SEISMIC VULNERABILITY AND AVERAGE DAMAGE GRADE ASSESSMENT OF RESIDENTIAL BUILDING STOCK IN SÃO MIGUEL ISLAND, AZORES

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ABSTRACT

The Azores, a nine island Portuguese archipelago located in the north Atlantic Ocean, between North America and Europe, in the Azores micro-plate, is an area of severe seismic activity, due to its geotechnical framing and volcanic activity. Earthquakes are inevitable, but their consequences are not. Since the hazard cannot be reduced, we have to reduce exposition and building stock vulnerability, to mitigate seismic risk. The purpose of this paper is to assess the seismic vulnerability and the average estimated damage grade, for moderate to high seismic intensities, of the residential building stock in São Miguel Island, Azores, based on a representative sample of buildings. Since buildings are not all the same, we can expect different consequences/damages on buildings facing the same earthquake. So, to have a detailed characterization of the building stock, regarding the structural characteristics and conservation state, a residential building stock survey was used. Four different classes of vulnerability were defined based on the survey and on historical data related to destruction that occurred during seismic events faced on other Azorean islands, namely the event which affected the islands of Faial and Pico in 1998. The vulnerability index was calculated for each building in the sample based on a series of eight relevant parameters. A weight was assigned to each parameter according to its importance. For each one of the parameters, the four vulnerability classes were considered. Afterwards, the mean damage grade was evaluated for each building. Finally, the average global vulnerability index and the estimated damage grade were calculated, for moderate to high seismic intensities. The results of this study are as expected when compared with a previous study performed in Faial. This methodology can be used on other islands and repeatedly with updated data as a powerful tool for local authorities.

Keywords: São Miguel Island, Azores, building stock, seismic vulnerability, vulnerability index, damage grade.

1 INTRODUCTION

The purpose of this paper is to assess the seismic vulnerability and the average estimated damage grade, for moderate to high seismic intensities, of the residential building stock in São Miguel Island, Azores, based on a representative sample of buildings, following three stages.

Since buildings are not all the same, we can expect different consequences/damages on buildings facing the same earthquake. So, first, to have a detailed characterization of the building stock, regarding the building typology, materials, construction technologies and conservation state, a residential building stock survey was used.

Secondly, since the construction scheme found in São Miguel can be translated directly to the other islands, four different classes of vulnerability were defined based on the survey and on historical data related to destruction occurred during seismic events faced on the Azorean islands, namely the major event which affected the islands of Faial and Pico in 1998.

Eight relevant parameters were selected, and a vulnerability index was calculated from this series of parameters, each parameter being assigned a weight according to its importance. For each one of the parameters, the four vulnerability classes were considered.

Subsequently, the vulnerability index and the mean damage grade were evaluated for each building in the sample.

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Finally, the seismic vulnerability evaluation of the building stock of São Miguel Island through the average of global vulnerability index and the average estimated damage grade is carried out, for moderate to high seismic intensities.

2 RESIDENTIAL BUILDING STOCK CHARACTERIZATION

The Residential Building Stock Survey (RBSS) was developed by the University of the Azores, in the framework of the Green Islands Project, a project which associated the Massachusetts Institute of Technology and several universities in Portugal [1]. With RBSS it was possible to characterize in a detailed manner the building stock of the Azores regarding the building envelope and surroundings. This survey was applied to a representative sample of 500 households in São Miguel, distributed by municipalities according to population concentration.

The methodology involved preliminary data collection followed by field work, consisting of building external and internal visual surveys upon arrival at the location of the building, and inhabitant interviews.

The external visual survey included the external pathologies of the building façade and, as much as possible, building dimensions and physical (envelope) characteristics. The objective of the internal visual survey was to gather information about the characteristics of the interior of the household unit (floor covering and ceiling covering, ceiling height, amongst others) and its interior pathologies (type and location). The data that could not be obtained by visual survey was retrieved from the interviewed residents.

From the survey results it is possible to define the most common residential household unit typology in São Miguel Island: single family buildings are the dominant type of housing. These residential buildings are mostly connected to other buildings on one side or two sides (row house) and there are also detached houses. Apartment buildings exist but in smaller numbers.

The most common number of floors in residential buildings is three (including ground floor), 57.6%, followed by two floors, 29.0%, and 11.2% of the buildings have four floors.

Of the 500 inquiries that were made, 33.2% did not know the approximate year of construction of the building. Of the remaining, the majority mentioned that the building was originally constructed before 1940. A high concentration of frequencies occurs between 1980 and 1999 with a continued concentration from 2000 to 2005 (Table 1). This is consistent with a construction boom that occurred after the 1980s and lasted until 2007.

Table 1: Percentage of buildings per year range of construction of the building [1].

