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A Methodology for Rapid Earthquake Damage Assessment of Existing Buildings

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Abstract: In an effort to contribute to the reduction of the potential seismic risk in Canada, the Geological Survey of Canada has recently undertaken a comprehensive quantitative risk assessment study. The proposed framework for risk assessment considers region-specific inventory of the building stock, definition of the seismic hazard and evaluation of respective vulnerabilities. Structural vulnerability represents the key component within the framework and is derived from the fragility functions combining the intensity of the seismic motion to the expected damage for a given building type. This paper focuses on the development of a rapid procedure for the development of analytical seismic fragility functions based on the structural characteristics of the existing buildings in Old Quebec City with emphasis to historic stone masonry buildings. The applied procedure incorporates: (1) capacity curves to characterize the nonlinear behaviour of the existing buildings; (2) displacement fragility curves to represent the probability of exceedance of specified damage state under various levels of structural response; and (3) response spectra to estimate the structural demand for a series of earthquake magnitude-distance combinations. A modified capacity spectrum method is proposed for rapid evaluation of expected damage as opposed to the usual iterative procedure for the displacement response, e.g., the one implemented in the Hazus software. The developed methodology revealed to be a powerful tool for rapid assessment of regional seismic risk as it significantly reduces the computation time. It was validated for damage assessment of 1220 buildings in the Old Quebec City for a scenario event of M6.2 and distance 15km. The results show that some 30% of the buildings would suffer a certain degree of damage with most of the damage attributable to the poor performance of masonry buildings. The damage results are almost identical with those obtained by applying the Hazus software for the same input parameters.

1 Introduction

Physical damage and social and economic losses observed during the past destructive earthquakes emphasize the need to reasonably predict the potential risks in seismic prone areas. A standard definition of seismic risk considers the combination of the seismic hazard, exposure, and respective vulnerability, where: the seismic hazard represents a measure of the probability of a given shaking intensity at the studied location over a given time period; exposure refers to the assets at risk, i.e, built environment in that area; and vulnerability introduces the susceptibility to earthquake impacts, generally defined by the potential for damage and economic loss as a result of the intensity of seismic loading. Key element in the vulnerability modelling is the capacity of a building to sustain loads and displacements due to seismic shaking. Physical damage is typically represented through a set of fragility functions assigned to given damage state (Coburn and Spence, 2002), whereas economic losses are given by vulnerability functions (Porter, 2009). The outputs of vulnerability modelling are estimates of the potential physical damage and direct economic losses. Indirect damage, indirect economic losses and social losses, which should also be considered in the mitigation strategy, are not considered in this study.

In an effort to reduce seismic risk and increase general resilience to seismic hazards in Canada, the Geological Survey of Canada has recently initiated a comprehensive quantitative risk assessment study. One of the activities of this study is focused on the definition of the seismic vulnerability of existing buildings. This paper presents the development of an effective procedure for rapid damage assessment in terms of seismic hazard compatible fragility functions conditioned to a structure-independent intensity measure IM (e.g. spectral acceleration at a particular period). The applied procedure incorporates: (1) capacity curves to characterize the nonlinear behaviour of the existing buildings; (2) displacement fragility curves to represent the probability of exceedance of specified damage state under various levels of structural response; and (3) response spectra to estimate the structural demand for a series of earthquake magnitude-distance combinations. It was validated for damage assessment of 1220 buildings in the Old Quebec City. A comparison of damage prediction with HAZUS software, the FEMA loss estimation methodology (FEMA, 2003), is presented.

2 Damage Assessment Procedure

The analytical damage assessment framework for existing buildings requires three input models: (1) inventory model of the existing buildings in the study region and their classification according to the structural type, construction material, height and design level, (2) seismic hazard model that applies a ground-motion prediction equation compatible to the seismo-tectonic settings to estimate the potential shaking intensity in terms of structure-independent IM (e.g. spectral acceleration at a particular period), and (3) vulnerability model represented with seismic hazard compatible fragility functions in terms of structure-independent IM. The damage estimates are given in terms of number of damaged buildings and damage states.

