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Data-driven probabilistic post-earthquake fire ignition model for a community

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ABSTRACT

Fire following earthquake (FFE), a cascading multi-hazard event, can cause major social and economical losses in a community. In this paper, two existing post-earthquake fire ignition models that are implemented in Geographic Information System (GIS) based platforms, Hazus and MAEViz/Ergo, are reviewed. The two platforms and their FFE modules have been studied for suitability in community resiliency evaluations. Based on the shortcomings in the existing literature, a new post-earthquake fire ignition model is proposed using historical FFE data and a probabilistic formulation. The procedure to create the database for the model using GIS-based tools is explained. The proposed model provides the probability of ignition at both census tract scale and individual buildings, and can be used to identify areas of a community with high risk of fire ignitions after an earthquake. The model also provides a breakdown of ignitions in different building types. Finally, the model is implemented in MAEViz/Ergo to demonstrate its application in a GIS-based software.

1. Introduction

Our built environment and communities have been developed towards an interconnected social and economic network. Such interconnectivity between different aspects of a system leads to cascading effects. In many cases, an extreme hazard causes direct infrastructure and asset losses, while subsequent losses due to disruptions in operations and functions can exceed the direct damage [1]. If a city has to stay functional after a hazard and recover from the event, then the performance of individual elements, connectivity of critical infrastructure elements in the system, and cascading effects on the system should be incorporated in the design of the community.

This paper focuses on the problem of post-earthquake fires at the community scale. A study of 20 previous earthquakes from seven countries, where 15 of which occurred between 1971 and 2014, shows that fire events that followed the earthquakes caused considerable damage [2]. The likelihood of a fire event is typically amplified following seismic events due to an increase and/or introduction of available fuel and ignitions sources, such as ruptured utility lines or toppled appliances. On the other hand, active fire protection systems, such as sprinklers, may be ineffective due to ruptured water lines, loss of water pressure, or inadequate water supply due to widespread firefighting efforts for multiple neighboring fires. Passive fire protection systems, such as spray-applied materials or compartmentation partitions, can also be damaged in case of an earthquake and/or compromised by seismic shocks.

The methodology to evaluate community resiliency for post-earthquake fires involves four main steps: (a) identifying areas of the community that may experience ignitions, (b) modeling spread of fire, from the burning area to the neighboring buildings, (c) modeling active suppression efforts by firefighters, which also affect the rate of fire spread, and (d) quantifying damage and performance of the buildings which experienced fire in the areas affected by ignition and spread. Within this context, ignition is defined as a structurally significant fire, which requires firefighter intervention. The fire spread quantifies the affected geographic area given the initial fire ignitions, while suppression is related to the work of extinguishing a fire, starting with the discovery time through the complete control of the fire by the firefighters. A holistic methodology has to consider the four steps mentioned above, in order to capture the performance of a community. The authors of this paper are working towards developing such a holistic approach considering different aspects of post-earthquake fires at individual buildings and at the community level. For example, in previous studies, the authors have adopted the concept of fragility function for quantifying fire damage in a building at system level [3,4]. Meanwhile, the authors are working

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towards developing a spread and suppression model that explicitly incorporates the available water for suppression efforts, given the earthquake damage to the water network [5]. As part of the holistic methodology, this paper focuses on modeling post-earthquake fire ignitions in a community.

The proposed model in this paper is based on empirical data from historical events in California to build a data-driven probabilistic model for predicting ignitions in a community. The empirical data are mainly obtained from firefighter reports, and are categorized as structurally significant fires, i.e. fires which ignited and grew to the point where a firefighter intervention was required. When a fire is developed in a building, the response not only depends on the structural behavior of elements, but also on the non-structural fire safety design of the building, such as the firefighting measures (e.g. sprinklers) or provision of compartments to prevent fire spread. When using the historical ignition data (structurally significant fires), it is implied that if active fire protection measures (e.g. sprinklers) were present, their probability of successful operation is inherently encompassed in the data. Therefore, the outcome of the proposed model provides recommendation to firefighters for allocation of their resources to areas with high risk of ignitions, and to some extent helps them plan their resources (e.g. number of fire houses and fire engines) based on the number of ignitions.

