Earthquake Loss Estimation Methodology For Prioritizing Seismic Mitigation At Federally Owned Facilities

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ABSTRACT

As a part of the implementation of the Executive Order (E. O.) 12941 requirements, the affected United States Federal Agencies submitted reports to Federal Emergency Management Agency (FEMA) on 12-1-1998, identifying likely seismically vulnerable buildings within their complex (based on the E. O. evaluation criteria), together with an estimate of costs to mitigate the seismic risks. Based on data collected from Federal agencies, FEMA was expected to prepare a report for US Congress, recommending funding, priorities, and schedule for seismic mitigation. The actual rehabilitation of buildings was proposed for completion over 30 years. However, a prioritization and mitigation plan need to be developed to optimize the use of limited resources.

FEMA funded methodology has been developed known as HAZUS 99 to estimate the extent and probability of damage to the building due to a scenario earthquake. In this approach Capacity Spectrum Method (CSM) is recommended to predict inelastic building displacements for damage estimation. This paper addresses the application of HAZUS 99 methodology to develop earthquake loss estimates for buildings, and details how it can be used for prioritizing the seismic mitigation of buildings.

INTRODUCTION

In the United States Federal agencies were required to comply with the E. O. 12941, "Seismic Safety of Existing Federally Owned Buildings" [1]. The affected agencies were to summarize the results of their efforts to comply with E. O. 12941 requirements and submit to FEMA their report no later than December 1, 1998. FEMA collected results from these Federal agencies, and was scheduled to submit a concise report by December 1, 2000, to the U. S. Congress for further action. Buildings with high seismic vulnerabilities were to be identified by each agency. This approach was based on likelihood/frequency of failure represented by the site seismic hazard, potential vulnerable model building types, and the consequences of failure represented by number of building occupants combined with building contents such as chemical or radiological inventory. For discussion purposes only, for this paper, a sample building of one of the Federal agency's building has been used. A practical tool utilizing recent developments in methods to estimate losses from an earthquake event to help prioritize has been presented herein.

BACKGROUND AND HAZUS CAPABILITIES

A methodology was developed for the Federal Emergency Management Agency (FEMA) by the National Institute of Building Sciences (NIBS) to provide a tool for developing earthquake loss estimates. HAZUS (the name is derived from *Hazards U. S.*) is a trade mark name of the computer software package (assigned to FEMA) developed to estimate losses due to natural hazards for the United States. HAZUS was prepared by Risk Management Solutions, Inc.(RMS) for the NIBS. HAZUS provides estimates of losses as a result of natural hazards such as ***earthquakes***, high winds, tornadoes, floods, etc. for nearly most types of model construction.

HAZUS uses geographic information system (GIS) software and scientifically developed algorithms to calculate, map and display earthquake loss data. It is capable of using two separate GIS to map and display ground shaking, the pattern of building damage, and demographic information about a community: MapInfo^{R} developed by RMS, and Arcview^{R} developed by Environmental Systems Research Institute (ESRI).

The methodology includes probabilistic seismic hazard contour maps developed by the United States Geological Survey (USGS) for Project 97 [2] and used as the basis for design value maps of the 1997 NEHRP Recommended Provisions [3]. However, it also allows the user to supply site-specific probabilistic or deterministic seismic demand in form of peak ground accelerations (PGA), or spectral acceleration maps. When user supplied accelerations are intended for use, the methodology assume that they include soil amplification, and attenuation factors based on the local soil conditions.

The HAZUS methodology was pilot tested in Portland, Oregon and Boston, Massachusetts and calibrated with data from Northridge, Loma Prieta and other earthquakes. Loss estimation module for earthquake was developed and first published in 1997, and later updated in 1999 as HAZUS 99 [4]. Subject to several limitations HAZUS has been judged capable of producing results that are credible for the intended purposes described below. One can selectively use only those features of the methodology that would help provide a reasonable estimate of the extent and probability of damage to the building stock. This method is one of the methods that could be used as a tool to help prioritize the seismic mitigation of facilities.

It should be noted that the earthquake loss estimates are merely forecasts based on current scientific and engineering knowledge, and not precise predictions. This paper presents a risk-informed (qualitative) tool to assist in prioritization of those buildings that are identified as seismically vulnerable. The guide (together with other acceptable methods) may be used as a preliminary tool to estimate the extent and the probability of structural damage to the building for a given site-specific seismic demand.