The vulnerability of a typical building type can be assessed based on: observed damage from past earthquakes for which adequate records of the seismic motion are available (empirical method); expert opinion; analytical methods involving simplified mathematical models of structural response of a building or a type of buildings; time-domain numerical modelling of structural response; and by a combination of any of these methods (Porter 2009). In the absence of observed earthquake damage patterns or sufficient data, analytical methods are often preferred. In such case, essential input components of the vulnerability assessment are the capacity curves and fragility functions. Capacity curves describe the nonlinear structural behaviour and are generally obtained from pushover analysis as a relationship between top displacement and lateral load capacity (FEMA356, 2000). On the other hand, fragility function define the probability of exceedence of a given physical damage state, e.g., slight, moderate, extensive and complete (Coburn and Spence, 2002). Fragility functions are usually given as lognormal distribution functions of a seismic IM, e.g., spectral acceleration at a given period ($S_a(T)$). They can also be conditioned on a structural specific IM, e.g., inelastic spectral displacement (S_d), defined as displacement based fragility functions.

The vulnerability modelling approach developed in this study was inspired by the procedure employed in Hazus, the well-known loss estimation methodology developed by US Federal Emergency Management Agency - FEMA (FEMA, 2003). The capacity curves and the displacement based fragility functions for stone masonry buildings were determined previously by Abo-El-Ezz et al. (2011). The vulnerability modelling procedure is graphically presented in Figure 1. For a given building type, it starts with the development of response spectra defined by structure-independent IMs, Sa(0.3sec) and Sa(1.0sec). The structural analysis is conducted in the spectral acceleration vs. spectral displacement (S_a-S_d) domain. The response is evaluated using the capacity spectrum method (CSM) (Mahaney et al., 1993; ATC 40, 1996). In the CSM, the performance point is obtained based on the assumption that the nonlinear response of the system can be modelled as a linear equivalent single degree of freedom with increased period and effective damping, both related to the ductility demand (i.e. displacement demand over the yield displacement). In order to avoid computationally costly iterations for the structural displacement response, i.e. the performance point, the CSM procedure was amended according to the suggestions proposed by Porter (2009), Figure 1.a. The performance point for the considered magnitude-distance scenario is determined on the capacity curve in the S_a-S_d domain. The corresponding effective damping is then calculated from the ductility-damping relationships (ATC-40, 1996). The associated values of the structure-independent IMs of the site-soil response spectrum (S_a(0.3sec) for 5% damping), are obtained next using the spectral reduction factor relationship between the performance point S_a with the effective damping and the Sa(0.3sec) with 5% damping.

The second step continues forward from the performance point into the set of previously developed displacement based fragility functions (Abo-El-Ezz et al., 2011) to determine the probability of damage states (Figure 1.b). The obtained probabilities are ranked with respect to the computed IM (indicated with hollow dots in Figure 1.c).

To establish a complete set of fragility functions in terms of the structure-independent IMs, the procedure is repeated for gradually increasing intensity levels, i.e., increasing demand response spectra (Figure 1.a). The computed probabilistic damage states are arranged in tabular format for respective structure-independent IM. The data is then fitted with lognormal cumulative probability functions with proper mean and standard deviation to provide suitable hazard compatible seismic fragility functions. More details of the computation procedure can be found in Porter (2009). The above procedure revealed to be a powerful tool for conducting rapid damage assessment before or immediately after a strong earthquake event.

