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A METHOLODGY TO ASSESS SEISMIC RISK FOR POPULATIONS OF UNREINFORCED MASONRY BUILDINGS

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SUMMARY

This paper introduces a generic methodology for seismic risk evaluation of populations of unreinforced masonry buildings. The methodology can be used by decision makers to layout effective mitigation strategies to reduce the consequences of future earthquakes in their region. The steps of the methodology are illustrated on a small town, San Giuliano di Puglia. This town was shaken during the October and November 2001 earthquakes (Mw = 5.7) in Molise.

INTRODUCTION

New technologies enabling rapid assessments of seismic damage, economic loss and risk across specified regions of stakeholder interest are being developed as part of the Damage Synthesis research thrust area of the NSF-sponsored Mid-America Earthquake Center, headquartered at the University of Illinois at Urbana-Champaign. As part of this effort, a methodology that can be used to quickly assess vulnerability of populations of unreinforced masonry buildings has been developed. Such regional seismic risk evaluation of existing buildings is necessary to help decision makers to prescribe effective mitigation strategies and thus limit consequences of future earthquakes to acceptable levels (Abrams *et. al.* [1]).

An earlier effort on development of regional risk/loss estimation tools was done with the HAZUS [4] earthquake loss estimation methodology funded by the Federal Emergency Management Agency (FEMA). In the HAZUS methodology, regional loss is estimated through utilizing vulnerability relationships defined for different classes of buildings. For most building classes these vulnerability relationships were empirically defined from expert opinions. Such opinion based vulnerability functions are highly static, i.e. do not provide flexibility for further development with advanced knowledge, and direct, i.e. they do not possess information regarding intermediate steps that identify the hazard–damage relationships. These drawbacks hamper the evaluation of uncertainty and likewise the accuracy of loss estimates. To overcome these issues, vulnerability functions (or similarly hazard loss functions) have to be developed through rational analyses that are conducted on robust and analytically sound models of buildings. Such an

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approach also allows identification of the building and region parameters that are significant for loss calculations. Furthermore, being explicit in terms of intermediate steps, the level of uncertainties at various stages of calculations can be estimated and if necessary can be improved with incorporation of new knowledge.

Considering these needs, a risk and loss assessment methodology has been developed. The tools and relationships of the methodology were based on extensive parametric investigations that were conducted on analytical models and were carried out as nonlinear time history analyses. The details of these investigations are beyond the scope of this paper. Interested readers may refer to Erbay [3].

The tools and the relationships of the methodology were developed for older clay brick unreinforced masonry buildings that have material, configuration, and construction characteristics similar to that found in urban regions of the United States. In general, these buildings were constructed in the late 19th and in the early 20th century. These buildings, typically, contain wood floor construction that results in flexible diaphragm response.

THE METHODOLOGY

General

In general, the methodology has three parts: 1) data collection, 2) grouping, and 3) evaluation. Figure 1 shows these three parts and their interaction among each other. In simple terms, the goal in the first part is to collect building and region specific data that will be utilized throughout the methodology. The collected information is used in the second part to identify the appropriate tools and relationships that represent the loss potential of the region or sub-regions. The outcomes of the first two parts are utilized in the final part to calculate the loss/risk estimate for the region.