THE HAZUS METHODOLOGY

Most buildings are presently designed or evaluated using linear-elastic analysis methods, primarily due to the relative simplicity of these methods in comparison to more complex Non-linear methods. Typically, building response is based on linear-elastic properties of the structure and forces corresponding to the design-basis earthquake. It has been observed that except for few brittle systems and acceleration-sensitive elements, building damage can be best correlated with building displacement, rather than force.

In the inelastic range of building response, increasingly larger damage would result from increased building displacement although lateral force would remain constant or decrease. Hence, successful prediction of earthquake damage to buildings requires reasonably accurate estimation of building displacement response in the inelastic range. In the real world, buildings respond in-elastically to the earthquake ground shaking. Building capacity (push-over) curves, used with capacity spectrum method (CSM) techniques provide simple and reasonably accurate means of predicting inelastic building displacement response for damage estimation purposes.

Table - 1 taken from HAZUS 99 [4] shows the 36 Model building types that are used by the methodology. These model building types are based on the classification system of FEMA 178 [5]. In addition, the methodology breaks down FEMA 178 classes into height ranges. These Tables summarizes the yield capacity and ultimate capacity control points for high, moderate, low and pre-code seismic design levels respectively, and also the structural damage fragility curve parameters for high, moderate, low and pre-code seismic design level for slight, moderate, extensive and complete damage states. For definitions of slight, moderate, extensive, and complete damages for various building model types refer to HAZUS 99 [4].

A building ***capacity curve*** (also known as a push-over curve) is a plot of a building's lateral load resistance as a function of a characteristic lateral displacement (i.e. a force-deflection plot). In order to facilitate direct comparison with earthquake demand (i.e. overlaying the capacity curve with a response spectrum), the force (base shear) axis is converted to spectral acceleration and the displacement axis is converted to spectral displacement. The capacity is dependent on peak response of the building for a given level of earthquake (spectral demand) and also the yield, ultimate strength, etc. of the building materials. Each curve is described by three control points that define model building capacity: Design Capacity, Yield Capacity, Ultimate Capacity. The capacity curve is assumed to remain plastic past the ultimate point. Refer to Figure - 1 for an example of building capacity curve.

A building fragility is defined as a probability of failure given an input parameter (e.g. spectral displacement). Fragility can be described by a ***fragility curve*** (plotted with spectral displacements on X axis, and probability of failure on Y axis). The uncertainty associated with the median value (Value of probability of failure = 0.5) defines the steepness of the fragility curve. Each fragility curve is characterized by median and log-normal standard deviation values of the seismic demand. Refer to Figure -2 for an example building fragility curve.

The log-normal standard deviation values that describe the variability of fragility curves are developed for each damage states (i.e. slight, moderate, extensive, and complete). As the issue of life-safety is more related to structural damages, this guide addresses basically structural fragility. The probability of slight, moderate, extensive, and complete damage to a building is estimated based on the building capacity, and the structural fragility. The fragility curve predicts the probability of reaching or exceeding specific damage states for a given peak earthquake response.

Once the probabilities of various states of damages are known, based on certain acceptance level of risk tolerance (in terms of property damage and/or life-safety) a priority can be assigned to mitigate seismic risks for these seismically vulnerable buildings. An example demonstrating the methodology described herein is included. The sample building is evaluated assuming "general building stock" as described in Chapter 5 of HAZUS 99. Sensitivity study was performed for the building to study the implications (if any) of using capacity and fragility parameters of "essential" building as described in HAZUS 99.

REQUIRED INPUT AND STEP-BY STEP PROCEDURE

Input required for an *estimate of direct physical damage to a building* using this method include the following:

- Building Model Type MBXX [ICSSC TR-17 [6, Table 5-4]
- Building Height (story)
- Year Built (to determine High, Moderate, Low, or Pre-code design level)
- Site-specific seismic demand (S_A) 5% damped spectral accelerations for particular building performance level desired, or
  - Seismic Accelerations from NEHRP 1997 Provisions [3], or from
  - USGS Seismic Maps For WUS, Coastal California, EUS (as applicable)

Notes:

1) Spectral Displacements $S_D = 9.8\ S_A\ (T)^2$(inches) where,
   T = Period (e.g. 0.0 sec, 0.2 sec., 1.0 sec., etc.)
2) 7 % to 10 % damped spectra if justified, may be used on a case-by-case basis.