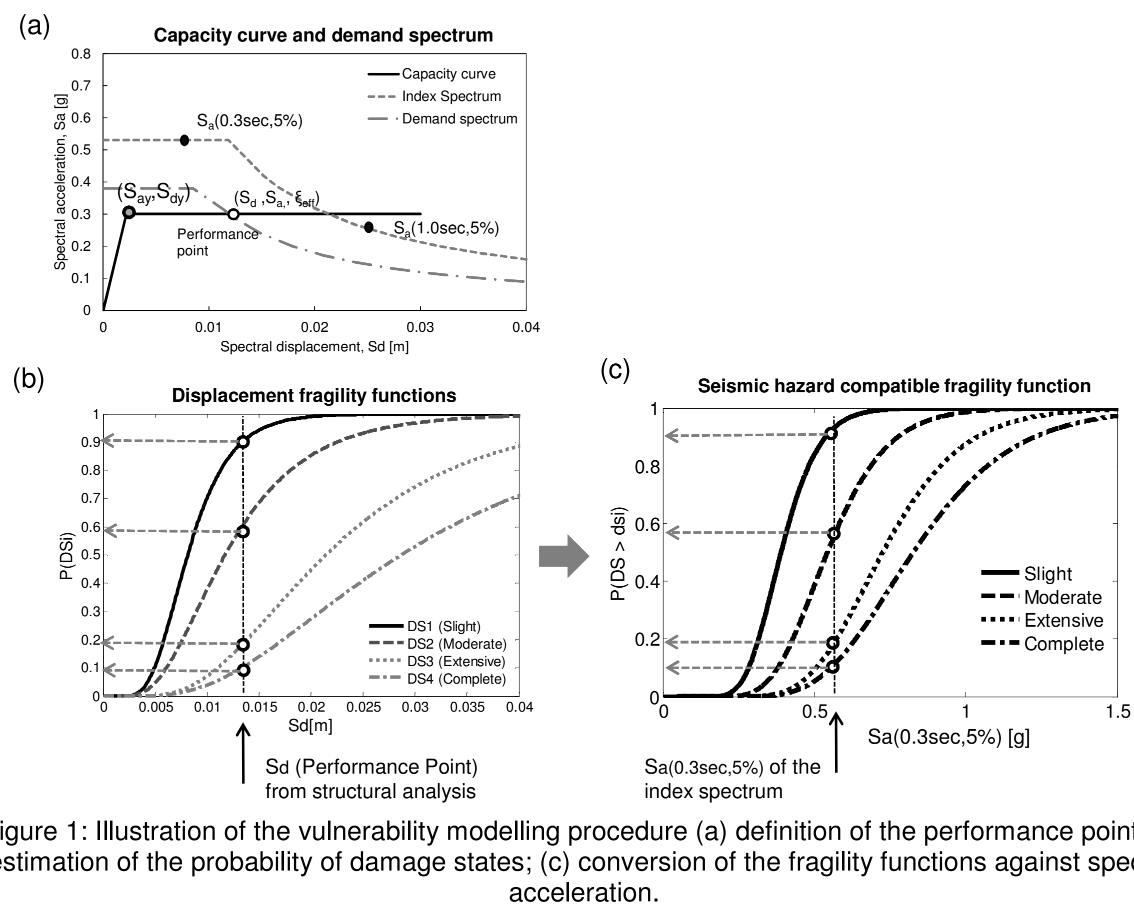

Figure 1: Illustration of the vulnerability modelling procedure (a) definition of the performance point; (b) estimation of the probability of damage states; (c) conversion of the fragility functions against spectral acceleration.

It should be noted that Hazus (FEMA, 2003) do not offer seismic fragility functions in a tabular or graphical form plotted against a structure-independent intensity measure. Moreover, Hazus vulnerability method involves iteration to estimate structural response with the help of the capacity spectrum method. It is thus difficult to relate back the predicted damage to a structure-independent intensity measure. In order to overcome these difficulties, the proposed methodology provides a non-iterative solution to the CSM starting with a given value for the structural response S_d, calculating the respective S_a for the performance point on the capacity curve, calculating the effective damping, and going back to the associated values of Sa0.3 sec and Sa1.0 sec for 5% of the site-soil-adjusted idealized demand (input) response spectrum. Then, the method uses the performance point to compute the probability of a given damage state and relates the two end products: damage vs. structure-independent intensity measure, Sa0.3 sec and 5% damping in this case. The HAZUS vulnerability computation, on the other hand, starts form the demand spectrum given Sa0.3 sec and Sa1.0 sec for 5% damping, calculating forward the performance point with Sd and Sa for respective effective damping, which requires iterative procedure, and then estimates the probability of the damage states. The computational demands of the iteration can be significant for a large portfolio or a probabilistic risk assessment, whereas having predefined fragility functions in terms of a structure-independent IM greatly reduces the computational demands.

