Seismic vulnerability and heritage losses of rammed earth minor heritage in Mula (Murcia)

Luisa Basset-Salom; Arianna Guardiola-Víllora
Departamento de Mecánica de Medios Continuos y Teoría de Estructuras. Universitat Politècnica de València. cno de Vera s/n, 46022 Valencia, Spain

Abstract

This study is aligned with United Nations, Sustainable Development Goal 11, concerned about making cities and human settlements inclusive, safe, resilient and sustainable, in particular, in line with resilience to disasters, and protecting the world's cultural heritage targets.
Focused on a small sample of rammed earth residential dwellings in the city of Mula, one of the areas of highest seismic hazard in Spain, the seismic vulnerability has been assessed adapting the Vulnerability Index Method (Risk-UE) to tackle the specificities of earthen residential buildings.
The majority of this humble earthen heritage, despite being an essential part of the Spanish Culture, suffers from the effects of abandonment and insufficient maintenance. As a consequence, these genuine buildings will be seriously damaged in the event of an earthquake of intensities from VII to VIII, with heritage losses representing 17% to 43% of the built area.
These research outcomes can be used to define repair and strengthening priorities among the buildings in the sample when financial resources are limited. The proposed indices and coefficients can be applied to similar earthen structures, widely built in the Iberian Peninsula and the Mediterranean region.

Keywords: rammed-earth, seismic vulnerability, vernacular heritage, Mula, Risk-UE, Vulnerability Index Method

1. introduction

It is well-known that Spain, as a legacy of the Arab domination, has an extensive earthen monumental and vernacular architecture (Jaquin et al. 2007, Mileto et al. 2011, Correia et al. 2011, Mileto et al. 2014). However, nowadays, the humble earthen heritage, despite being an essential part of the Spanish Culture, suffers the effects of abandonment, disuse and lack of maintenance due to changes in the way of life.
Being the rammed earth residential buildings a valuable heritage at risk, it is a must to rescue the ones which have survived the effects of natural catastrophes, anthropic hazards and the passage of time.

This research is focused on a small sample of rammed earth residential dwellings in the city of Mula that are at risk, since they were built in one of the areas of highest seismic hazard in Spain. Furthermore, most of them show a state of poor maintenance and abandonment due, basically, to the lack of social recognition.

The city of Mula is located in the centre of the Region of Murcia, in the southeast of Spain (see figure 1). Archaeological sites near Mula show evidence of human settlements during Prehistoric and Roman times. The Arabs settled in the same place where the city is today.

During the Almohade period (1181-1228), Mula experienced great urban and cultural wealth (Zapata, 2016). In 1244, the Infant Alfonso conquered the city and the Muslim population was exiled. Finally, after the fall of the Kingdom of Granada (1492), the city of Mula increased significantly its population, expanding the city beyond the medieval walls (see figure 2a).

Mula was declared Asset of Cultural interest (ACI) in 1982 (Ministerio de Cultura, 1982). The declaration stated: "*The city of Mula is located on the skirts of a small hill. It constitutes one of the main historic-artistic areas of the region of Murcia, not only because of the importance of its buildings, but also because of the urban layout of the town, being considered an important architectural and artistic ensemble, maintaining a historic atmosphere, a period style and artistic uniformity that must be preserved*".

The historic centre of Mula (in red in figure 2a) is formed by the “Medieval Quarters”, also known as “Upper Quarters” due to their position on the slope of the castle-crowed hill, and the “Renaissance Quarters” (see figure 2b). The Renaissance Quarters are the result of the spread of the city beyond the medieval walls in the XVI century. They correspond to the streets where the houses of the distinguished families of Mula, adorned with their family coats of arms, were built (González 1990; González and González 2005).

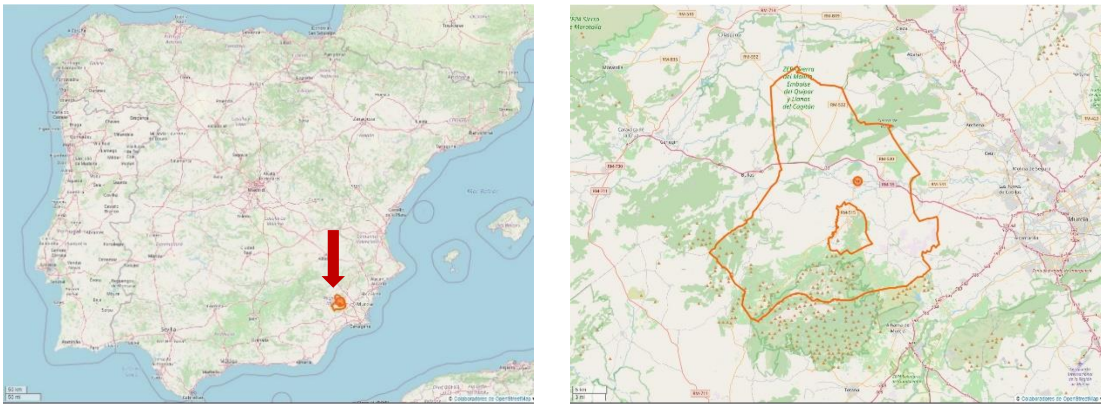


Figure 1 Location of the city of Mula in Spain and in the Region of Murcia. Source: OpenStreetMap®

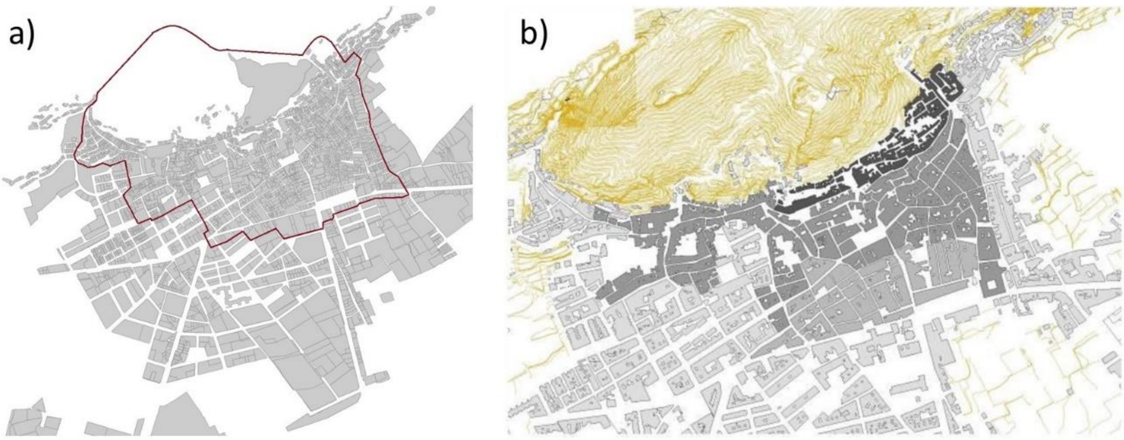


Figure 2. a) Historic Centre of Mula. Source: Authors 2023; b) Areas in the historic centre of Mula: Medieval area (black), XVI c. (dark grey) and XVIII c. (light grey). Source: Ródenas, 1991; López Martínez et al., 2020.

In 1999 a Special Protection Plan was approved *(“Plan Especial de Protección y Revitalización del Conjunto Histórico de Mula”)*. The document included a catalogue with the listed buildings considering three listing grades:

- Grade 1. Integral protection. Only works of consolidation, restoration and conservation of all or part of the building that do not affect its structural configuration, image or use are permitted.
- Grade 2. Structural protection. In addition to works of consolidation, restoration and conservation, rehabilitation works are allowed, provided that the elements specified in the individualised files (stairs, towers, bays, etc.) are maintained.
- Grade 3. Partial protection. Much more free interventions are allowed in the buildings. Only the specific elements specified in the files have to be preserved. Generally, it affects only the external image of the building, trying to maintain the environmental interest of the area.

