk for areas with insufficient earthquake records since such records are needed in estimating the PEFI model parameters. In this paper, the correlation between normal condition ignition risk, peak ground acceleration, and PEFI risk is examined in an effort to offer a means for predicting post-earthquake ignition events. An illustrative example is presented to demonstrate how such correlation can be employed in a seismic area to predict PEFI hazard.

***Keywords*—**Fire risk, post-earthquake fire ignition (PEFI), risk management, seismicity.

I. INTRODUCTION

THE destruction caused by post-earthquake fires (PEFs) can be more severe than the direct damage from the earthquake itself. Following the 1906 San Francisco earthquake, around 80% of the city was destroyed due to PEFs [1]. Over the last 20 years, nearly all large earthquakes in US have caused PEFs, including the 1989 Loma Prieta earthquake, with 41 PEFs [2], and the 1994 Northridge earthquake, with 82 PEFs [3]. Although it is nearly impossible to prevent the occurrence of PEFs, local jurisdictions can use PEFI models to estimate local PEFI risks and use this risk to impose certain local building code requirements, such as requiring water heaters to be strapped to the wall. Such actions help reduce the PEFI risk, and prevent the potential associated conflagration following an earthquake.

PEF models are typically categorized into two groups: 1) Models which estimate the local level of PEF focused on ignition, and 2) Models which predict the global level of PEF including fire spread and fire suppression. As nearly all PEFI (local level) models are calibrated using historic earthquake data, numerous published empirical PEFI models exist for areas with sufficient earthquake records (e.g. California). However, there exists no PEFI model for regions of moderate to high seismic risk with limited or no significant earthquake data. Therefore, in order to predict the PEFI for such areas, it is crucial to develop PEFI models that are independent of historic data.

In order to predict ignition occurrences following an earthquake, it is necessary to identify the ignition sources which fall into three categories: fuel sources, heat sources and oxygen, respectively. These three ignition sources, known as the ‘fire triangle’, must be simultaneously present for an ignition to occur. Hence, removing each one of those sources prevents ignition. With the availability of oxygen in all buildings, presence of both fuel and heat sources are required to create an ignition. Heat sources and fuel sources are generally associated with various fuel consuming equipment and electronic devices within a building. As the number of equipment and devices is constant prior and after an earthquake event, it is possible to use the normal condition ignition data to evaluate the increase risk of ignition due to an earthquake.

In this paper, a model for estimation of PEFI is developed that is based on calculation of correlation between normal condition ignition risk, peak ground acceleration (PGA), and PEF risk. Using this model, the PEFI is considered as an elevated normal condition ignition risk which can be used for areas with moderate to high seismicity and limited PEFI available data.

II. HISTORICAL BACKGROUND

One of the earliest PEFI models, based on earthquake records between 1906 and 1989, was developed by Scawthorn (1986). The model defined the number of PEFIs per 1000 single family equivalent dwellings (SFEDs) as a linear function of the modified Mercalli intensity [4].

In 1999, the Multi-Hazard Loss Estimation Methodology Earthquake Model (HAZUS-MH) was developed based on analysis of 30 PEFI data sets from major metropolitan areas caused by 10 earthquakes occurring between 1906 and 1989. The earthquakes considered in the data sets are 1906 San Francisco, 1933 Long Beach, 1957 San Francisco, 1964 Alaska, 1969 Santa Rosa, 1971 San Fernando, 1983 Coalinga, 1984 Morgan Hill, 1987 Whittier, and 1989 Loma Prieta . The

P. Farshadmanesh is a PhD Candidate in the Department of Civil, Architectural and Environmental Engineering at Illinois Institute of Technology, Chicago, IL 60616 USA (e-mail: pfarshad@hawk.iit.edu).

J. Mohammadi, is a Professor in the Department of Civil, Architectural and Environmental Engineering and Associate Dean of the Graduate College at Illinois Institute of Technology, Chicago, IL 60616 USA (e-mail: mohammadi@iit.edu).

M. Modares is an Assistant Professor in the Department of Civil, Architectural and Environmental Engineering at Illinois Institute of Technology, Chicago, IL 60616 USA (e-mail: mmodares@iit.edu).