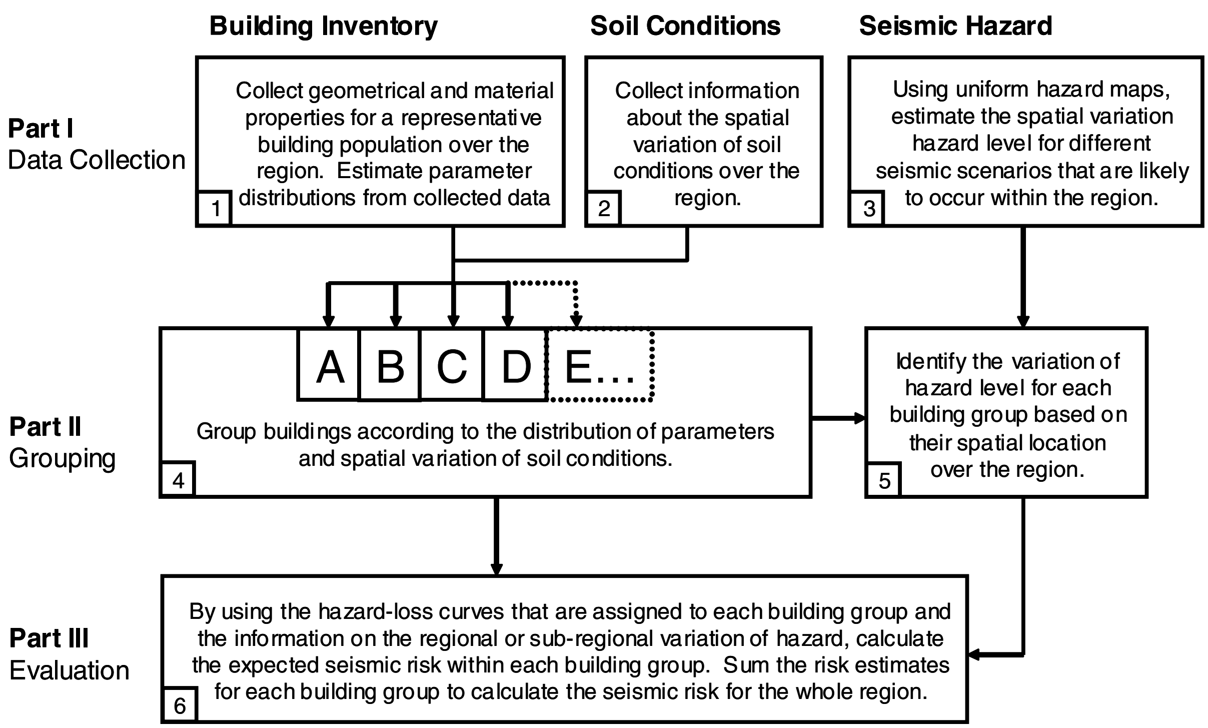

Figure 1 General layout of the methodology

Depending on the region and building population properties, one or more steps of the methodology can be skipped to simplify the overall procedure. The combination of region and building population properties and the associated steps that can be eliminated from the overall procedure are explained in section 2.3 "tiers of the methodology".

Calculation of regional risk and loss

Calculation of seismic risk for population of buildings involves estimation and summation of expected losses due to all possible earthquakes within the region of the building population. For a given region the occurrence of earthquakes and their consequences are mutually exclusive and collectively exhaustive events therefore, the previous statement can be expressed in terms of the total probability theory (Ang and Tang [2]) as follows:

$$Total\ Seismic\ Risk = \sum_{\substack{for\ all\ possible \\ hazard\ levels}} E(Loss \mid Hazard = H_i) \cdot P(Hazard = H_i) \tag{1}$$

where, $E(Loss \mid Hazard = H_i)$ = the expected amount of losses, consequences, for a given level of hazard, H_i.

$P(Hazard = H_i)$ = the probability of getting a hazard level of H_i.

The hazard level is represented by spectral acceleration, S_a. A period that is representative of the fundamental periods of the buildings over the whole region or sub-regions is used in estimating the spectral acceleration. In the absence of region specific seismicity data, the United States Geological Survey (USGS) National Earthquake Reduction Program (NEHRP) Maps [6] can be used to estimate spectral accelerations for a given zip code. These maps provide the parameters that can be used to generate elastic response spectra of probable earthquakes with different return periods. For most of the applications, the spectral acceleration corresponding to the plateau region (constant velocity) of the elastic response spectrum can be used as the representative hazard level for the region, since fundamental period of masonry buildings typically falls in this region.

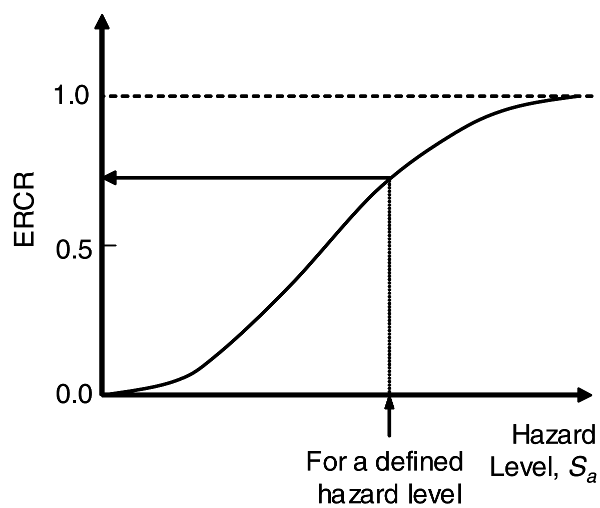

Figure 2 A typical hazard–loss relationship and its use.

