System Dynamics Modeling of the Earthquake-induced Interruption of a Business - Risk Analysis Models Details

In a damage probability matrix, each number expresses the probability that a given building will experience a particular level of damage when exposed to a given intensity or ground shaking (Whitman, 1973). Therefore, it can be used to determine the building damage ratio immediately after an earthquake considering the seismic vulnerability of the building and the earthquake magnitude. The numbers in the damage probability matrix presented in Table 6 are generated using the seismic risk analysis approach described below.

Risk-analysis approaches often take a "hazard curve" as the initial step. A seismic hazard curve describes the relationship between a ground motion parameter (e.g., peak ground acceleration or one of the spectral accelerations) and its exceedance frequency. The underlying models of seismic hazard curves characterize earthquake magnitude, location, and the propagation of rupture energy.

Hazard location models aim to predict the earthquake location. The model proposed Mahsuli and Haukaas (2013), which generates earthquake location as a random variable, is one of the models that can determine the occurrence location of the probable future earthquakes. This model takes a set of random variables as input and estimates the location of a probable future earthquake as the output. The model takes two random variables as input, together with the longitude and latitude of the end points, as well as the longitude and latitude of potential intermediate points for multi-segment line that represent the fault. One of the random variables represents the epicenter location along the line, which is usually a uniform random variable. The other represents the earthquake depth. As a result, each realization of this random variable set is associated with an earthquake location. Once the epicenter location is known, its distance from the site of a given asset can be computed.

A truncated exponential distribution is commonly used to describe the magnitude frequency statistics of earthquakes generated by a given source (see, e.g., McGuire (2004) for details). The lower bound of magnitude distribution, $m_{\min}$, reflects the minimum magnitude that can cause damage and loss. The magnitude distribution is truncated at an upper-bound value, $m_{\max}$, to account for the saturation of the magnitude scale and the fact that a given zone cannot generate magnitudes above a certain threshold. The development of the truncated magnitude distribution starts by generating the magnitude exceedance probability curve using the activity catalogue of the fault in question, which characterizes its potential seismicity. It continues by generating a bounded exponential distribution such as the one shown below. By sampling from the size distribution of the earthquakes, realizations of the magnitude of the probable future earthquakes can be generated. Please note that, instead of using the above models, one can make assumptions about the magnitude and location of a probable future earthquake and move to the following steps, which are the estimation of the earthquake intensity at the location of interest, characterization of the asset response, and determination of the damage it may sustain.

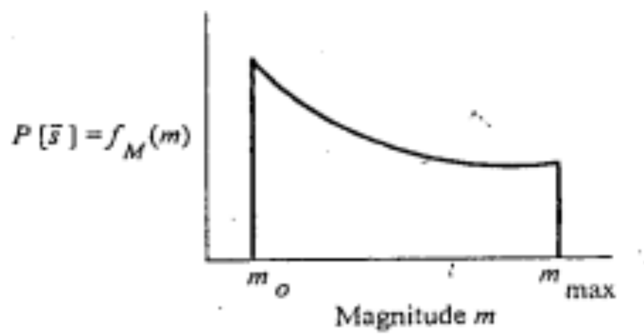

Figure 1. Schematic view of the size distribution of magnitude and rate of occurrence for a seismic source (Adopted from McGuire 2004)

Various earthquake intensity models and measures are presented in the literature. In general, an earthquake intensity model determines the site-specific ground shaking parameters using inputs such as the characteristics of the earthquake (i.e., magnitude and location), features of the path of shock wave propagation (e.g., soil type), and the attributes of the structure in question. For each magnitude and location (i.e., distance) pair, the ground shaking parameter (e.g., spectral acceleration, S_a) at the location of each asset is computed using one of several available models, including those proposed by Atkinson and Boore (2003) and Boore and Atkinson (2008). For each given asset, the ground shaking parameters are the inputs to the capacity spectrum method, which compares the capacity of a structure against the demands of earthquake ground motion (see, e.g., Freeman et al., (1975) for more details). The peak displacement (i.e., drift) and acceleration responses from the capacity spectrum method are used as inputs to the fragility and loss functions (see, e.g., FEMA-NIBS 2003 and Mahaney et al., 1993) to determine the damage sustained by the asset.