Additionally, some buildings pertaining to the influence area of the Historic Centre of Mula are included in the Catalogue, having to follow specific rules related to the environmental interest of the area. The listed buildings in the Historic Centre of Mula and their corresponding grades of protection are displayed in figure 3.

According to the city council, despite having been declared ACI in 1982, the Medieval Quarters of Mula are characterised by a general state of degradation, abandonment and ruin. The population density, the origin of the population and the household income are represented in figure 4. These maps show that these quarters are quite uninhabited, with about 35% of the low-income population being immigrants.

In order to reverse *“this process of urban, economic and social dereliction”*, the City of Mula, led the European Project Kairós, Heritage as Urban Regeneration with the participation of seven other European cities. Kairós is an Action Planning Network of the EU URBACT III Programme, co-funded by the European Regional Development Fund and by the Member and Partner States (Kairós, 2019).

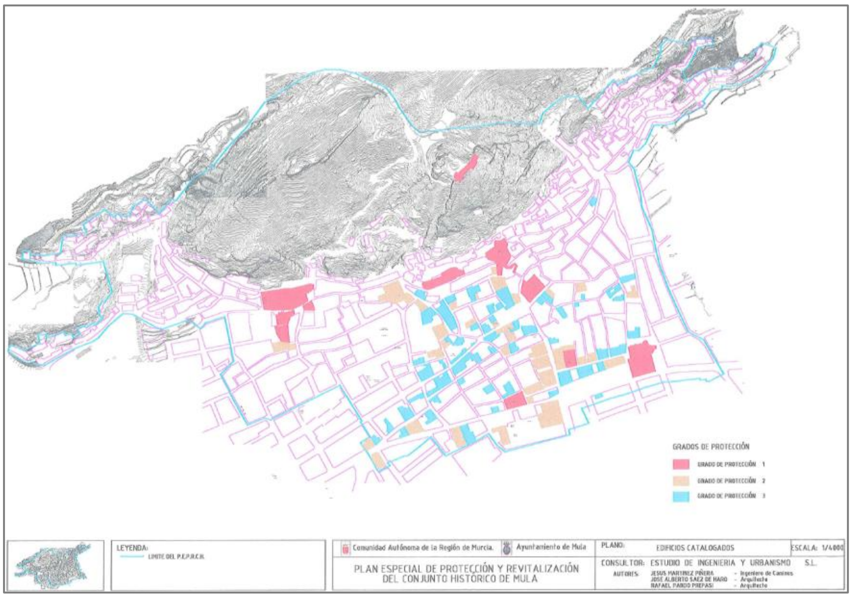


Figure 3. Listed buildings and grades of protection in the Historic Centre of Mula. Source: Ayuntamiento de Mula, 1998.

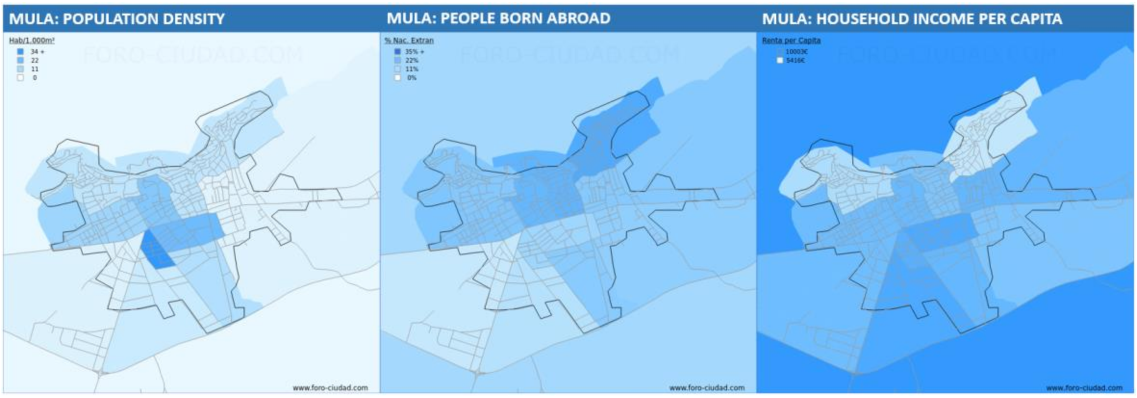


Figure 4. Demography and household incomes in the city of Mula. Source: www.forociudad.com

To promote the urban regeneration of the Upper Quarters, a roadmap was draft under the umbrella of the Kairós project to guide the elaboration of the Integrated Action Plan (IAP), proposing strategies and actions focused on their social and economic revitalization. According to this roadmap: "*an effort will be made to limit the intervention to priority areas. The regeneration plan should not be understood as a maximalist approach but should rather consist in a selection of a single package of actions with a driving effect on reverting the degradation process. A conscious strategy should be designed regarding its intended implication in the funding of the Plan to the Regional and Central Governments"* (Ayuntamiento de Mula 2022).

Taking into account the above-mentioned statement, the authors believe that, being the rammed earth residential buildings part of the genuine heritage of the city of Mula, it is essential to preserve this architecture. Therefore, although usually considered minor heritage, strategies for its enhancement should be included in the IAP. Additionally, being Murcia one of the areas of highest seismic hazard in Spain (see map in figure 5), and assuming that the earthen residential buildings in Mula will be classified as an EMS-98 vulnerability class A or B (Grünthal, 1998), it is worth pointing out that the results of the seismic risk assessment presented in this paper could be a criterion for optimally allocating resources by selecting the most urgent area or dwellings to intervene in.

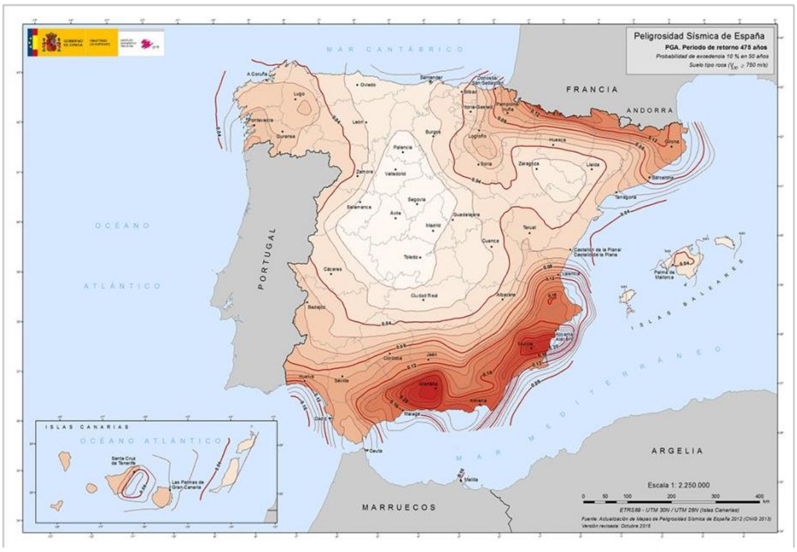


Figure 5. Map of the Seismic hazard in Spain (return period 475 years), Source: IGN 2015

In this case-study, the level 1 Risk-UE Method (L1-Risk-UE VIM) (Milutinovic and Trendafiloski 2003) was chosen to obtain the seismic vulnerability of the earthen residential buildings in Mula, initially developed to assess the seismic performance of Barcelona, Bucharest, Nice, Bitola, Sophia, Catania and Thessaloniki, European cities with various levels of seismic risk (Mouroux et al. 2004a). This method, has also been widely and successfully employed in many European urban areas (Feriche et al. 2009; Vicente et al. 2011; Irizarry et al. 2012, Riedel et al. 2014, Riedel et al. 2015, Maio et al. 2016, Ferreira et al. 2016, Martínez-Cuevas and Gaspar-Escribano 2016, Lestuzzi et al. 2016; Ródenas et al 2018, Guardiola-Víllora and Basset-Salom 2020) and also beyond the European borders (Boukri and Bensaibi 2008, Odmidvar et al. 2012, Cherif et al. 2017, Liu et al. 2019, Liu et al. 2023).