Step 1:

From Table 5.1
With known model building type MBXX and story height determine building label (e.g. S2L, or C3M, etc.)

Step 2:

With known year built and the location (seismic zone) of the building, determine seismic design code level using the following guidelines: [4, Table 5.20]

Seismic Design - Code Level

Table – 1

UBC Seismic Zone (NEHRP Map Area)	Post-1975	1941-1975	Pre-1941
Zone 4 (Map Area 7)	High-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 3 (Map Area 6)	Moderate-Code	Moderate-Code	Pre-Code (W1 = Moderate-Code)
Zone 2B (Map Area 5)	Moderate-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 2A (Map Area 4)	Low-Code	Low-Code	Pre-Code (W1 = Low-Code)
Zone 1 (Map Area 2 / 3)	Low-Code	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-code)
Zone 0 (Map Area 1)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)	Pre-Code (W1 = Low-Code)

Note: The years shown as break-off points should be considered very approximate for many seismic regions, particularly regions of low and moderate seismicity where seismic codes have not been routinely enforced. Prior to assigning seismic design group users must apply engineering judgement with full knowledge of the type and history of construction. The building may have some lateral strength, yet not adequate ductility for seismic design.

Step 3:

From Tables 5.7a through 5.7d
With known Building Type determine the building-specific capacity:
D_Y (Inches) - spectral displacements based on yield strength

A_Y (g) - spectral accelerations
D_U (Inches) - spectral displacements based on ultimate strength
A_U (g) - spectral accelerations

Plot the displacements on X axis and the accelerations on the Y axis to generate a median **Capacity Curve** (See Figure - 1)

Notes: 1) The design strength capacities are approximately based on e. g. 1994 NEHRP Provisions [7].

2) NEHRP Model Building Type MB07, MB10, MB15 are listed as having zero capacity for High-code, and Moderate-code buildings in Tables 5.7a through 5.7d, as these types of buildings are no longer permitted in these seismic areas.

3) Beyond the ultimate capacity point (A_U, D_U) the spectral displacements increases indefinitely for a given acceleration (i.e. the capacity curve remains plastic beyond this point).

Step 4:

Using available recent site-specific seismic demand for the desired level of performance (at various periods) superimpose the seismic demand curve on the capacity curve generated in Step 3 above by plotting spectral accelerations (Y), and spectral displacements (X) [See Figure - 1]

To convert spectral acceleration (S_A) in units of (g) to spectral displacements (S_D) in units of inches for a given value of period (T) use the following Equation:

$$S_D = 9.8\ (S_A)\ T^2$$

Note that the accelerations at the zero period are the peak ground accelerations (PGA) for a given performance category. Determine the spectral displacements at the intersection of the seismic capacity curve and the seismic demand curve [See Figure -1] for desired level of performance for subsequent use.

Step 5:

From Structural Fragility Tables 5.9a through 5.9d determine median spectral displacements (inches) and the corresponding beta values for slight, moderate, extensive, and complete damage state for the given building and design seismic code level. Using these basic Median Displacement (X) and Beta, compute the displacements at various log-normal standard deviations: (e.g. + 1 Beta; - 1 Beta; + 2 Beta; - 2 Beta, etc.). Note that in this example only the structural fragilities are considered. The non-structural fragilities: drift-sensitive and the acceleration-sensitive are ignored. They may be addressed separately if judged to be of any significant impact from the life-safety point of view (or otherwise). Plot the Displacements "X" (inches) at various probabilities "Y" to generate the Structural **Fragility Curve** for the given damage state. [See Figures - 2, and -3]

Step 6:

With known spectral displacements (Step 5 above) superimpose the data for Performance Category – Life-Safety on the fragility curve [See Figures - 2, and -3]. The intersection of these vertical lines for desired level of performance with the corresponding damage state structural fragility curve represent the **Damage Probabilities** ranging from zero to one hundred percent for the various damage states. Prepare a summary Table listing damage probabilities for applicable level of seismic demand and damage states. [See Table - 2].