HAZUS-MH model estimates the number of ignitions as a quadratic function of PGA [5].

The coefficients of the HAZUS model were updated in 2009 using 7 post-1970 earthquake records [6]. Fig. 1 shows the number of ignitions by earthquake considered in the 2009 HAZUS revision. According to the HAZUS documentation, only PEFI data from post-1970 earthquakes were considered as these ignitions occurred in a building stock more representative of modern buildings (e.g. construction practices, building code, appliance types, increased urbanization).

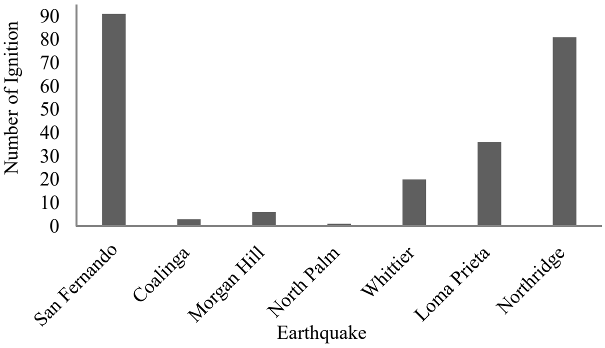

Fig. 1 Number of PEFIs by earthquake used in HAZUS model (2009)

III. METHODOLOGY

A. Significant Parameters in Previous Normal Condition Ignition (NCI) and PEFI Models

Ignitions can be categorized for a given unit of time (say one year) in two groups: 1) normal condition ignitions (NCI) which are those occurring due to mechanical failures and malfunctions, misuse of heat source, ignitable materials, or operational deficiencies, which happen at a relatively constant frequency in the population from day to day; and 2) special condition ignitions, such as ignitions caused by natural hazards, fireworks, or explosions (Fig. 2).

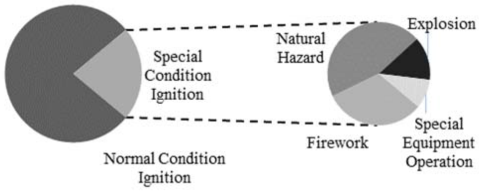

Fig. 2 Ignition causes

Based on data from the National Fire Incident Reporting System (NFIRS), which collects and maintains fire records from over 23,000 local fire departments, natural hazards include high wind, earthquakes, floods, and lightning [7].

Fig. 3 conceptually shows the two types of ignitions that may occur over one year. The solid line in Fig. 3 represents the average number of NC ignitions and the dashed line represents the total ignitions. The spikes in the graph represent days that have Special Condition (SC) ignitions.

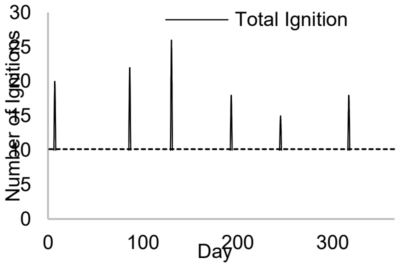

Fig. 3 Daily ignitions occurring over a year

The first step in developing this new PEFI model is to determine the model parameters. In order to identify the significant factors to consider for a new PEFI model, previous NCI and PEFI models are investigated. To avoid complexity and develop a more practical and direct model, the significant factors are identified based on their relative frequencies in previous NCI and PEFI models. Significant normal condition model parameters include building characteristics, such as the building category, structural type, and floor area, and ignition source characteristics such as the appliance or equipment type. Significant PEFI model parameters include the NCI model parameters as well as earthquake characteristics such as intensity and PGA.

After identifying the potential significant parameters, the next step is to evaluate the relative frequency of each parameter in NCI and PEFI models. Conceivably, the relative frequency of parameter used in previous NCI and PEFI models can be considered as the representative of the significance of each parameter in predicting NC and PEF ignitions. Floor area is one of the most common factors used in both NCI and PEFI models. Table I shows the relative frequency of common ignition model parameters in previous NCI and PEFI models. In this table, the right-most column shows the average relative frequencies from NCI and PEFI models. In this work, parameters with less than 1% average relative frequency are considered insignificant and are ignored to reduce the dimensionality of the developed PEFI model.