In this methodology, the losses are due to direct structural damage. The relationship between the hazard level and the expected loss is defined through hazard-loss relationships. A typical hazard-loss relationship and its use in estimating expected value of loss for a given level of hazard is illustrated in Figure 2. Note that in a hazard-loss relationship, the loss is defined as the ratio of the actual monetary loss to the total replacement cost of the buildings in the region or sub-regions (i.e. the term "loss" is normalized). In this regard loss value corresponds to 0.0 for no damage or no hazard case and 1.0 for full damage or high hazard level. Selection of appropriate hazard-loss relationships for a specific region will be discussed in the upcoming sections.

Once the hazard level and the appropriate hazard-loss relationship for the region of sub-regions are identified, the total expected loss in each building group can be calculated as follows:

$$TLG_i(S_a) = ERCR_i(S_a) \times TBA_i \times MVPA \qquad (2)$$

where, $TLG_i =$ for a defined level of hazard, S_a , the total expected loss in the ith building group.

$ERCR_i =$ for a defined level of hazard, the expected value of the replacement cost ratio for the ith building group (the value read from the hazard-loss curves).

$TBA_i =$ total building area in the ith building group.

$MVPA =$ monetary value per unit area of buildings over the analysis region.

From this calculation the total loss over the region can be computed as:

$$TRL(S_a) = \sum_{i=1}^{n} TLG_i \qquad (3)$$

where, $TRL(S_a) =$ total regional loss for a defined hazard level.

$n =$ number of building groups used in the analysis.

The seismic risk for a given hazard level, the scenario-based risk, can be determined by multiplying the calculated loss with the probability of occurrence of the assumed hazard:

$$SR(S_a) = TRL(S_a) \times P(Hazard = S_a) \qquad (4)$$

where, $SR(S_a) =$ seismic risk for the assumed hazard.

$P(Hazard = S_a) =$ probability of hazard level being equal to S_a .

As expressed in Equation 1, the total seismic risk can be calculated as the summation of scenario based risk estimates for all possible hazards.

Tiers of the methodology

The methodology can be applied to any generic region. However, the procedure can be simplified if the properties of the region or building population show similarities with the assumptions that were used in developing the tools and relationships of the methodology. Different levels of simplifications based on different combination of region and building parameters formed the tiers of the methodology. The tiers of the methodology and associated conditions are summarized in Figure 3.

	S_a and soil type variation is constant.	S_a and soil type variation is not constant.
Parameter distributions per Fig. 5 and population size is greater than 25 buildings.	**A**	**B**
Parameter distributions not per Fig. 5 and population size is greater or less than 25 buildings.	**C**	**D**

Figure 3 Tiers of the methodology

Tiers	Information required	Action required
A	- Number of buildings. - Sa value and soil type. - Monetary value per unit area of buildings.	- Simple summation. - Can be carried out by a non-expert.
B	- Numbers of buildings in each soil and S_a category. - Representative S_a value and soil type in each S_a and soil category. - Monetary value per unit area of buildings.	- Integration of loss over sub-regions. - Can be carried out by a non-expert with some assistance from an engineering profession.
C	- Number of buildings. - Distributions for the building parameters that are listed in Table 1. - Sa value and soil type. - Monetary value per unit area of buildings.	- Field measurements from sample buildings to determine parameter distributions. - Grouping of buildings according to Figure 6. - Integration of loss over building groups. - Can be carried out by an engineering profession.
D	- Numbers of buildings in each soil and Sa category. - Representative Sa value and soil type in each Sa and soil category. - Distributions for the building parameters that are listed in Table 1. - Monetary value per unit area of buildings.	- Field measurements from sample buildings to determine parameter distributions. - Grouping of buildings according to Figure 6. - Integration of loss over building groups and sub-regions. - Can be carried out by an engineering profession.