RESULTS AND CONCLUSIONS

An example to help understand the earthquake loss estimation methodology of HAZUS 99, and to formulate a tool to assist in prioritizing seismically vulnerable building was presented in this paper. The results are presented in Table - 2 below. A sensitivity study was performed to understand the variations in capacities and fragilities of "general building stock" versus "essential building" parameters [4, Chapter 6]. It was noted that for a given building, comparatively lower probabilities were derived for various damage states using the "essential building" parameters. It was also noted that using "general building stock" parameters would be slightly conservative for sites located in high seismicity region (e.g. Coastal California). However, for sites located in moderate, and low seismicity region (e.g. inter-mountain and Eastern United States) the results using "essential buildings" parameters would be insignificantly different than those using "general building stock" parameters.

Based on certain acceptable level of risk tolerance (in terms of property damage and /or life-safety) HAZUS 99 is a valuable tool to assign the priorities for seismic risk mitigation of buildings. The probability of extensive damage states may

be the most useful in terms of establishing priorities of seismic vulnerabilities. For example, a building with 50% or higher probability of extensive damage from code required minimum seismic demand could be given a relatively higher priority ranking. The lower damage state probabilities (slight damage, moderate damage) does not appear to be adequately reliable to use for relative priority ranking purposes.

BUILDING [C3M – Precode] DAMAGE PROBABILITIES
LIFE-SAFETY SEISMIC DEMAND

TABLE – 2

(Model Building Type)	Probability of Slight Damage PFS	Probability of Moderate Damage PFM	Probability of Extensive Damage PFE	Probability of Complete Damage PFC
SITE 1 Bldg. ABC (MB10) – 1956	77 %	61 %	24 %	7 %

NOTES: 1) The results shown here are for *general building stock life-safety* seismic demand unless noted otherwise.
2) Priority ranking is recommended to be based on the probabilities of extensive damage state (Say >= 50 %) from the life-safety consideration.

ACKNOWLEDGMENT

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Ref. HAZUS 99 - Table 5.7d *Site 1, Site-Specific PSHA*
Bldg. C3M -
MB- 10) Precode

Capacity Curve

X	Y
0	0
0.26	0.083
1.95	0.188
2	0.188
3	0.188
4	0.188
5	0.188
6	0.188
7	0.188
8	0.188
9	0.188
10	0.188

Seismic Demand Values
Performance Category-Life-safety

Period' T '	X	Y
0.0 sec.	0	0.14
0.2 sec.	0.13	0.33
1.0 sec.	1.57	0.16
2.0 sec.	3.14	0.08

Displacements @ Intersection of Capacity & Demand Curve
PC - Life Safety

X	Y
1.7	0
1.7	1

X = Sd = 9.8 x Sa x T x T (inches)
Y = 5% damped elastic response spectral accelerations. Y may be adjusted by Velocity-Domain reduction factor (if known). See HAZUS 99 for further details.

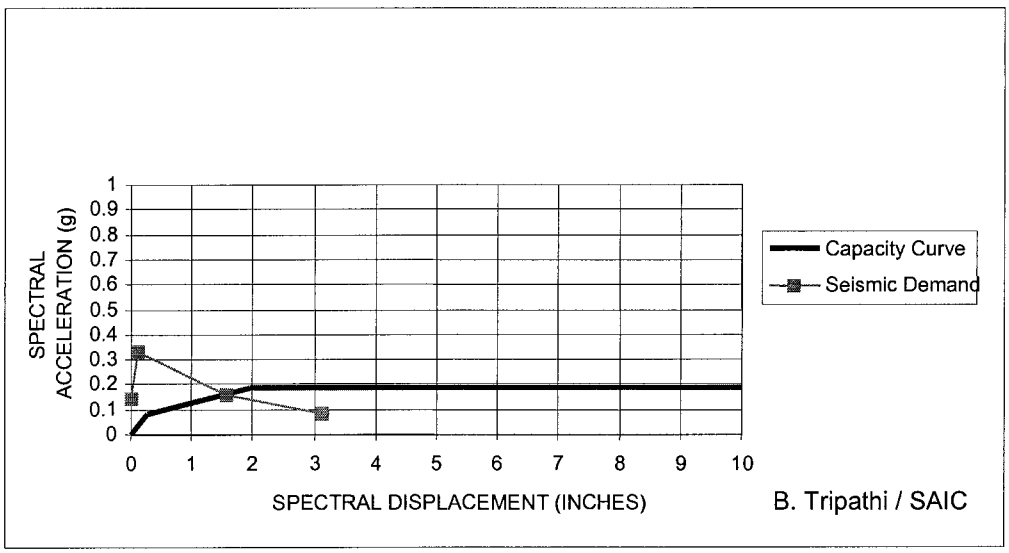


FIGURE – 1 CONCRETE FRAME WITH (URM) INFILL SHEAR WALLS (PRE-CODE)