3 Validation Case Study

The above procedure was used to conduct a rapid damage assessment of the existing buildings in the Old Quebec City. The study was motivated by the presence of numerous historic masonry buildings with unique heritage value and the obvious need to evaluate their behaviour under potential earthquake scenarios. The assessment was performed for a hypothetical M6.2R15 event which corresponds roughly to the probability of exceedence of 2% in 50 years according to the National Building Code of Canada (NBCC, 2010; Adams and Halchuk, 2003). The response spectrum for the selected scenario was developed using the ground motion prediction equation given by Atkinson and Boore (2006). The ground motion parameters retained for the damage assessment were the spectral accelerations $S_a(0.3s)=0.38g$ and $S_a(1.0s)=0.07g$ as representative IMs for short and long periods for the predominant site class B (rock) in the study area. The building inventory was compiled by a combination of data from the municipal database of the City of Quebec and a field survey of 1220 buildings (Nollet et al., 2012). The inventoried buildings were classified according to (1) construction material: wood, steel, concrete, masonry; (2) structural system: frame or wall structure; (3) seismic design code level: pre-code for building not seismically designed (before 1970) and mid-code for buildings designed according to seismic provisions (between 1970 and 1990); (4) height: low-rise with 1 to 3 stories, mid-rise with 4 to 7 stories. This classification scheme corresponds to that employed by the Hazus methodology (FEMA, 2003). The inventory results are given in Table 1.

Table 1: Distribution of building classes within Old Quebec City study area.

Building type	Height	Number of buildings	Code level	
			Pre-code (before 1970)	Mid-code (after 1970)
W1L (wood light frame)	Low-rise	131	86	45
S1L (Steel Moment Frame)	Low-rise	32	20	12
S1M (Steel Moment Frame)	Mid-rise	12	12	-
S2L (Steel braced frames)	Low-rise	30	14	16
S2M (Steel braced frames)	Mid-rise	24	24	-
S5L (Steel frames with URM infill)	Low-rise	33	33	-
C1L (Concrete moment frame)	Mid-rise	25	0	25
URMBL (Unreinforced Brick masonry)	Low-rise	469	469	-
URMBM (Unreinforced Brick masonry)	Mid-rise	296	296	-
URMSL (Unreinforced Stone masonry)	Low-rise	168	168	-
Total number		1220	1122	98

Table 1 shows that the dominant building types are the pre-code unreinforced brick masonry (62%) and stone masonry buildings (14%). 91% of the existing buildings are built before 1970. Although the first seismic design provisions were introduced in the 1941 National Building Code edition, they evolved considerably over the years and most buildings constructed prior to 1970 are considered as pre-code buildings, especially unreinforced masonry. Due to similar construction practices in Canada and in the United States, the same capacity curves and displacement based fragility functions as those applied by Hazus (FEMA, 2003) were used for the vulnerability modelling of the building types listed in Table 1. The only exception was the stone masonry buildings, which are not explicitly considered by Hazus. Their capacity curves and fragility functions were generated by Abo-El-Ezz et al. (2011).

The estimated damage levels for the considered M6.2R15 scenario are given in **Figure 2**(a). The total number of buildings that will be subject to certain degree of damage is 369, or 30% of the buildings. A summary of the proportion of buildings by construction material type and damage states is shown in **Figure 2**(b). Predictably, most of the expected damage is due to the poor performance of the pre-code stone and brick masonry buildings. Approximately 39% of the stone masonry buildings (65 buildings out of 168) and 33% of the brick masonry buildings (252 buildings out of 765) will suffer certain damage.