Figure 4 Information and action required in each tier

In general, more time and expertise are required to complete the regional loss/risk analysis for increasing tier letters (i.e. from A to D). Among provided tiers, tier A provides the simplest case in estimating the regional loss/risk. In this case, user neither needs to collect inventory data nor he needs to categorize buildings according to different soil conditions and hazard levels. In tier B, no building inventory data needs to be collected however, buildings need to be grouped according to soil conditions. Tiers C and D require collection of sample building data to identify the representative parameter distributions over the region. Data collection and analysis process requires assistance from an engineering profession.

The goal of the user is to select one of the tiers that best describes his region. For selection purposes, a rapid field survey can be conducted to estimate the variation of building parameters over the region. Once the analysis tier is selected, additional field surveys can be conducted to refine initially collected data based on the required information in the analysis tier. The types of data required in each analysis tier are summarized in Figure 4. Also provided in Figure 4, are the types of calculation and the level of expertise that are needed to carry out each analysis tier.

Parameters of the methodology

The parameters used in the methodology and the possible resources to obtain them are listed in Table 1. Figure 5 shows the distribution of building parameters that are assumed to be typical for the building populations at urban regions of the United States.

Table 1 Region and building parameters that are used in the methodology

Seismic Hazard and Soil Conditions	Building Parameters
• Elastic response spectra and its spatial variation over the region. • Soil variation over the region	• Monetary value • Aerial location • Number of stories • Floor area • Floor aspect ratio • Normalized wall density index • *Story height • *Elastic modulus of masonry
Possible resources	Possible resources
• USGS (2000) Hazard Maps (provide parameters to generate elastic response spectra for a given region and defined scenario).	• Existing city inventories • Tax assessor's database • Aerial photography • Field surveys

The building parameters that are listed in Table 1 are self explanatory except the floor aspect ratio and the wall density. The floor aspect ratio is the ratio of the longer floor dimension to the smaller one. The wall density is defined as the ratio of total effective wall area at the ground level to the floor area of the building. Normalized wall density index is calculated as follows:

$$\alpha_{wx} = \alpha_x / \alpha_x' \text{ and similarly } \alpha_{wy} = \alpha_y / \alpha_y' \quad (5)$$

where, $\alpha_{wx,y}$ = normalized wall density index

$\alpha_{x,y}$ = actual wall-area-to-floor-area ratio

$\alpha'_{x,y} = 2L_{x,y}t_{wx,y}/A_f$ = wall-area-to-floor-area index ratio with $t_{wx,y}$ = sum of the wall thicknesses in directions x or y, $L_{x,y}$ = plan dimensions of the floor, and A_f = floor area.