The significant factors in the developed model can be combined in four major groups including spatial, ignitability, earthquake, and temporal characteristics (Fig. 4). Spatial characteristics include floor area, building category, structural and non-structural components damage, and structural type. Floor area and building category are two of the most significant factors in NCI models. In PEFI models, floor area and structural and nonstructural damage are the most significant factors.

Ignitability factors include ignition sources and fire prevention systems. The concentration and types of ignition sources vary by building type. Fire prevention systems, such as sprinkler systems, help prevent multiple ignitions within a building. However, the performance of fire prevention systems dramatically reduces following an earthquake. As an example, sprinkler systems, which generally properly operate around 95% in normal condition fire ignitions, only operate around 59% of the time following an earthquake [8].

TABLE I
THE WEIGHT OF COMMON IGNITION FACTORS IN NC/PEFI

NC/PEFI Model Parameters	Relative Frequency (%)		
	NC	PEFI	Average
Floor Area	47.37	27.18	37.28
Building Category	42.11	7.77	24.94
Structural and Nonstructural Damage	00.00	17.48	8.74
Intensity	0.00	13.59	6.80
Peak Ground Acceleration	0.00	11.65	5.83
Ignition Source	5.26	5.83	5.54
Prevention System	5.26	3.88	4.57
Structural Type	0.00	2.91	1.46
Fuel Type	0.00	1.94	0.97
Population	0.00	1.94	0.97
Ground Motion	0.00	1.94	0.97
Peak Ground velocity	0.00	1.94	0.97
Spectral Acceleration	0.00	0.97	0.49

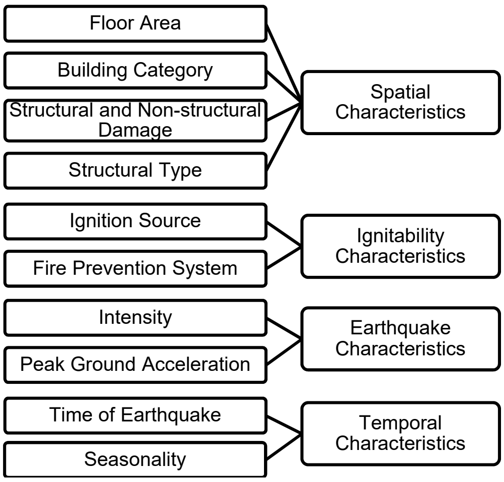

Fig. 4 Categorization of significant parameters considered in the PEFI model

Earthquake characteristics include PGA and the earthquake intensity. These two parameters are highly correlated and thus often only one of them will be used in a PEFI model.

Temporal factors are generally not an explicit model parameter, however they are important to consider in ignition modeling. A few researchers, such as Tillander [9], investigated the seasonality (calendar month) and diurnal (time of day) ignition frequency variations in normal condition ignitions, concluding that the diurnal ignition variation follows a sinusoidal function. The seasonality and diurnal variations in ignition frequencies are due to both operational and behavior variations. For example, during winter, heating systems are utilized at a much higher rate, and thus the probability of ignition due to heating equipment is increased. Seasonality is equally significant in PEFI models. The time of earthquake occurrence also influences the number of ignitions; an earthquake occurring around dinner time would likely cause a greater number of cooking related PEFIs in residential buildings than if the earthquake occurred in the middle of the night.