Before 1940	**1940–1949**	**1950–1959**	**1960–1979**	**1980–1989**	**1990–1999**	**2000–2005**	**2006–2008**	**2009–2010**
14.6	2.0	5.2	11.8	11.8	10.2	8.6	2.2	0.4

The residential building stock in São Miguel Island, like in the other Azorean islands, is still mostly constituted of a traditional construction system, basically stone masonry load-bearing walls and timber floor slabs and roof trusses. In some cases, this traditional construction has been subject to modifications, namely the replacement of the timber floor structure (planks and beams) with a reinforced concrete slab, again being supported by load-bearing stone masonry walls. This modification can affect only the service areas (kitchens and bathrooms) or a more extended area.

The most common types of external walls are stone walls, with or without masonry mortar (45.8%), and aggregate concrete masonry units' walls (35.4%). There are only a few cases of double aggregate concrete masonry unit walls (0.8%).

As to the external rendering of the external walls, the most used material is cement mortar (63.2%). Lime mortar is also referred in the case of external stone walls. Ceramic wall tiles, wood or natural stone are not very common.

In most cases the walls are 25 cm thick or 35 cm thick. For about four decades, 25 cm walls have dominated. Before 1950, walls are typically thick. After a progressive transition period, thinner walls (35 cm and 25 cm) become more common. However, it is expected that 35 cm thick walls (including rendering) will become dominant in the future, as opposed to thinner walls, due to thermal legislation. It is worth noting that in 22.4% of the cases the walls are 55 cm thick or more, most of them pertaining to buildings built before 1960, probably stone walls.

According to the RBSS results, the most common resistant structure of the buildings is reinforced concrete (54.6%), followed by stone masonry resistant structure (33.0%). Other types (steel, wood) are very uncommon.

Most dwellings are covered with a roof (94.8%), namely a gable roof (73.0%). One-part roof refers to 4.2% of the cases and the remaining (17.6%) refers to more than two-part roofs. Flat (2.4%) or leaning slabs (0.4%) are only used in a small part of the sample.

Most roofs are supported by a discontinuous support structure of wood (39.2%) or by a slab (30.2%). However, in a noticeable number of cases the type of support of the roof could not be determined (30.6%).

In the majority of the cases, the type of floor structure is a slab, usually solid (44.4%) or slight (18.4%). It is also common to find wood floor structures (10.2%). Mixed cases are also represented (5.6%) but not so much metallic structure, which are found only in 0.2% of the cases.

In the study sample, many buildings are placed between two buildings of equal size (43.8%) or between two unequal-sized buildings (23.6%). A smaller portion are isolated buildings (10.2%) and an even smaller number of buildings are placed between two larger buildings (4.8%). Cases of buildings connected to a smaller (4.8%) or larger (5.0%) building are not very significant.

To complete the characterization of the existing residential building stock, the degradation state was evaluated using an empirical method based on field work, through which the existing (detectable) defects were gathered. The methodology was applied to each of the surveyed household units, resulting in an external degradation level (EDL) for each of them [2].

The index EDL has six possible discrete values: 0, no visually detectable degradation; 1, good; 2, light; 3, medium; 4, broad; and 5, extensive degradation.

The first task was to identify the main external pathologies that can affect the residential buildings (only the façades) and the affected location on the building façade. The approach was based on a ranking of importance concerning the affected area (extension) and depth of the problem. The results are shown in Fig. 1.

From these results, 40% of the surveyed residential building stock shows no visually detectable degradation. However, 25% of the surveyed residential buildings need medium to large repair works (EDL = 2, 3, 4 or 5).

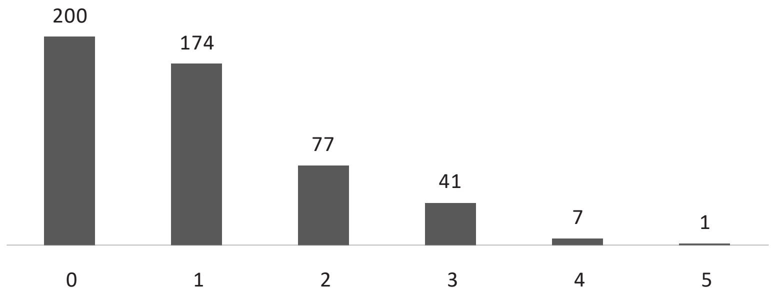

Figure 1: EDL results [2].

3 VULNERABILITY ASSESMENT METHODOLOGY

The assessment of the building stock vulnerability proposed is based in a vulnerability index calculated from a series of parameters, each parameter being assigned a weight according to its importance, as described in Table 2 [3].

Table 2: Parameters description and their assigned weight.