After quantifying the seismic quality of each building with a vulnerability index, the probability of suffering a certain grade of damage has been calculated for each of the considered seismic scenarios, defining the damage probability matrices. Then the seismic risk of the earthen residential buildings has been estimated, specifying the damaged built area that would need to be rebuilt or repaired if an earthquake strikes the city of Mula. Finally, the results have been presented by means of charts and maps via a geographic information system.

2. Mula's rammed earth minor heritage

This research is focused on a sample of 185 humble residential dwellings, located in the "Medieval" and "Renaissance" Quarters of Mula, that showed evidence of being built with rammed earth.

The majority of the analysed constructions were identified during a fieldwork carried out by the authors in March 2021[1]. They are residential buildings in which the abandon and decay of the renderings brought the real nature of the structural walls to light. In addition, a small percentage of the sample is formed by repaired houses identified as earthen architecture in the images retrieved from the cadastral database (taken in 2014), showing the structural materials before the rehabilitation.

Given that many of them would have gone unnoticed had the bad state of maintenance not shown the rammed earth load-bearing walls, the authors are fairly certain that there are many more earthen residential buildings in the city which cannot be confirmed, due to the impossibility of taking samples for testing.

A previous analysis of the earthen construction techniques in the city of Mula (Lopez Martinez et alt, 2020) identified the existence of three different typologies:

- simple rammed earth (figure 6a).
- supplemented rammed earth: mostly lime-crusted rammed earth walls, but also rammed earth walls with brick courses (figure 6b and 6c).
- mixed rammed earth: earth walls combining brick quoins and brick courses (figure 6d).

Despite this classification and considering the conditions in which the identification of the buildings took place, only two different earthen typologies have been considered in this study: simple rammed-earth, SRE, (with different types of aggregate) and rammed earth reinforced with ceramic brick courses, RRE. It must be pointed out that the presence

[1] The fieldwork was carried out during the 2021 partial lockdown, where the use of face masks and maintaining a security distance was compulsory.

of quoins (brick quoins or stone quoins) has been taken into account by means of a behaviour modifier instead of a different earth wall typology. The map in figure 7 shows the percentages of each typology and the distribution in the studied area.

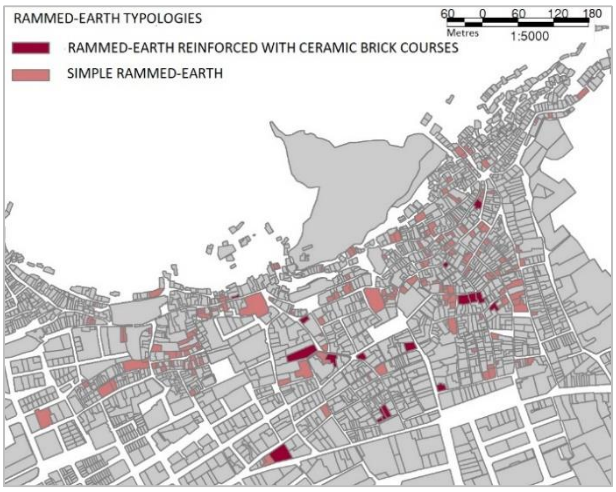
Buildings with different states of preservation were identified within the sample, ranking from very bad to very good, as described in figure 8 and mapped in figure 9a, with 22% being in very bad or bad state of maintenance.

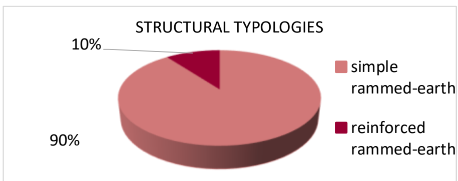
Moreover, as it is directly linked with the regular presence of inhabitants in the buildings, notes about possible inhabitants in the dwellings under study were taken during the onsite survey. The inhabited status according to the researchers' perception is displayed in figure 9b. Buildings with air-conditioning units or antennae, linen laid out, pets or well-kept plants were considered to be inhabited (see examples in figure 10).

Finally, the age of the buildings in the sample was retrieved from the cadastral database. As shown in figure 11, the majority of them were built before 1920 (72%), from which 7.6% were built in the XIX century.

a) Simple rammed earth | b)Lime-crusted rammed earth wall | c) Rammed earth, with brick courses | d) Mixed rammed earth

Figure 6. Rammed earth typologies in Mula Historic Centre. Source: The authors 2021





The Building Typology Matrix (BTM) includes 19 rammed-earth dwellings reinforced with ceramic brick courses and 166 simple rammed-earth dwellings

Figure 7. Rammed earth typologies in the sample.

Very bad
Roof and/or floors seriously damaged.

Very bad
Lack of connection between orthogonal walls

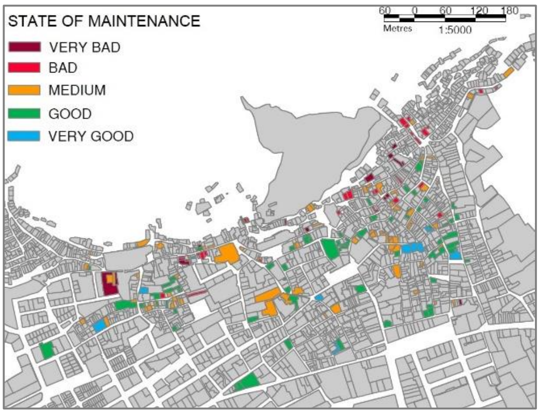
Bad
Bearing walls seriously damaged

Medium
Cracks in bearing walls, extended moisture in the lower part.

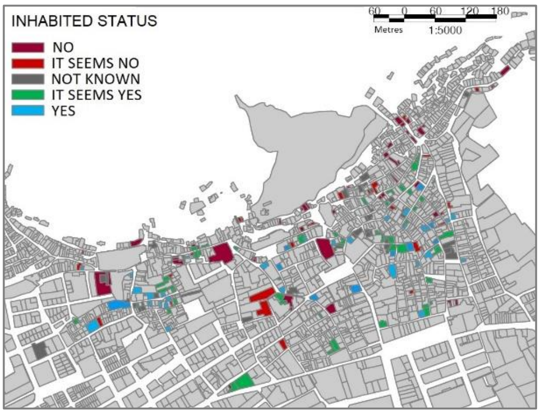
Good
Small cracks in the renderings. Small stains of moisture

Very good
No presence of cracks nor moisture

Figure 8. Examples of buildings’state of maintenance. Source: The authors 2021



a)



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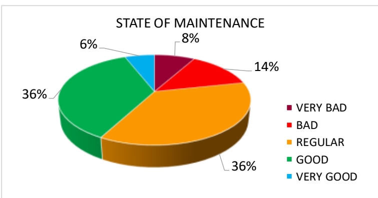


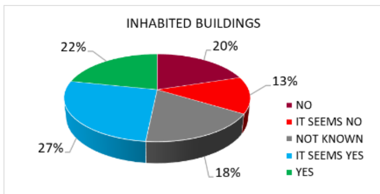


Figure 9. a) State of maintenance b) Inhabited status.

Inhabited | Possibly inhabited | Not known | Possibly uninhabited | Uninhabited

Figure 10. Examples of inhabited status of the buildings. Source: The authors 2021

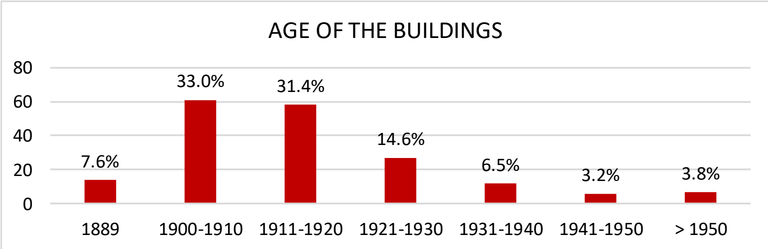


Figure 11. Age of the buildings.