B. PEFI Model Assumptions and Limitations

In this work, it is assumed that NCIs encompass all spatial and ignitability parameters existing in PEFIs, and thus by considering the NCI probability and an earthquake characteristic, the PEFI probability can be estimated. Given the normal condition ignition risk, the developed model identifies the increased ignition risk following an earthquake. The elevated total ignition risk following an earthquake can be defined as the normal condition ignition risk plus the PEFI risk. The PEFI risk in the proposed model is considered as the NC ignition risk multiplied by a functional *F(X)*, which is a function of earthquake characteristics. Equation (1) shows the general form of the proposed PEFI model.

$$P_{Ig_{PEFI}} = P_{Ig_{NC}} * F(X) \tag{1}$$

or

$$\frac{P_{Ig_{PEFI}}}{P_{Ig_{NC}}} = F(X) \tag{2}$$

in which P_{IgPEFI} is probability of ignition upon earthquake occurrences, and P_{IgNC} is the probability of ignition under normal condition. Thus, (2) defines *F(x)* as the ratio of probability of ignition following earthquakes over the probability of ignition during normal condition. Regression analyses can be used for estimating *F(X)*. This method assumes that the ignition sources (heat and fuel sources) in normal condition are the same as those following earthquakes. The types and quantities of ignition sources vary by the building type. General building categories included in the HAZUS model are commercial, industrial, residential, agriculture, religious, government, and education [5]. In this work, residential buildings, defined as single family dwellings, multi-family dwellings, and mobile homes, are considered.

It is assumed that the fuel sources within buildings leading to ignition are caused by leakage, misuse, failure, or malfunction of fuel consuming equipment (gas, liquid and solid–fuel burning appliances). Heat sources in residential buildings include heat and sparks from fuel consuming equipment; sparks due to malfunction of electrical equipment, short circuit, or loose connections; smoking materials; and heat from open flame or high temperature surfaces.

C. Determination of F(X)

In order for establishing a PEFI model, the functional *F(X),* can be evaluated using different mathematical/statistical approaches. For example, classic regression analysis can be performed on PEFI data from previous earthquakes to estimate model parameters. Fault tree modeling is another method for defining a PEFI model which seeks to estimate probability of ignition by examining the cascading failure events which lead to ignition. As PEF ignition frequency is very limited, the use of fuzzy logic provides a viable epistemic approach for PEFI modeling that explicitly models the variability in PEFI frequency. With sufficient data, neural networks may yet offer another alternative in identifying *F(X)*. In cases where the data is limited, one may resort to discrete values of $F(X)$ computed for each data point in the population and then use some type of averaging method to have an estimate for $F(X)$ as a constant value. For example, the Root-Mean-Square (RMS) value can be computed and used. The RMS value includes the dispersion of data about the mean.

To calculate the probability of ignition in both normal and post-earthquake conditions, the number of ignitions in residential buildings was estimated for both conditions using the NFIRS database and earthquake data published in HAZUS documentations. To evaluate the function $F(X)$, the number of PEF and NC ignitions and the stock of residential households are determined in the specific year of each earthquake occurrence. Equations (3) and (4) define the probability of ignition in residential buildings for both NC and PEF ignitions for a region of interest, where $n_{Ig_{NC}}$ is the number of normal-condition ignitions, $n_{Ig_{PEFI}}$ is the number of PEFIs, and N_{bldgs} is the number of residential buildings, all in the region of interest.

$$P_{Ig_{NC}} = \frac{n_{Ig_{NC}}}{N_{bldgs}} \tag{3}$$

$$P_{Ig_{PEFI}} = \frac{n_{Ig_{PEFI}}}{N_{bldgs}} \tag{4}$$

The proposed model is more explicitly stated in (5), where $P_{Ig_{PEFI}}(PESH)$ is the PEFI probability in residential building as a function of the Potential Earth Science Hazard (PESH); and $F(PESH)$ is the ignition risk coefficient for residential building as a function of the PESH. PESH is a generic earthquake characteristic in the developed model and is considered as PGA in our analysis [5].

$$P_{Ig_{PEFI}}(PESH) = P_{Ig_{NC}} * F(PESH) \tag{5}$$

D. Case Study

In order to examine the validity of the developed method, six recent California earthquakes occurring after 1980 were considered. These earthquakes are the 1983 Coalinga, 1984 Morgan Hill, 1986 N. Palm Springs, 1987 Whittier Narrows, 1989 Loma Prieta, and 1994 Northridge earthquakes. The probability of normal condition ignitions in residential buildings is assumed to be constant in all residential buildings across the entire state of California in any given year. The number of households was estimated using the U.S. Census data. As Census data is published in ten year intervals, the number of households in intermediate years was estimated using an average occupancy rate (person per building) between 1970 and 2000 and an interpolated state population in each year of earthquake occurrence, as shown in Table II. The average occupancy rate between 1970 and 2000 is 2.725 person/building.