Parameter	Description	Weight
P1	Type of resisting system	1.50
P2	Quality of the resisting system	2.50
P3	Maximum distance between floors	0.75
P4	Number of floors	1.50
P5	Household position	1.50
P6	Horizontal diaphragms	1.00
P7	Roofing system	1.00
P8	Conservation state	1.00

The parameters were defined from the survey variables and their combinations. For each one of the eight parameters, four vulnerability classes are considered, based on the RBSS results and on recent historical data related to destruction occurred during seismic events faced on other Azorean islands, namely the major event which affected the islands of Faial and Pico in 1998. The relationship between the survey variables and the parameters is explained below (Tables 3–10).

The type of resisting system was obtained from the knowledge of the main resisting structure of the building and the type of external walls.

The quality of resisting system was obtained from the knowledge of the main resisting structure of the building, year of construction and last rehabilitation/strengthening.

Table 3: P1 – Type of resisting system.

Type of resisting system	Vulnerability class
Reinforced concrete/steel	A
Timber	B
Stone masonry and mortar	C
Stone masonry; unknown	D

Table 4: P2 – Quality of the resisting system.

Type of resisting system	Year of construction of the buildings/ Nature of last rehabilitation or strengthening	Vulnerability class
Reinforced concrete/ metallic	Before 1959	C
	From 1960 to 1979	B
	From 1980	A
Stone masonry with or without mortar; Unknown	Before 1959	D
	From 1960 to 1979	D
	From 1980	D
Stone masonry with or without mortar; Unknown	Reinforcement of structure with braces Reinforcement of structure with walls' reinforcement	A

Table 5: P3 – Maximum slenderness of resisting walls.

Slenderness	Vulnerability class
$\frac{h}{s} \leq 9$	A
$9 < \frac{h}{s} \leq 15$	B
$15 < \frac{h}{s} \leq 20$	C
$\frac{h}{s} > 20$	D

Table 6: P4 – Number of building floors including ground floor.

Number of building floors	Vulnerability class
1 floor	A
2 or 3 floors	B
4 or 5 floors	C
6 or more floors	D

The maximum slenderness of resisting walls was obtained from the knowledge of the average ceiling height (h) and external walls thickness (s).

In Tables 6, 7 and 8, the parameters were obtained directly from the survey. The roofing system was obtained from the knowledge of the type of coverage of the housing unit, type of support structure of inclined roof coverage and predominant type of resistant structure of the building.

The conservation state was obtained from the knowledge of the complementary EDL.

Finally, the vulnerability index was determined (Table 11).

Table 7: P5 – Household position.

Typology	**Household position**	**Vulnerability class**
Single-family row house	Between two buildings of equal size	A
	Between two larger buildings	B
	Between two smaller buildings	D
	Between two unequal-sized buildings	C
	1 smaller building	C
	1 larger building	B
Single-family isolated dwelling house Single-family connected house		A

Table 8: P6 – Horizontal diaphragms.

Horizontal diaphragms	**Vulnerability class**
Solid slab Slight slab Flat slab Metallic Mixed Slab	A
Wood floor structure Unknown	C

Table 9: P7 – Roofing system.

Roofing system	**Vulnerability class**
Slab + Flat paving stone	A
Slab + Leaning paving stone	B
Slab + One part roof	B
Flexible roofing system + One part roof	B
Slab + Roof with more than two parts	C
A, B, C + Predominant type of resistant structure (stone masonry, metallic)	D
Flexible roofing system + Roof with more than two parts	C

Table 10: P8 – Conservation state.

Conservation state	**Vulnerability class**
0 or 1	A
2	B
3	C
4 or 5	D

Table 11: Vulnerability index.

Parameters	**Class C_{vi}**				**Weight**	**Vulnerability index**
	A	**B**	**C**	**D**	p_i	$I_v^* = \sum_{i=1}^{8} C_{vi} \times p_i$
1. Structural building system						$0 < I_v^* \leq 537.5$ Normalized index $0 \leq I_v \leq 100$
P1 Type of resisting system	0	5	20	50	1.50	
P2 Quality of the resisting system	0	5	20	50	2.50	
P3 Maximum slenderness of resisting walls	0	5	20	50	0.75	
P4 Number of floors	0	5	20	50	1.50	
2. Interaction						
P5 Household position	0	5	20	50	1.50	
3. Floor slabs and roofs						
P6 Horizontal diaphragms	0	5	20	50	1.00	
P7 Roofing system	0	5	20	50	1.00	
4. Conservation status and other elements						
P8 Conservation state	0	5	20	50	1.00	

A vulnerability level is also proposed, by aggregating values into levels or classes, as shown in Table 12.

Table 12: Vulnerability levels.

Vulnerability index	I_v
Very low	0–20
Low	20–40
High	40–60
Very high	> 60

The mean damage grade (MDG, μ_D) of a building subjected to a certain seismic intensity, *I*, according to the macroseismic scale, can be calculated as below [4]:

$$\mu_D = 2.5(1 + \tanh(I + 6.25V_i - 13.1)/2.3), \tag{1}$$

with V_i given by [3]:

$$V_i = 0.592 + 0.0057 \times I_v, \tag{2}$$

and the vulnerability index I_v taken from Table 11.