3. Seismic vulnerability assessment

The L1-Risk-UE VIM has been used to estimate the seismic vulnerability of the rammed-earth dwellings analysed in the study (Milutinovic and Trendafiloski 2003). In this method, each structural typology is characterised by an initial coefficient, V_I*, representing the most likely value of the vulnerability index, a feasible range $[V_I^-; V_I^+]$ and the maximum and minimum possible values $[V_{Imin}, V_{Imax}]$ (Giovinazzi and Lagomarsino 2004).

In WP04 of the Risk-UE project, a Building Typology Matrix (BTM) consisting of 65 different structural typologies is proposed. All the masonry typologies included in this BTM are shown in table 1 and their corresponding vulnerability indices in table 2 (Milutinovic and Trendafiloski 2003).

The percentage of people that live in earthen structures worldwide is around 17 % (Correia 2016). In the Iberian Peninsula, the great amount of existing rammed earth structures is probably due to the settlement of the Muslims since the 8th century, and to the fact that, from the 15th century onwards, Christians continued using rammed earth in vernacular architecture. Considering the number of remaining earthen buildings in the Iberian Peninsula and in the Mediterranean area, seismic vulnerability assessment methodologies should include these typologies taking into account their specificities.
However, in Goded’s opinion (Goded et al. 2012), since rammed earth architecture was not found in the area assessed by Lagomarsino and Giovinazzi (2006), this structural typology is not included in the proposed BTM. Rismur project conclusions (Benito et al. 2006) stated that the Spanish Statistical Office should provide data on structural typology, including adobe and rammed earth typologies, in the census of the building stock of Spain.

Adobe (M2L) is the structural typology closest to rammed earth included in BTM. It should be noted that the number of published research studies on the application of the VIM to different cities that include the adobe typology is quite scarce, since they are exceptionally rare in European urban areas and were considered out of interest for seismic risk assessment at urban scale.

In RISK-UE WP04 the adobe typology (M2L) was reported to be identified in Bitola and Nice. To study the Risk-UE approach to adobe buildings to apply it to rammed earth residential buildings, the final reports of both cities were consulted. However, neither the final reports of the application to the city of Bitola, WP9, (Milutinovich et al, 2004) nor to the city of Nice (Mourox et al 2004b), did include the M2 typology. Therefore, in none of the seven European cities that took part of the RISK-UE European Project the structural typology of adobe load-bearing walls and wooden floors was assessed.

Table 1. RISK-UE BTM for masonry typologies.

RISK-UE Building Typology Matrix (masonry)					
Nº	Label	Description	name	Height Classes (Nº of stories)	Height range (m)
1	M11L	Rubble stone, fieldstone	Low-Rise	1-2	≤ 6
2	M11M		Mid-Rise	3-5	6-15
3	M12L	Simple stone	Low-Rise	1-2	≤ 6
4	M12M		Mid-Rise	3-5	6-15
5	M12H		High-Rise	6+	> 15
6	M13L	Massive stone	Low-Rise	1-2	≤ 6
7	M13M		Mid-Rise	3-5	6-15
8	M13H		High-Rise	6+	> 15
9	M2L	Adobe	Low-Rise	1-2	≤ 6
10	M31L	Wooden slabs URM	Low-Rise	1-2	≤ 6
11	M31M		Mid-Rise	3-5	6-15
12	M31H		High-Rise	6+	> 15
13	M32L	Masonry vaults URM	Low-Rise	1-2	≤ 6
14	M32M		Mid-Rise	3-5	6-15
15	M32H		High-Rise	6+	> 15
16	M33L	Composite slabs URM	Low-Rise	1-2	≤ 6
17	M33M		Mid-Rise	3-5	6-15
18	M33H		High-Rise	6+	> 15
19	M34L	RC slabs URM	Low-Rise	1-2	≤ 6
20	M34M		Mid-Rise	3-5	6-15
21	M34H		High-Rise	6+	> 15
22	M4L	Reinforced or confined masonry	Low-Rise	1-2	≤ 6
23	M4M		Mid-Rise	3-5	6-15
24	M4H		High-Rise	6+	> 15
25	M5L	Overall Strengthened masonry	Low-Rise	1-2	≤ 6
26	M5M		Mid-Rise	3-5	6-15
27	M5H		High-Rise	6+	> 15

Table 2. Vulnerability indices for BTM masonry buildings typologies.

Vulnerability indices for BTM masonry buildings typologies						
Label	Building type	Vulnerability indices: representative values				
		V_{Imin}	V_I^-	V_I^*	V_I^+	V_{Imax}
M11	Rubble stone, fieldstone	0.62	0.81	0.873	0.98	1.02
M12	Simple stone	0.46	0.65	0.74	0.83	1.02
M13	Massive stone	0.30	0.49	0.616	0.793	0.86
M2	Adobe (earth bricks)	0.62	0.678	0.84	0.98	1.02
M31	Unreinforced masonry (old bricks) with wooden slabs	0.46	0.65	0.74	0.83	1.02
M32	Unreinforced masonry (old bricks) with masonry vaults	0.46	0.65	0.776	0.953	1.02
M33	Unreinforced masonry (old bricks) with composite slabs	0.46	0.527	0.704	0.83	1.02
M34	Unreinforced masonry (old bricks) with RC slabs	0.30	0.49	0.616	0.793	0.86
M4	Reinforced or confined masonry	0.14	0.33	0.451	0.633	0.70
M5	Overall Strengthened masonry	0.30	0.49	0.694	0.953	1.02

According to Arto el al. (2020), before their analysis of medieval rammed earth fortification in south-eastern Spain, "*Rammed earth structures were not yet being studied using the vulnerability index method, despite the fact that there are quite common medieval structures in Spain and other areas of the Mediterranean region*".

In fact, Feriche (2012) included different images of rammed earth techniques examples in Granada's BTM and Salgado et al. (2014) evaluated the replacement values for the exposed assets in Lorca after the 11th of May earthquake, concluding that the earthen buildings, represented the 14.1% of the total replacement costs. Regrettably neither Granada's vulnerability assessment (Feriche, 2012) nor any of the post-earthquake studies carried out in Lorca with the L1-Risk-UE VIM (Feriche et al. 2012; Martínez-Cuevas and Gaspar-Escribano 2016; Ródenas et al. 2018) included earthen buildings, confirming Arto et al.'s above mentioned statement.

In 2020, two interesting papers studying the seismic vulnerability of earthen structures were published. On the one hand, Liu et al (2020) assessed the seismic vulnerability in rural Weinan (China) where the building stock included buildings with adobe load bearing walls and wooden-frame roofs. For that typology, the authors considered the initial vulnerability index recommended in Risk-UE for M2L.

On the other hand, Arto et al. (2020) assessed the seismic vulnerability of medieval rammed earth fortifications in south-eastern Spain with the Vulnerability Index Method (VIM), proposing a new value for the initial vulnerability index for lime-crusted and lime-concrete city walls and defensive towers. This paper constitutes the only published reference that applied the VIM to rammed earth structures, and according to the researchers, the proposed values included material modifiers, namely typology, quality, cohesion, porosity and biodeterioration of the rammed earth. These modifiers cannot be determined in a visual survey, but with tests on earth samples.