The NFIRS database was utilized for estimating the probability of NCI by using the number of normal condition ignition occurring in earthquake years in California. Table III shows the probability of ignition occurrence in normal condition in California.

TABLE II
NUMBER OF RESIDENTIAL HOUSEHOLDS, POPULATION, AND OCCUPANCY RATES IN CALIFORNIA, 1970-2000 (US CENSUS DATA)

Year	California		
	Number of Residential Household	Population	Occupancy Rate (person/building)
1970	6,976,261	19,971,069	2.863
1980	9,220,319	23,667,764	2.567
1990	11,058,249	29,760,021	2.691
2000	12,183,304	33,871,648	2.780

TABLE III
PROBABILITY OF NCI OCCURRENCE IN CALIFORNIA

Year	California		
	Total Number of Residential Household	Average Daily NC Ignitions (Ignitions/Day)	$P_{Ig_{NC}}$
1983	9,201,352	82	8.89E-06
1984	9,388,857	86	9.15E-06
1986	9,812,671	82	8.32E-06
1987	10,049,714	85	8.41E-06
1989	10,557,190	47	4.42E-06
1994	11,551,226	36	3.11E-06

TABLE IV
PROBABILITY OF PEFI OCCURRENCE IN CALIFORNIA

Year	California		
	Number of Residential Household Impacted	Number of PEF Ignitions	$P_{Ig_{PEFI}}$
1983	5,472	2	3.66E-04
1984	260,682	2	7.67E-06
1986	11,039	1	9.06E-05
1987	1,460,881	14	9.37E-06
1989	281,715	26	9.11E-05
1994	1,341,128	63	4.66E-05

The next step is to evaluate the PEFI probability. Based on data from a technical report of MCEER [3], the city affected by each PEFI is identified. The number of households in each city which had a PEF ignition was estimated based on the average occupancy rate and city populations from U.S. Census data. The portion of all PEFIs occurring in residential buildings was approximated based on analysis of the NFIRS databased and MCEER report. Table IV shows the probability of PEFI for each earthquake; and Table V summarizes the discrete estimates for $F(X)$.

Finally, the RMS of this ratio computed, which is 20.24. Therefore, based on the six data samples, the model predicts about a 20-fold increase in the occurrence of ignitions for any probable earthquake within the PGA limits of the six earthquakes that were used as the statistics-based data in our model.

TABLE V
RELATIVE INCREASE IN RISK OF PEFI OVER NCI

Year	California			
	$P_{Ig_{NC}}$	$P_{Ig_{PEFI}}$	$F(X)$	PGA (g)
1983	8.89E-06	3.66E-04	41.1	0.31
1984	9.15E-06	7.67E-06	0.8	0.29
1986	8.32E-06	9.06E-05	10.9	0.22
1987	8.41E-06	9.37E-06	1.1	0.27
1989	4.42E-06	9.11E-05	20.6	0.16
1994	3.11E-06	4.66E-05	15.0	0.47

IV. SUMMARY AND CONCLUSIONS

This study investigated a new direction in estimating the risk of ignition after an earthquake based on the normal condition ignition risk and PGA. The correlation between both NCI risk and PGA was examined to determine the proposed methodology by examining six past earthquakes causing PEFIs in California. Our research currently is looking into developing a form of *F(X)* function based on the classics regression analysis as well as more advanced logic-based methods.

The following are the main conclusions of this study:

- Statistics-based earthquake data can be used as a means of correlating the post-earthquake ignition occurrences and PGA and normal condition ignition occurrence rate.
- With sufficient data, correlation based on the regression analysis can be established. However, with limited data, RMS value can be estimated based discrete values of ratios of post-earthquake ignition probability and normal-condition ignition probability and used as a predictive factor for estimating the risk of post-earthquake ignitions.

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