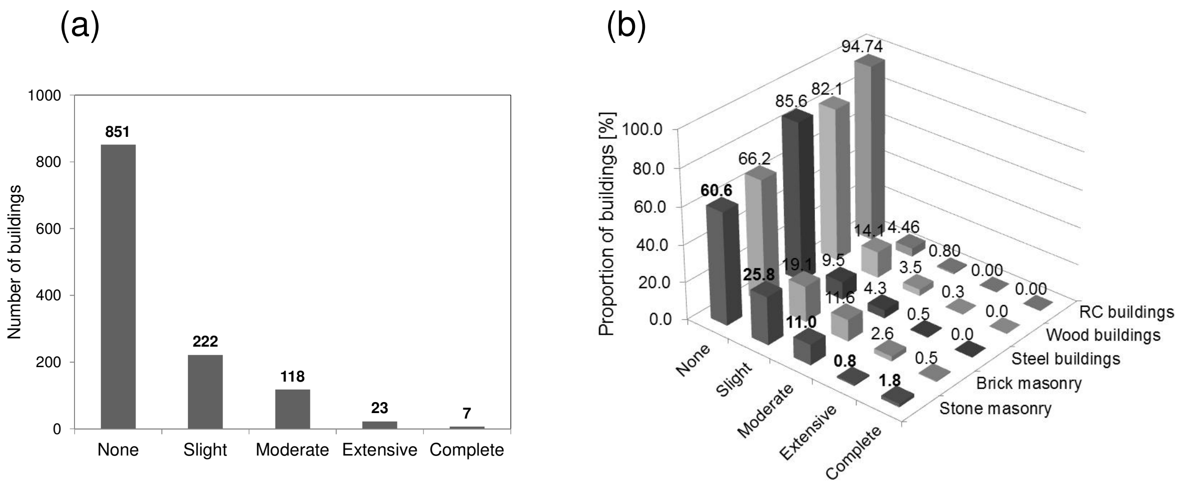

Figure 2: Damage prediction for the considered M6.2R15 scenario: (a) Total number of buildings in each damage state for event and (b) Proportion of buildings in given damage state according to the construction material.

4 Comparison with HAZUS

The obtained results were compared with damage estimates obtained applying the Hazus software for the same ground motion of Sa(0.3s)=0.38g and Sa(1.0s)=0.07g (Table 2). The comparison of probability of structural damage was conducted for the four building classes: pre-code unreinforced masonry low-rise buildings (URML_Precode), pre-code steel braced frame buildings (S2L_Precode), pre-code light wood frame buildings (W1L_Precode) and pre-code steel moment frame buildings (S1L_Precode). The Table 2 indicates almost identical results for both methods.

Although this comparison is only between results obtained from two numerical models and there are no field observations to corroborate the damage estimates, it confirms the validity of the developed procedure. Note that the Hazus methodology has been subjected to extensive testing against occurred damages during past earthquakes to ensure accurate risk assessments. Still the obtained results are sensitive to the assumed input parameters and uncertainties can result in considerable deviations.

Table 2 Comparison of probability of damage using the developed methodology with HAZUS software.

	URMBL_Precode		S2L_Precode		W1L_Precode		S1L_Precode	
Probability [%]	Fragility functions	HAZUS software	Fragility functions	HAZUS software	Fragility functions	HAZUS software	Fragility functions	HAZUS software
None	64	66	86	87	79	79	89	84
Slight	19	18	9	9	16	16	8	13
Moderate	13	12	5	4	5	5	3	3
Extensive	3	3	0	0	0	0	0	0
Complete	1	1	0	0	0	0	0	0

Figure 3 shows an example of the fragility functions for low-rise stone and brick masonry buildings in terms of Sa(0.3s). Steeper fragility functions in the case of stone masonry buildings indicate higher vulnerability when compared with those for the brick masonry buildings. This difference is attributed to the input capacity curves **Figure 4**(a,b) and displacement based fragility curves **Figure 4**(c,d) for the respective building classes. Stone masonry buildings show lower strength and deformation capacity compared to brick masonry buildings. This comparison highlights the importance for the development of capacity and fragility curves that reflect the specific characteristics of the considered structures.

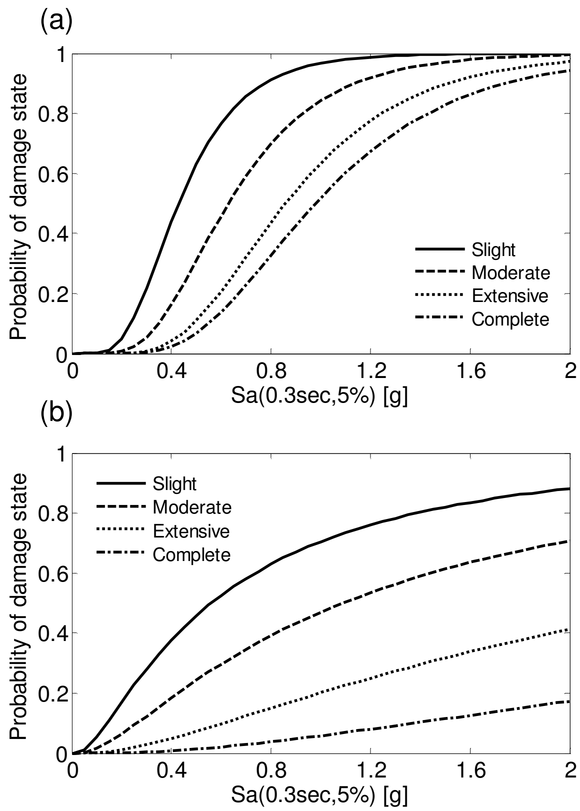

Figure 3: Fragility functions for (a) stone masonry buildings, and (b) brick masonry buildings.