Different studies on the mechanical behaviour of earthen materials can be found in literature. Some of them concentrate on a specific material (Rodriguez Mariscal et al 2018, Silva et al, 2014; Maniatidis and Walker 2008; Lilley and Robinson 1995), while others are focussed on the comparison of the mechanical properties of adobe, rammed earth and cob (Miccoli et al. 2014), or the seismic performance of different masonry vernacular constructions (Yamín et al 2007, Miccoli et al 2017, Ortega et al. 2018). A conclusion to be taken from these studies is that the performance of the rammed earth is slightly better than the adobe when considering, in addition to the mechanical properties, the load factor that corresponds to the maximum strength of the building (suffering not-negligible structural damage and therefore having lost a substantial amount of the original stiffness, the building maintains some lateral resistance and margin against failure even though it is unusable after the earthquake).

The values for the initial vulnerability index (V_I^*), based on the maximum compression load obtained by different authors compared with the values proposed by the Eurocode 6 for Unreinforced Masonry (URM), are slightly bigger than the recommended by Milutinovic and Trendafiloski (2003) for old bricks unreinforced masonry (0.74) and smaller than the corresponding to adobe (0.84), as shown in table 3.

Based on post-seismic observations after the 2003 Bam earthquake, Omidvar et al. (2012) calculated the values for the vulnerability index for brick masonry and adobe typologies in Iranian buildings from experimental vulnerability curves, concluding that, in Iran, the unreinforced masonry buildings are more vulnerable than the European ones, and, therefore, proposing larger values for the initial vulnerability index V_I^* (table 4).

Taking into account that the Arab domination of the Iberian Peninsula lasted until the XV century, it seems reasonable to assume that the adobe and rammed earth bearing walls have more in common with the structures of Iran than with the ones of northern Europe. Therefore, considering that the choice of the V_I^* value is based on expert judgement, in this study, the initial vulnerability index, and the thresholds adopted for rammed earth reinforced with bricks are equated with the values proposed by Arto et al. (2020).
For simple rammed earth, a slightly higher value of the initial vulnerability index is considered (0.78), adopting for V_{Imax} the value of 1.02 and equating V_{Imin} with the value proposed by Risk UE for adobe (0.62), (see table 4).

The specific characteristics that improve or worsen the seismic performance of the analysed buildings (number of storeys, state of maintenance or preservation, geometry, location within the block, among others) are considered by means of the behaviour modifiers (Vm) that decrease or increase the initial value of the vulnerability index V_I*. Additionally, to take into account the quality of the technical, structural and constructive design according to the seismic codes in force when the buildings were built, it is possible to define a regional vulnerability coefficient VR. However, in this study, as no structural code on earthen architecture has ever been published in Spain, the regional vulnerability factor VR has been taken equal to zero.

Hence, the total value of the vulnerability index V_I is calculated according to equation 1. It must be pointed out that higher values mean more vulnerable structures.

$$V_I = V_I^* + \sum Vm \qquad \text{(eq. 1)}$$

Table 3 Maximum compression load and Vulnerability Index values

Building type	Range of Maximum compression load f_c (MPa)		Vulnerability Index		
			V_{Imin}	V_I^*	V_{Imax}
Adobe (earth bricks)	[0.98-1.33] Rodriguez Mariscal et al (2018)		Milutinovic and Trendafiloski (2003)		
			0.62	0.84	1.02
URM (old bricks)	[1.90 - 4.20] Eurocode 6 (CEN 2006)		Milutinovic and Trendafiloski (2003)		
			0.46	0.74	1.02
Rammed earth	[1.20 -3.88], Lilley and Robinson (1995) Maniatidis and Walker (2008)		Arto et al.		
			0.58	**0.76**	**1.02**

Table 4. Values of V_{Imax}, V_I*, V_{Imin} proposed by several authors and values adopted in this study

	Vi* and Risk UE			V_{i*} proposed by Omidvar et al (2012) calculated based	Vi proposed by Arto et al (2020)			Vi adopted by the authors in this study		
	V_{Imin}	V_I*	V_{Imax}	V_I*	V_{Imin}	V_I*	V_{Imax}	V_{Imin}	V_I*	V_{Imax}
Adobe (earth bricks)	0.62	0.84	1.02	0.9	0.62	0.84	1.02			
URM (old bricks)	0.46	0.74	1.02	0.8	0.46	0.74	1.02			
Rammed earth	-	-	-	-	0.58	0.76	1.02			
Rammed earth reinforced with bricks	-	-	-	-	-	-	-	**0.58**	**0.76**	**1.02**
Simple rammed earth	-	-	-	-	-	-	-	**0.62**	**0.78**	**1.02**

The values of the behaviour modifiers proposed initially by WP04 for masonry buildings, and later by other authors (Giovinazzi 2005; Lantada 2007; Feriche et al. 2012, Arto et al. 2020) who adjusted them based on the seismic behaviour and the grade of damage in recent earthquakes, are displayed in table 5. Additional modifiers proposed by other authors are not included in the above-mentioned table because they are not applicable. (i.e. the alignment modifier proposed by Martínez-Cuevas et al. 2017).

The behaviour modifiers considered in this study to tackle the specificities of rammed earth residential buildings in Mula historic centre and the adopted values are given in figure 12. These modifiers refer to the state of maintenance, the number of floors, the geometric horizontal and vertical irregularities (plan and elevation), the presence of aseismic devices, the aggregate building position and elevation and the soil morphology. Other modifiers are not applicable to the buildings under study.

In unreinforced masonry buildings (Basset-Salom and Guardiola-Víllora 2013), the good maintenance or state of preservation has been demonstrated to be a decisive factor in decreasing the vulnerability of structures in historic centres and, consequently, in improving their seismic performance. In this particular case, five different states have been reckoned, described previously in detail in figure 8.

Table 5: Behaviour modifiers for Masonry buildings proposed by several authors.

Behaviour modifiers ↓	Authors →	Wp 04 (2003)	Giovinazzi (2005)	Lantada (2007)	Feriche (2012)	Arto et al. (2020)
State of preservation	Good maintenance	- 0.04	- 0.04	- 0.04	- 0.04 (rehab.) Good 0.00 (> 1925)	Good: 0.00
	Bad maintenance	+0.04	+0.04	+0.04	+ 0.04 (≤ 1925)	Medium: +0.02
	Ruin				+ 0.06	Poor: +0.06
Number of floors (Masonry)	Low (1 or 2)	- 0.02	- 0.08	- 0.02 (≤ 1940) - 0.04 (> 1940)	- 0.02 (≤ 1925) - 0.04 (> 1925)	-0.02
	Medium (3, 4 or 5)	+0.02	0.00	+ 0.02 (≤ 1940) 0.00 (> 1940)	- 0.02 (≤ 1925) 0.00 (> 1925)	0.00
	High (6 or more)	+0.06	+0.08	+0.06 (≤ 1940) +0.04 (> 1940)	+0.06	+0.06
Structural system	Wall Thickness Distance between walls Connection between walls Tie-rods, angle bracket Connection horizontal structures-walls	- 0.04 / +0.04	- 0.04 / +0.04		+0.04 (≤ 1925) 0.00 (> 1925) +0.04 (rehabilitation)	
Soft story	Demolition/Transparency	+0.04				
Plan Irregularity	…	+0.04	Geometry Mass distribution + 0.04	+ 0.04 if Rc* < 0.5 + 0.02 if 0.5 > Rc* > 0.7		
Vertical Irregularity	…	+0.02	Geometry Mass distribution + 0.04	+0.02 if 1 < δ** ≤ 3 +0.04 if δ** > 3	+ 0.02	
Superimposed floors		+0.04	+ 0.04			
Roof	Roof weight + Roof Thrust Roof connections	+0.04	+ 0.04	+0.04	+ 0.04	
Retrofitting interventions		- 0.08 / +0.08	- 0.08 / +0.08	- 0.08 / +0.08		
Aseismic Devices	Barbican, Foil arches, Buttresses		- 0.04			
Aggregate building: position	Middle	- 0.04	- 0.04	- 0.04	- 0.04	
	Corner	+0.04	+0.04	+0.04	+0.04	
	Header	+0.06	+0.06	+0.06	+0.06	
Aggregate building: elevation	Staggered floors	+ 0.02	+ 0.04			
	Buildings of different height	-0.04 / +0.04	-0.04 / +0.04	Both same height 0.00		
				One same height other lower + 0.02		
				Both lower +0.04		
				One same height other higher -0.02		
				Both higher -0.04		
Foundation	Different level foundation	+0.04	+ 0.04			
Soil Morphology	Slope	+0.02			Slope + 0.04	Hill+0.04
	Cliff	+0.04			Cliff + 0.04	Ridge+0.04
Length of the façade				If $L_f \geq 15m$ Mf = 0.04/15 *(Lfaçade) -0.04		