In recent years, a number of fire ignition models have been developed to simulate post-earthquake ignitions [6]. Lee et al. [6] list and compare the existing ignition models and conclude that "[FFE] data include a great deal of uncertainty, only some of which is captured in reported statistics." Among the existing models, two have been implemented in computer programs, Hazus [7] and MAEViz/Ergo [8]. Both computer programs are Geographical Information System (GIS) based platforms developed to estimate potential losses from hazards on communities. The U.S. Geological Survey recently led a group of over 300 scientists and engineers to study the consequences of a potential earthquake in California, which resulted in "the Shakeout Scenario" [9]. The Hazus-based study found that a hypothetical 7.8 magnitude earthquake on the southern San Andreas Fault could cause approximately 1600 fire ignitions, out of which 1200 would spread over large areas, and a few would grow into conflagrations [9]. Another example is the Hazard Mitigation Plan (HMP) released for the New York City in 2014 [10], which included a study [11] showing that a moderate earthquake could result in an estimated 1100–1200 deaths, and ignite up to 900 fires simultaneously in the NY-NJ-CT area. The study used Hazus, and compiled comprehensive soil information for the region, and a complete building inventory of Manhattan.

This paper starts with an overview of Hazus and MAEViz/Ergo platforms. A discussion on the current FFE modules implemented in Hazus and MAEViz/Ergo is provided, and the shortcomings of the available FFE ignition modules are discussed. The original contribution of this paper is a new probabilistic post-earthquake fire ignition model that is proposed based on historical FFE events. The proposed model can be used to estimate the number of ignitions in a region after an earthquake. One of the objectives in developing the FFE ignition model is to have a model that can be implemented in GIS based programs for community resilience assessment. Therefore, the new ignition model is implemented in MAEViz/Ergo to show the application.

2. Gis-based tools for hazard risk management

A general comparison of Hazus [7] vs. MAEViz/Ergo [8] is given in Table 1. Hazus, a GIS based platform, estimates potential losses from earthquakes, floods, or hurricanes based on the performance of buildings, essential facilities, transportation, or utilities, and can be obtained from the Federal Emergency Management Agency (FEMA) website. Hazus is a tool designed to provide local, state and regional officials with information for emergency response, recovery, and mitigation planning to reduce risk of disaster damage [7]. The program provides an inventory of data for the United States based on census tract areas. Hazus comprises an earthquake module with a fire following earthquake model embedded. The Hazus manual states that there are areas that the available research is limited, such as the fire following earthquake area. The potential losses due to fire are not based on rigorous calculations, and therefore the program does not include the potential loss due to fire in estimating the total economic loss, casualties or loss of shelter. The fire following earthquake module is discussed further in Section 3.1.

Table 1
Comparison of Hazus and MAEViz/Ergo.

		Hazus	MAEViz/Ergo
General	Type of hazard	Earthquake, floods, hurricanes	Earthquake
	Accessibility	Free but requires ArcGIS (not free)	Free
	Source code	Not available	Available to user (open source)
	Inventory	Includes default inventory data for U.S.A.	Limited inventory data available
	Scale of analysis	Census tract, county or state[a]	Individual buildings
FFE	Model	Empirical	Analytical
	Components	Ignition, spread, suppression	Ignition
	Output	No. of ignitions	Probability of ignition for each building and no. of ignitions

[a] Hazus has recently introduced an "Advanced Engineering Building Module" that performs analysis at the building level, but the user needs to provide the inventory data.

MAEViz/Ergo is an open source platform for earthquake hazard risk management [8,12] developed in association with the MAE Center (Multi-hazard Approach to Engineering) at the University of Illinois, Urbana Champaign. This is a tool designed to model earthquake events, evaluate risk and potential losses, and develop mitigation strategies. MAEViz/Ergo provides an extension to a post-earthquake fire plug-in that was developed by Turkish researchers [13]. Similar to Hazus, the accuracy of results greatly depends on the accuracy of the inventory data. MAEViz/Ergo does not provide a default inventory dataset, and it is up to the user to input the most recent and available detailed inventory for the analysis. The data for inventory should be collected and is available from a number of sources including the United States Census Bureau, the Bureau of Labor Statistics, the Department of Education, the Department of Agriculture, and the Federal Communications Commission.

3. Existing fire following earthquake ignition models

Table 1 provides a comparison of the Fire Following Earthquake (FFE) models available in Hazus and MAEViz/Ergo. The fire ignition models are discussed further in this section.

3.1. Ignition model in Hazus

The FFE module in Hazus consists of three different components: (1) ignition, (2) spread, and (3) suppression [7]. The module requires, as inputs, general building stock inventory (i.e. square footage), essential facility inventory (i.e. fire stations and their available resources), and the Peak Ground Acceleration (PGA). In addition, the user should provide the wind condition, and simulation properties such as the maximum simulation time. The module outputs the number of ignitions, total burned areas, population exposed to fire, and the building value consumed by the fire.

The ignition model calculates the number of fires that are expected to occur after the earthquake in a region of interest [14]. In this model, ignition implies a fire that requires the fire department response to suppress. The ignition is provided in terms of ignition rate, or in other words the frequency of ignitions per million square feet of total building floor area per district under consideration. The model is empirical and is based on seven historical FFE events in the United States post 1970s. The historical events and their corresponding number of ignitions are shown