SEISMIC CAPACITY AND DEMAND

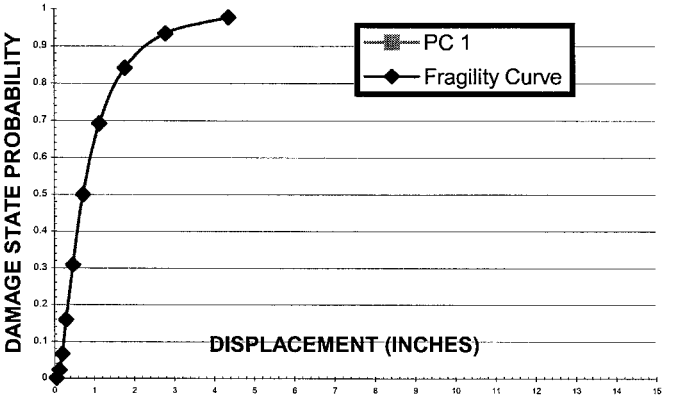
Site 1 Bldg. ABC - Bldg. Type (MB10)
X = Displacements (inches) Y = Probability
Ref. HAZUS 99 - Table 5.9d Bldg. C3M - Precode (Median & Beta)

Fragility Curve
Slight Damage State

X	Y	[TYP Std. Dev.]
0.05	0.0013	[- 3 Beta]
0.12	0.0227	[- 2 Beta]
0.19	0.0668	
0.29	0.1587	[- 1 Beta]
0.46	0.3085	
0.72	0.5	[Median]
1.13	0.6915	
1.77	0.8413	[+ 1 Beta]
2.78	0.9332	
4.36	0.9773	[+ 2 Beta]

Fragility Curve
Moderate Damage State

X	Y
0.11	0.0013
0.26	0.0227
0.4	0.0668
0.61	0.1587
0.94	0.3085
1.44	0.5
2.22	0.6915
3.4	0.8413
5.23	0.9332
8.06	0.9773



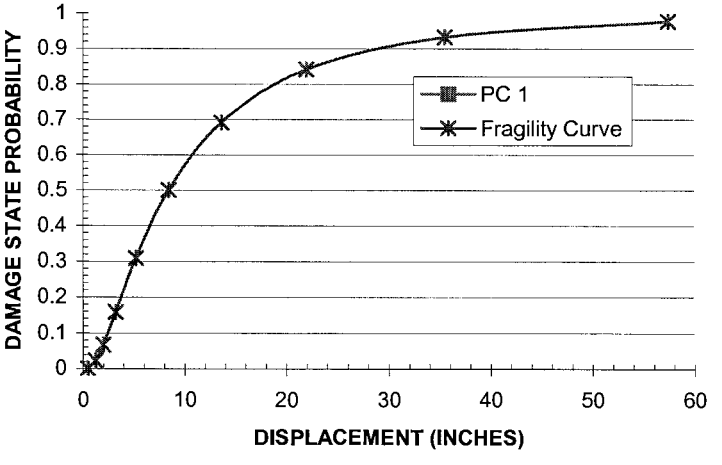
BLDG. FRAGILITY - SLIGHT DAMAGE
Figure - 2

Fragility Curve
Extensive Damage State

X	Y
0.24	0.0013
0.6	0.0227
0.93	0.0668
1.46	0.1587
2.3	0.3085
3.6	0.5
5.65	0.6915
8.85	0.8413
13.89	0.9332
21.8	0.9773

Fragility Curve
Complete Damage State

X	Y
0.47	0.0013
1.23	0.0227
1.99	0.0668
3.22	0.1587
5.19	0.3085
8.4	0.5
13.61	0.6915
21.92	0.8413
35.45	0.9332
57.29	0.9773



BLDG. FRAGILITY - COMPLETE DAMAGE
Figure - 3