4 RESULTS AND DISCUSSION

With the methodology adopted for the seismic vulnerability evaluation, a normalized vulnerability index is obtained for each building, and it is possible to estimate the MDG.

It should be pointed out that in this study ruins and buildings not inhabited were not considered.

Fig. 2 shows the results of the vulnerability index assessment method applied to the 500 buildings sample. As can be seen, around 54% of the building stock has a vulnerability index under 30. Still, about 8% have a vulnerability index over 55.

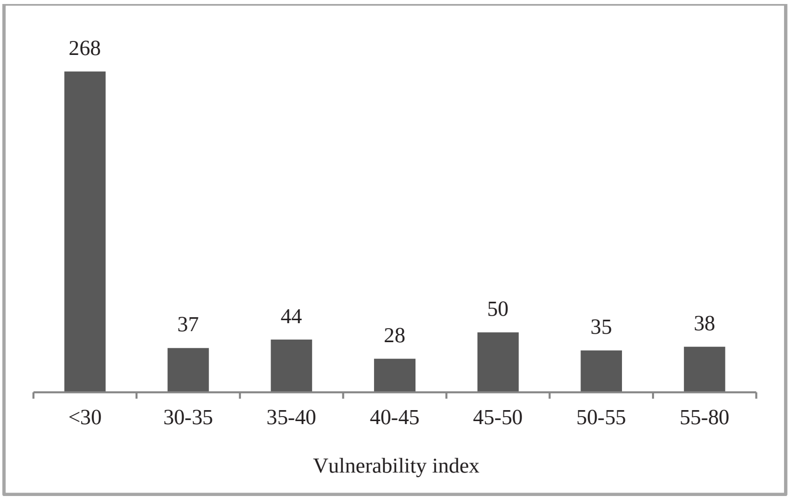

Figure 2: Vulnerability index results distribution per number of buildings.

The results also show that the mean value of the vulnerability index for the studied buildings is 28. This is not unexpected, since more than 50% of the building stock in the sample is reinforced concrete.

The results of this study are as expected when compared with a previous study performed in Faial [3], since the construction scheme found in São Miguel can be translated directly to the other islands.

According to the study performed in Faial, the vulnerability index obtained was 41.62. These two cases when compared indicate that a lower seismic risk exists in São Miguel Island, when considering a hypothetical scenario of equal seismic hazard and exposure.

As can be seen in Fig. 3, most buildings pertain to very low or low vulnerability levels and only a few to very high level.

Concerning the MDG, a mean value of $\mu_D = 1$ and $\mu_D = 2$ for moderate to high intensities (I = VII and I = VIII), respectively, was obtained.

Since 30% of buildings pertain to high to very high vulnerability levels, for seismic intensity I = X we can expect a MDG $\mu_D = 4$.

Since this is not a complex methodology, homeowners can apply it as a first step to evaluate buildings vulnerability and identify retrofit needs. Applying this methodology can also aid as a guidance to potential home buyers providing information on their prospective home vulnerability.

It could be used on any Azorean island to map risk areas of high and very high vulnerability index buildings, to help local emergency teams identify specific measures and actions needed in case of an earthquake.

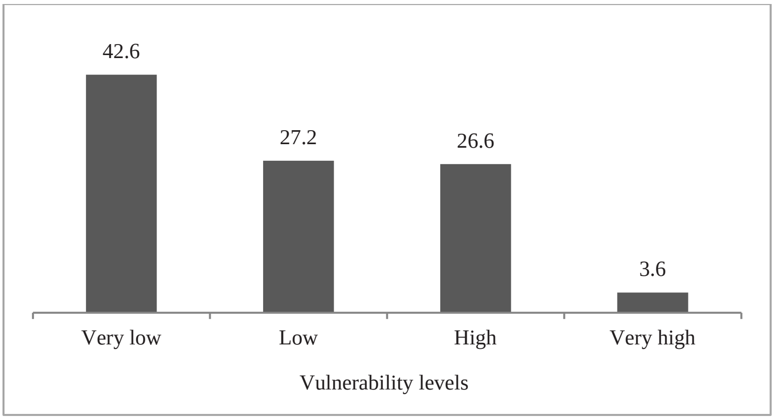

Figure 3: Vulnerability levels results distribution per percentage of buildings.

Local and regional authorities can also use this methodology to outline incentives and subsidies to achieve a resilient building stock.

With a growth in tourism due to government policies there has been an increase in building rehabilitation mostly in urban areas, so it would be interesting for future work to apply this innovative methodology now presented to an updated building stock.

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