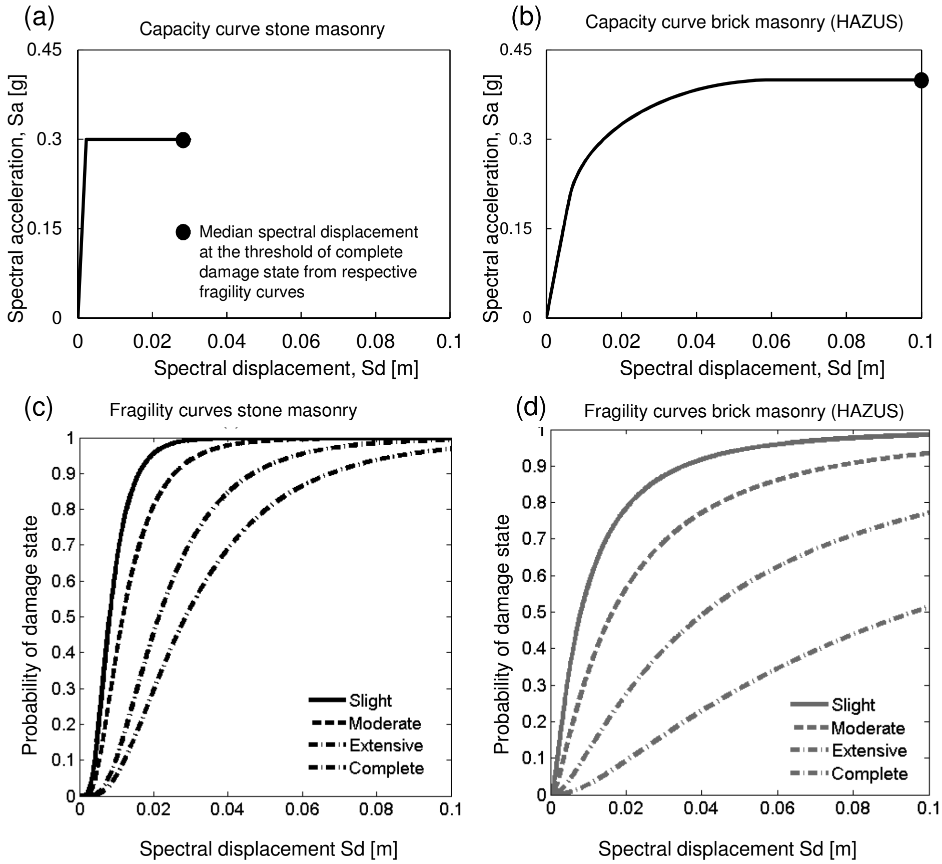

Figure 4: Input parameters for vulnerability modelling of masonry buildings: (a) capacity curve for stone masonry buildings used in this study, (b) capacity curve for brick masonry employed by Hazus, (c) and (d) fragility curves for stone and brick masonry buildings, respectively.

5 Conclusions

A methodology was presented for rapid damage assessment in terms of seismic hazard compatible fragility functions conditioned to a structure-independent intensity measure IM (e.g. input spectral acceleration at a particular period for elastic 5% damping). The procedure combines (1) capacity curves to characterize the nonlinear behaviour of the existing buildings; (2) displacement fragility curves to represent the probability of exceedance of specified damage state under various levels of structural response; and (3) input response spectrum for a scenario earthquake to estimate the structural demand. A modified capacity spectrum method is proposed for rapid evaluation of the potential damage opposite to the standard Hazus iterative procedure for obtaining the displacement response. The developed methodology revealed particularly powerful for rapid regional-scale damage assessment as it significantly reduces the computation time. The results of damage assessment for an inventory of 1220 buildings in the Old Quebec City for a scenario event of magnitude 6.2 at distance 15km, corresponding to a probability of exceedence of 2% in 50 years, showed that most of the expected damage would be concentrated in the old brick and stone masonry buildings, with 33% and 39% of damaged buildings in the respective class. The damage results are almost identical with those obtained by applying the Hazus software for the same input parameters.

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