*Rc is the compactness ratio which relates the area of the building and the area of the circle with the same perimeter (Lantada 2007)

** coefficient δ which represents the difference between the number of floors in the analysed building and the number of floors of an equivalent regular building with the same volume and plan area (Lantada 2007)

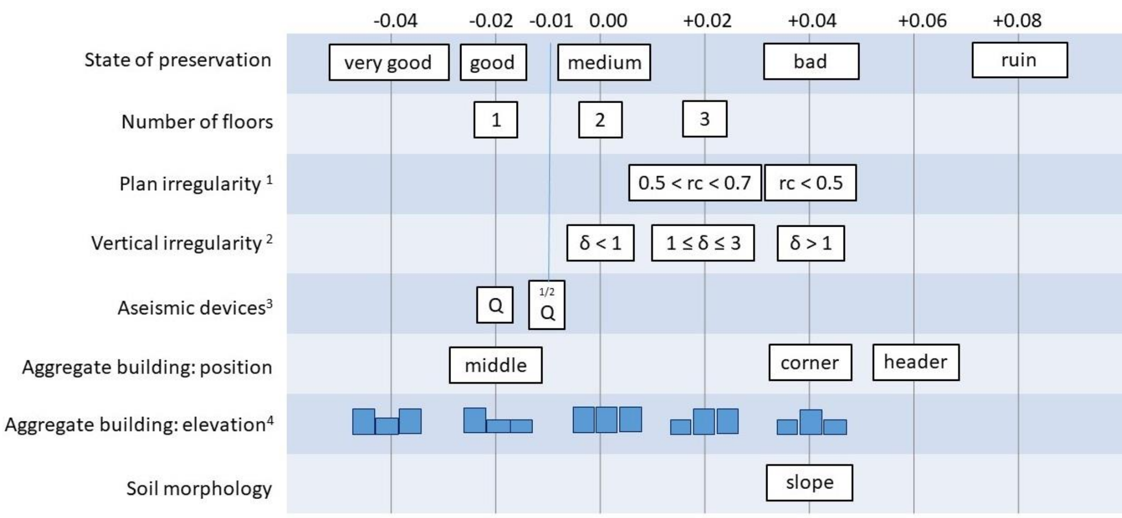
The number of floors of the rammed earth buildings assessed in Mula, varies from 1 to 3. In view of the capacity curves derived by Ortega et al (2018), with one-floor constructions showing a more ductile behaviour, this modifier benefits the one-floor houses and penalises the three-floor ones.

The horizontal and vertical irregularities are considered by means of behaviour modifiers based, respectively, on the compactness ratio rc and the coefficient δ (see table 5), as defined by Lantada (Lantada, 2007),

The presence of quoins in some buildings, either along their whole height or only up to the first floor, improves their seismic performance acting as aseismic devices, hence a behaviour modifier has been assigned for each situation.

The influence of the relative position of the building in the block with respect to the position of the others is a factor of paramount importance, hence it has been taken into account in Mula. However, the aggregate building elevation (relevant when the difference in the number of storeys with the adjacent dwellings is greater than or equal to two, due to the possible damage caused by pounding) is not applicable in this study, since none of the analysed buildings has more than one floor of difference with respect to the adjoining ones.

Finally, a soil morphology modifier has been included in the proposal, as the “Upper Quarters” of Mula’s historic centre are built on the skirts of the mountain.



[1] rc is the compactness ratio, relating the area of the building and the area of the circle with the same perimeter
[2] δ = total height – (total built area / area at groundfloor level)
[3] Q = Quoins are placed along all the height of the building $^1/_2$Q = Quoins exists only in groundfloor
[4] Coefficients applied when the differences between the number of floors is two or more

Figure 12. Behaviour modifiers

All the data retrieved from the cadastral database and other official sources, and from the onsite survey (geometry, structural typology, construction system, maintenance, age, listed grade, etc.) have been implemented in a new created database to obtain the final vulnerability index V_I of each building from the initial vulnerability index (V_I*) and the corresponding behaviour modifiers (Vm). This database is linked to a geographic information system (gvSIG association 2009), which is used to map the results.

The map showing the seismic vulnerability index of every analysed building and the graph with the distribution of the values within the sample are shown in Figure 13.
As expected, the most vulnerable buildings are mostly located at the “Upper Quarters”, where the income per capita and the population density have the lower values (see figure 5), being the least vulnerable buildings in the “Renaissance Quarters”. Furthermore, the vulnerability index distribution reveals the low seismic performance of the buildings.

Most of them (76.7%) have a final vulnerability index bigger or equal to 0.8, and 14.1% bigger than 0.9.

In both structural typologies, simple rammed-earth (SRE), and rammed-earth reinforced with ceramic brick courses (RRE), the minimum values for the seismic vulnerability index are equal ($V_{I,min}$ = 0.74), while the maximum values are different, with SRE buildings more vulnerable ($V_{I,max}$ = 0.96) than RRE ($V_{I,max}$ = 0.90).

Results show that the effect of the presence of quoins (observed only in 6% of the buildings in the sample) is anecdotal, being the influence of other features more relevant in the final value of the vulnerability index.

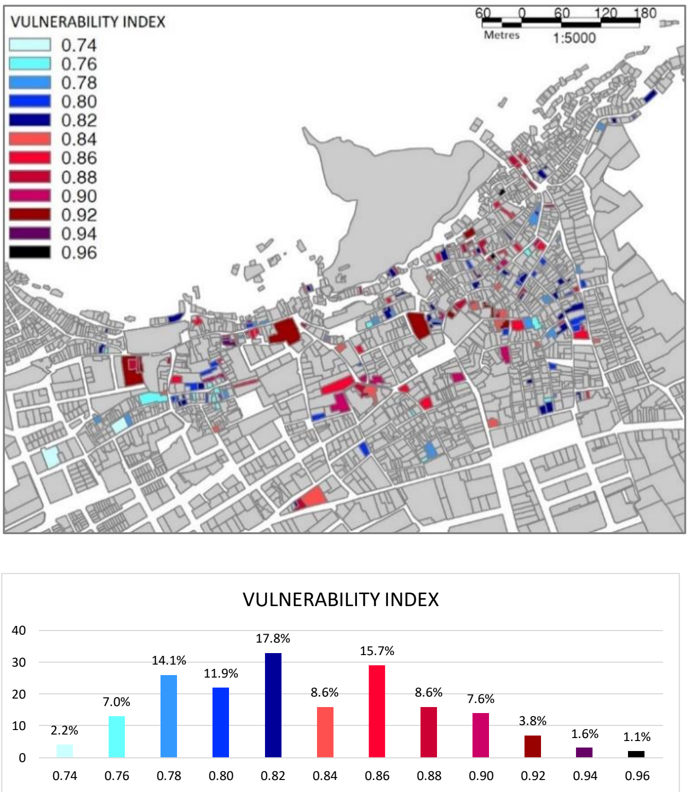
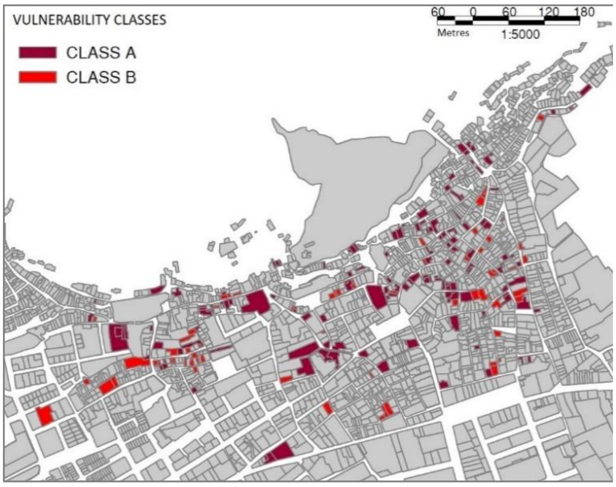


Figure 13. Map of Vulnerability Indices of the residential buildings of the sample and distribution of the values.