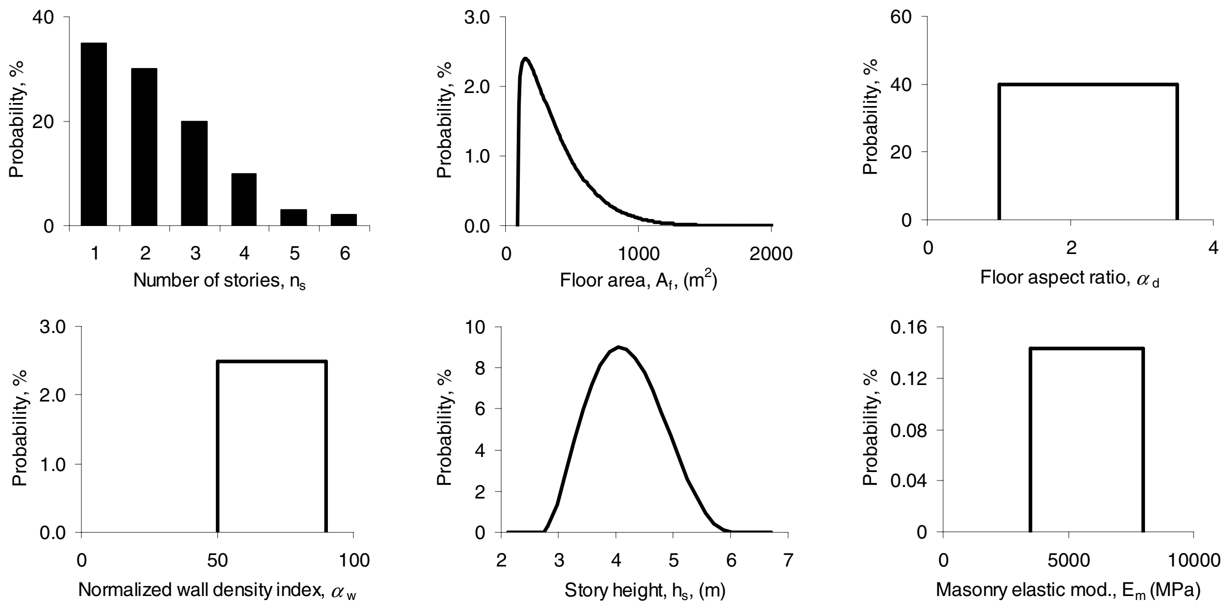

Figure 5 Assumed distributions for building parameters.

Selection of hazard-loss curves

As introduced in the earlier sections, the loss in a building population is estimated through using the hazard-loss relationships. In the methodology, a set of hazard-loss relationships are defined to represent the loss potential of different building populations. Selection of appropriate hazard-loss relationship depends on the analysis tier as well as the properties of the region and the building population.

In analysis tiers A and B the hazard-loss relationships that were developed for typical building populations at urban regions (Figure 5) are used. To account for different soil properties (for analysis tier B), soil specific hazard-loss relationships are also provided. The hazard-loss data for tier A and B is provided in Table 2.

Table 2 Hazard-loss relationships for analysis tiers A and B

S_a, g	0.02	0.04	0.08	0.14	0.2	0.3	0.4	0.5	0.6	0.8	1.0	2.0	3.0
Tier A													
ERCR	0.06	0.13	0.25	0.38	0.47	0.58	0.66	0.73	0.79	0.87	0.92	0.99	1.00
Tier B													
ERCR SC* A	0.10	0.22	0.37	0.49	0.57	0.65	0.71	0.77	0.81	0.89	0.93	0.99	1.00
ERCR SC* B	0.06	0.12	0.23	0.35	0.45	0.56	0.65	0.72	0.78	0.87	0.93	1.00	1.00
ERCR SC* C	0.02	0.05	0.15	0.29	0.41	0.54	0.63	0.71	0.77	0.87	0.92	0.99	1.00

For tiers C and D user needs to conduct additional field surveys to estimate the distribution of building parameters across the region. The collected data is used to identify the groups of buildings that can be represented by a single hazard-loss relationship. To identify the building groups, collected parameters need to be categorized into ranges that are defined in Table 3. Based on these ranges and utilizing Figure 6, user can identify the buildings that have similar loss potential. Once the building groups are identified, user can estimate the loss in each building group by using the hazard-loss relationships that are provided in Table 4.

Table 3 Intervals to categorize parameters

Parameter	SC	n_s	α_d	α_w (%)	h_s (m)	E_m (MPa)	A_f (m^2)
Range 1	A	1	1.0-1.8	50-62	2.7-3.8	3500-4900	90-215
Range 2	B	2-3	1.8-2.8	62-78	3.8-4.5	4900-6800	215-450
Range 3	C	4-5-6	2.8-3.5	78-90	4.5-6.0	6800-8300	450-2800