HAZUS – MH2.1 (FEMA-NIBS 2003) proposes a set of procedures to characterize the response of assets such as buildings to an earthquake, which involves applying fragility curves. Fragility curves are cumulative distribution functions that determine the probability of exceedance of a given damage state based on a ground motion intensity measure (e.g., peak ground acceleration or spectral acceleration). The damage state describes the nature and extent of the earthquake-induced physical damage sustained by assets. The FEMA-NIBS approach defines four damage states for buildings: slight damage, DS_1, moderate damage, DS_2, extensive damage, DS_3, and complete damage, DS_4. Associated with each damage state is a fragility curve that follows a lognormal distribution given the value of the building response (e.g., the peak drift or the peak acceleration) from the capacity spectrum method. The parameters of the said distribution are a median response and a variability term, which is defined as the standard deviation of the logarithm of spectral response. These parameters depend on the building type and its code level. Given the peak spectral response evaluated in the previous step, the fragility curves provide the probability of falling in or exceeding each damage state. Accordingly, it is possible to compute the probability of falling only in damage state i, $P(DS_i)$, where i=1, 2, 3, 4. The probability of exceedance of each damage state given an earthquake intensity is calculated as follows

$$P_{S \geq S_i | IM} = \Phi\left\{\frac{1}{\beta_{\mathrm{S_i}}} \ln\left(\frac{IM}{m_{S_i}}\right)\right\} \quad (1)$$

where $P_{S \geq S_i | IM}$ is the probability of exceedance of the state of the asset from the damage state s_i, Φ is the standard normal cumulative distribution function, IM is the ground motion intensity measure, m_{S_i} is the state-dependent median value of ground motion intensity with damage state i, $\beta_i(s_t)$ is the dispersion factor (i.e., the state-dependent standard deviation of ground motion intensity) of damage state i. The methodology provided by HAZUS – MH2.1 (FEMA-NIBS 2003) predicts structural and non-structural damage states in terms of one of five damage states: None, Slight, Moderate, Extensive, and Complete.

Associated with each damage state i is a range of damage ratios and thus, a central damage ratio η_{i} as the center of the damage range. FEMA-NIBS (2003) classifies buildings into 33 occupancy classes (e.g., residential, commercial, industrial, and education) based on how they are used. The η_{i}-values can be determined based on recommendations of FEMA-NIBS (2003), considering the occupancy class of each given building. Based on the probability of falling in each damage state and the corresponding central damage ratio, the mean damage ratio, E[η], is determined as follows

$$E[\eta] = \sum_{i=1}^{4} P(DS_i) \cdot \eta_i \quad (2)$$

The mean damage ratio can be calculated for various damage types (i.e., structural damage, non-structural drift-sensitive damage, non-structural acceleration-sensitive damage, and content damage).

FEMA-NIBS (2003) argues that acceleration-sensitive non-structural damage is an appropriate indicator of the business inventory damage and losses since business inventory losses most likely occur due to the events such as objects falling off the shelves or water damage when piping breaks. Business inventory losses are estimated as the product of the total inventory value of buildings of a given occupancy, the percent loss to the inventory for the damage state, and the probability of the damage state. Note that FEMA-NIBS (2003) provides a similar methodology for the seismic risk analysis of the components of various infrastructure systems (.e.g, electricity, water, and gas networks).

This study uses the methodology described above to determine the impact of probable future earthquakes on the structures across the community. The damage to the business building's structural and non-structural components, contents, and inventory were also determined using the abovementioned methodology. The models mentioned above are implemented in Rtx software (Mahsuli & Haukaas (2013a), which was used in this study.

In this study, a scenario, which represented the occurrence of an earthquake with magnitude 8 was devised. The earthquake location was considered the point on the Rock River fault closest to the city's centroid. For each earthquake magnitude scenario, 10000 random realizations of the ground shaking parameters at the location of each given building were generated. For each randomly generated realization, the corresponding structural, non-structural, contents, and inventory damage ratio of the business building were estimated. Then, the means of the business building's structural, non-structural, contents, and inventory damage ratios were calculated for the scenario, as shown in Table 6 of the manuscript. A similar approach was used to estimate the damage ratio of other relevant structures across the community for each randomly generated realization. The mean of the damage ratios was calculated for the scenario and used as the SD model input. For brevity, the details of the risk analysis approach used in this study are not included in the main manuscript. However, the above details are added to this supplementary online document to provide the readers with an overview of this method.

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