Considering the vulnerability membership functions (Milutinovic and Trendafiloski 2003), the assessed dwellings have been assigned to one of the six vulnerability classes (Grünthal 1998): A to F (being A the more vulnerable). This classification (see figure 14) reflects the ability of the buildings to withstand earthquake loads, being 64% class A and 36% class B. At this point, it is worth noting that that the most vulnerable (class A) are the abandoned ones, where the lack of maintenance has led them into decay and ruin.



VULNERABILITY CLASSES

The sample consists of:
66 class A earthen residential buildings and 119 class B earthen residential buildings

Figure 14. Map of Vulnerability classes according to EMS-98.

4. Seismic scenarios

According to the Special Civil Protection Plan for Seismic Risk in the Region of Murcia (SISMIMUR, 2021) in the last century, the earthquakes which stroke the Region of Murcia reached moderate magnitudes, never higher than Mw 5.0. However, in the catalogues of historical seismicity, more than ten earthquakes of intensity (MSK) greater than or equal to VIII were recorded in the last 500 years, causing numerous human and material losses. Due to this fact and the occurrence, in recent years, of several series of earthquakes which caused numerous damages as well as great social alarm, the Region of Murcia is considered a seismically active area.

Among other data, this document specifies the seismic hazard, including the map of theoretical intensities, obtained by correlation with the accelerations estimated in the hazard study with a 475 years-return period (figure 15a). According to this map in which the limits of the municipality of Mula have been drawn (figure 15b), the theoretical expected intensities are VII, VII-VIII and VIII.

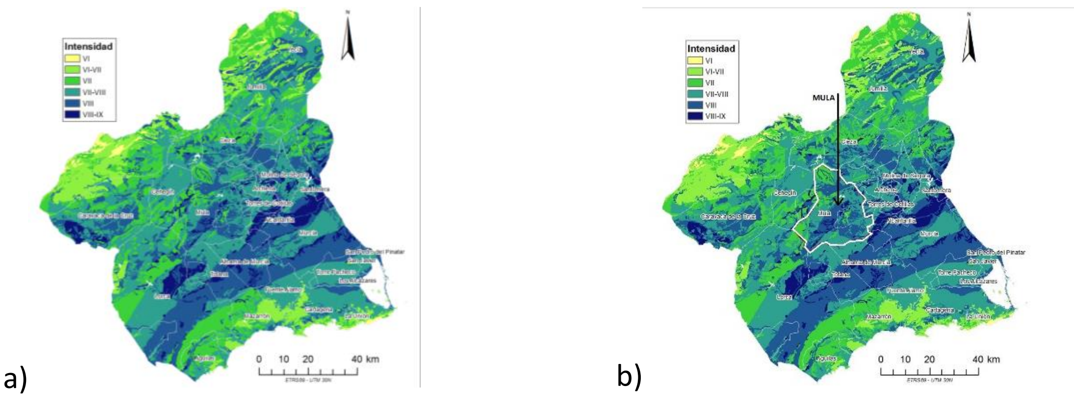


Figure 15. a) Expected intensity considering a 475-return period. b) Expected intensities in Mula. Source SISMIMUR 2021

5. Direct losses

Being this study focused on heritage losses, both, the mean damage grade (μ_D) and the probability of reaching different damage grades have been calculated.

Equation 2 (Giovinazzi 2005) shows the semi empirical vulnerability function employed to calculate μ_D from V_I (final vulnerability index), I (macroseismic intensity) and Q (ductility index, Lagomarsino and Giovinazzi 2006).

$$\mu_D = 2{,}5 \cdot \left[1 + tanh\left(\frac{I + 6{,}25 \cdot V_I - 13{,}1}{Q}\right)\right] \quad \text{(eq. 2)}$$

To define the damage probability distribution, a beta probability density function (equation 3) has been adopted. This function is equivalent to the binomial density function (equation 4) assigning to t and r the following values: t=8 and r = $t \cdot (0.007 \cdot \mu_D^3 - 0.0525 \cdot \mu_D^2 + 0.2875 \cdot \mu_D)$ (Giovinazzi 2005)

Beta function: $$p_\beta(x) = \frac{\Gamma(t)}{\Gamma(r)\,\Gamma(t-r)} \frac{(x-a)^{r-1}\,(b-x)^{t-r-1}}{(b-a)^{t-1}} \qquad a \le x \le b \quad a=0 \;\; b=6 \quad \text{(eq. 3)}$$

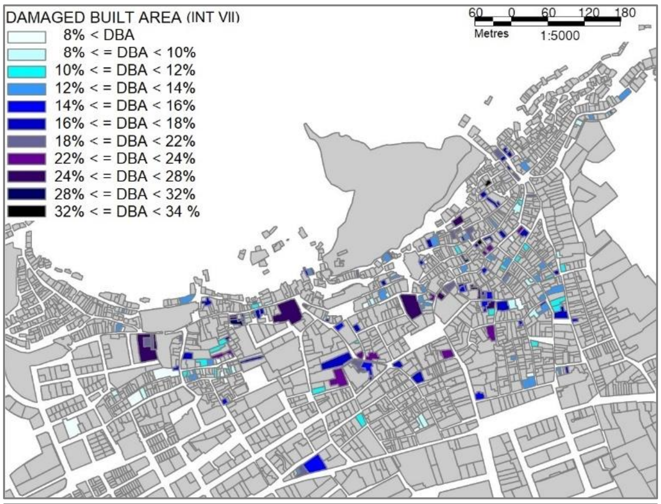
Binomial function: $$p_B(k) = \frac{5!}{k!(5-k)!}\left(\frac{\mu_D}{5}\right)^k \left(1 - \frac{\mu_D}{5}\right)^{5-k} \qquad k = 0,1,2,3,4,5 \quad \text{(eq. 4)}$$

Then, by means of the beta cumulative density function in equation 5, the probability of reaching each damage grade k (from no-damage k=0 to collapse k=5) is obtained (eq. 6), for each seismic scenario.

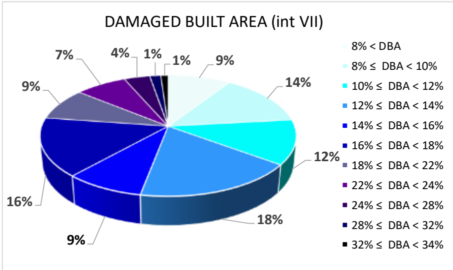
$$P_\beta(k) = \int_0^x p_\beta\,(y)dy \quad \text{(eq. 5)}$$
$$p(k) = \int_k^{k+1} p_\beta\,(y)dy = P_\beta(k+1) - P_\beta(k) \quad \text{(eq. 6)}$$

Heritage losses depend on the probability of each building to reach each damage state and the cost of rebuilding or repairing. HAZUS- 4.2 SP3 Technical Manual (FEMA-2020), considers a loss percentage of 2, 10, 45, 100 and 100 of the construction replacement cost for damage states D1, D2, D3, D4 and D5 respectively. The building replacement or rebuilt costs are calculated multiplying the built area by the probability of reaching each damage state and the corresponding loss ratio costs summed over all the damage states.