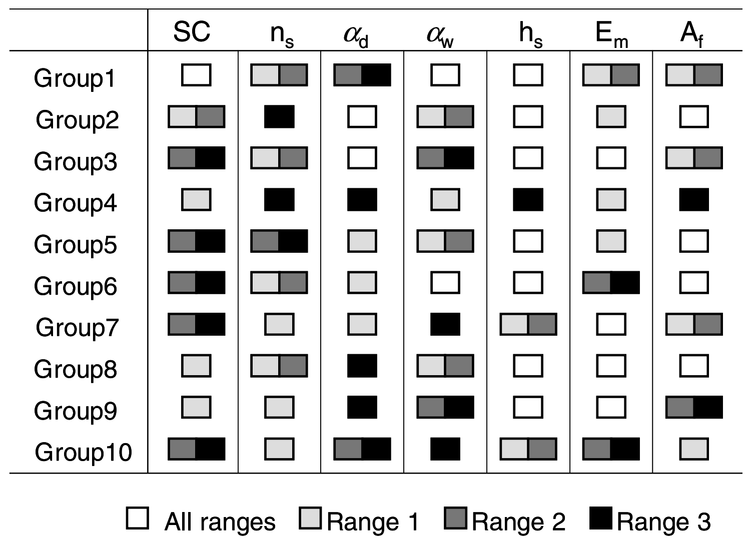

Figure 6 Parameter ranges associated with each hazard-loss group

Table 4 Hazard-loss relationships associated with each group (analysis tiers C and D).

Sa, g	0.02	0.04	0.08	0.14	0.20	0.32	0.40	0.50	0.65	0.80	1.0	1.5	3.0
Group													
1	0.04	0.10	0.23	0.36	0.45	0.57	0.63	0.70	0.79	0.86	0.91	0.98	1.00
2	0.12	0.26	0.42	0.56	0.66	0.79	0.85	0.90	0.95	0.97	0.99	1.00	1.00
3	0.01	0.03	0.06	0.12	0.19	0.32	0.39	0.47	0.56	0.65	0.73	0.87	0.99
4	0.27	0.42	0.56	0.69	0.78	0.89	0.93	0.96	0.98	0.99	1.00	1.00	1.00
5	0.02	0.05	0.17	0.39	0.56	0.77	0.85	0.92	0.97	0.99	1.00	1.00	1.00
6	0.02	0.02	0.04	0.12	0.23	0.44	0.56	0.69	0.81	0.89	0.94	0.99	1.00
7	0.01	0.02	0.02	0.03	0.04	0.08	0.14	0.24	0.38	0.52	0.65	0.85	0.99
8	0.17	0.35	0.48	0.51	0.52	0.55	0.58	0.62	0.70	0.78	0.86	0.96	1.00
9	0.04	0.11	0.23	0.36	0.45	0.50	0.51	0.52	0.54	0.58	0.64	0.78	0.97
10	0.01	0.02	0.04	0.07	0.12	0.23	0.29	0.37	0.44	0.47	0.51	0.63	0.94

TEST-BED APPLICATION: SAN GIULIANO DI PUGLIA

The steps of the methodology are illustrated on a small town, S. G. D. Puglia, Italy. This town was shaken on October 31 and November 1, 2001 with two moderate size (M_L = 5.4 and 5.3) earthquakes. Comparison of the local damage intensities with the ones for the historic events have shown that the recent events generated a similar level of damage as the event that occurred on May 12, 1456 in the Bojano basin (Mola *et. al.*, [5]). This suggests that the recent events may have a return period of about 500 years.

At the time of the earthquakes, there were no recording stations in the town. Therefore, the exact value of the hazard level is not well known. Based on region-specific attenuation relationships and measurements taken from close by recording stations, Mola *et. al.* [5] estimated the peak ground accelerations in S. G. D. Puglia to be 0.36g for the first event and 0.17g for the second event. The PGA level for the first event is used as the hazard level in the current illustration. An amplification value of 2.0 is assumed to estimate the S_a value that is representative of the region.

The local soil conditions in S. G. D. Puglia ranged from limestone (for older part of the town) to talus and anthropic refillings (for recently developed part of the town) (Mola *et. al.* [5]). Overlapping of the region soil map with the location map of the buildings has shown that the soil type under the building population is constant and is equal to artificial fillings. Focus in this illustration is on buildings in the recently developed part of the town therefore a soil category of SC-C is assumed in this application.

The town has about 100-150 buildings among which 45-65% consists of two to three story residential engineered and non-engineered masonry houses. To understand the distribution of building parameters, a total of 66 unreinforced masonry buildings were investigated in the recently developed part of the town. Comparison of the parameter distributions with the ones that were provided in Figure 5 showed some differences. Due to these differences tier D is selected to carry out the regional risk assessment.

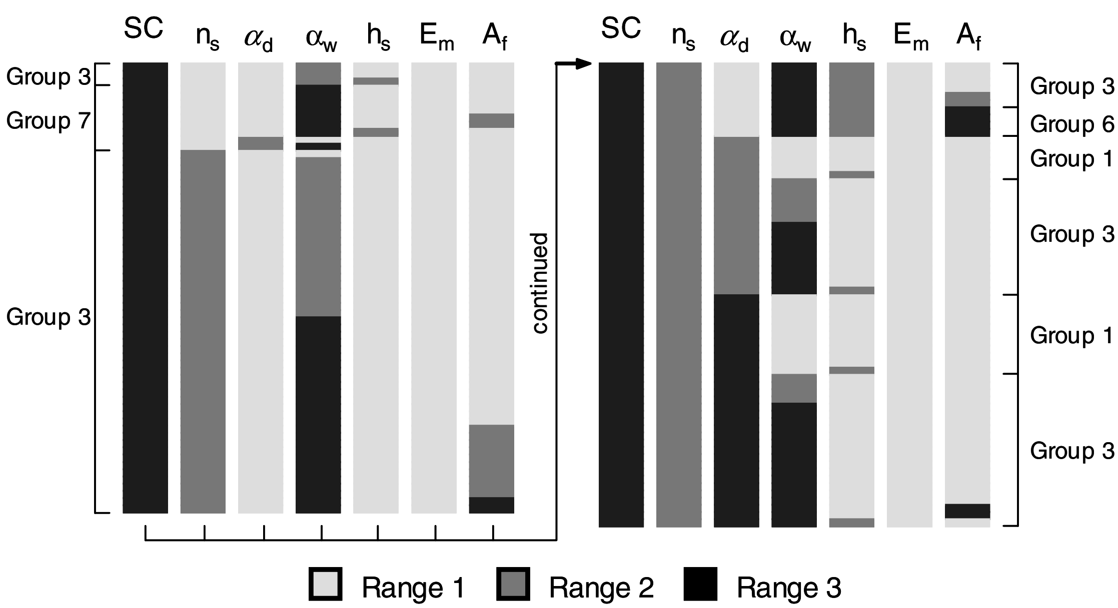

Figure 7 Building parameters after classified into intervals

Table 5 Total value, ERCR, and estimated loss in each building subgroup

	Group A (1)*	Group B (3)*	Group C (6)*	Group D (7)*	Total
Value, %	6.5	79.7	10.2	3.6	100
ERCR	0.82	0.60	0.85	0.45	-
Loss, %	5.3	47.8	8.4	1.6	63.1

* Value represents the group number that is associated with that subgroup

In order to identify building groups with similar hazard-loss relationship, the building parameters are categorized according to the intervals defined in Table 3. The resulting parameter distributions are shown in Figure 7. Based on these distributions and the parameter combinations presented in Figure 6, the building population is divided into 4 subgroups. In this case, hazard-loss curves were taken from groups 1, 3, 6, and 7. The properties of the building population are summarized in Table 5. The first row provides the normalized building value for each subgroup. The remaining two rows provide the ERCR and associated loss for each subgroup at a hazard level of $S_a = 0.72g$. Based on this calculation the total normalized loss is estimated to be 63% for the events of October 31 and November 1.

Using the estimated regional loss, the annual seismic risk can be calculated by using an appropriate probability distribution that can model occurrence of earthquakes in time. In this case, a Poisson's distribution is assumed to model earthquake occurrence. Using the estimated return period (T_r ~ 500 years) for the events, the annual risk is calculated as follows:

$$\begin{aligned} Seismic\ Risk &= TRL \times P\left(n = 1 \middle| S_a = 0.72g\right) \\ &= 63.1 \times \frac{\left(\frac{1}{500} \cdot 1\ year\right)^1}{1!} \cdot e^{\left(-\frac{1}{500} \cdot 1\ year\right)} = 12.5\% / year \end{aligned} \quad (6)$$

The result in Equation 6 means that each year there exists a 12.5% loss potential due to a 500-year return period event in S. G. D. Puglia.

CONCLUDING REMARKS

A generic methodology for seismic risk assessment of populations of masonry buildings is introduced. The tools and relationships of the methodology were developed for regional risk and loss assessments and should not be used for individual building evaluation.

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