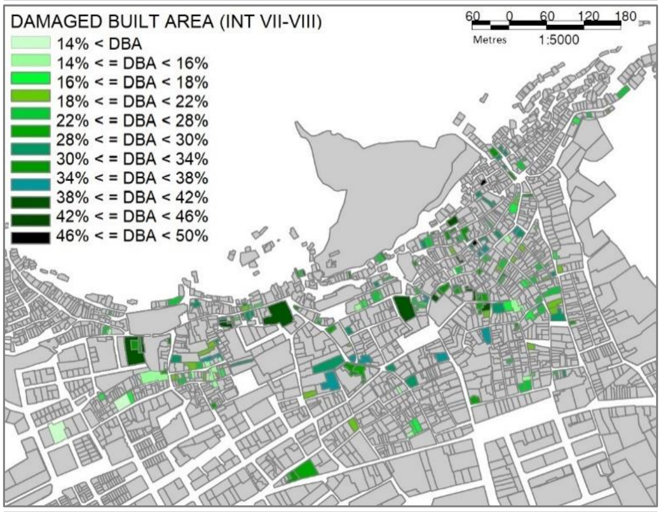
Usually, the repair or replacement costs, are calculated from an estimated price per square metre for the reconstruction of the buildings according to the quality and the market prices in force at the moment of the study. However, due to the singularity of the rammed earth buildings, and the difficulty to obtain a market price for the reconstruction of such typology, the authors have decided to map the damaged built area (DBA) which represents the ratio (or percentage) of the damaged area to be reconstructed in a building to its total built area. Therefore, maps in figure 16 represent the DBA for each building, in each seismic scenario.



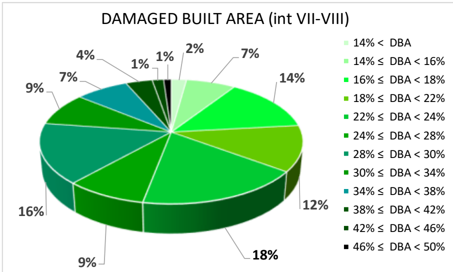
INTENSITY VII



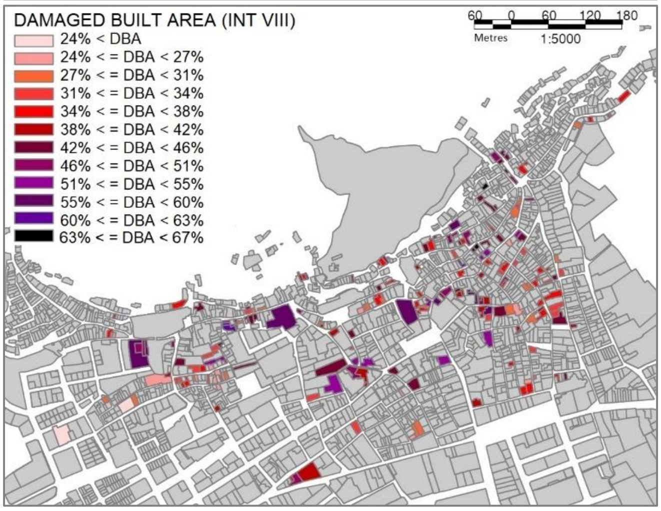
The Damaged Built Area (DBA) will be:
less than 10% for 43 buildings
between 10% and 24% for 143 buildings
more than 24% for 12 buildings



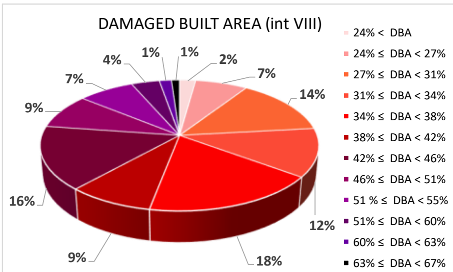
INTENSITY VII-VIII



The Damaged Built Area (DBA) will be:
less than 24% for 98 buildings
between 24% and 30% for 45 buildings
more than 30% for 42 buildings



INTENSITY VIII



The Damaged Built Area (DBA) will be:
less than 30% for 43 buildings
between 30% and 50% for 116 buildings
more than 50% for 26 buildings

Figure 16. Damaged Built Area for the three scenarios.

Additionally, the built area (in sqm) that, in the case of a seismic event in Mula, will probably need to be rebuilt (DBA), has been calculated (figure 17). It represents 16.67% of the total built area of the analysed sample (6730 sqm), 28.13% (11355 sqm) or 42.91% (17318 sqm), respectively, for an earthquake of an intensity VII, VII-VIII or VIII.

In all the seismic scenarios, the minimum values for the expected Damaged Built Area are equal for both typologies, SRE and RRE. However, the maximum values correspond to SRE buildings, not only because the initial vulnerability index V_I* is slightly bigger, but also because the abandoned buildings pertain to this typology and the lack of maintenance has led them into decay and ruin. The expected minimum and maximum values for the DBA expressed in percentages of the built area for each typology are shown in table 6.

The results for each seismic scenario have also been analysed considering the age of the buildings (figure 18), the listed status (figure 19), and the inhabited status (figure 20). Data show that great part of the expected damaged area was built before 1925.
Additionally, for the lower seismic intensity, nearly 50% are listed buildings (in any grade), highlighting the fact that listed buildings are the more vulnerable, and therefore, the first which have to be intervened to reduce their seismic vulnerability.

From the point of view of the authors, it is important to take action as soon as possible to minimise any future damage, as well as to prevent any seismic event to be used as an excuse to demolish the damaged buildings, despite their listing grade. It is a pity that rammed earth houses within the area of influence of the ACI are demolished and replaced by new ones with load bearing concrete blocks walls, as observed during the fieldwork (see figure 21).

With regards to the inhabited status, it does not seem to be any clear trend as the probable damaged sqm in the "no-inhabited" cases are quite balanced with respect to the "yes-inhabited" cases. It doesn't worth to analyse the rest of the cases: "not known" or "it seems no" or "it seems yes", as the reliability of the classification is quite low.

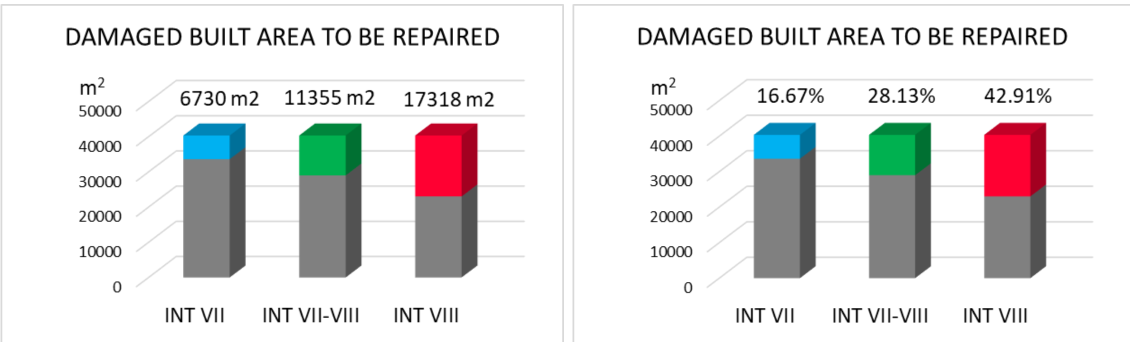


Figure 17. Damaged built area to be repaired in sqm and percentage for the three scenarios.

Table 6: Damaged Built Area for each seismic scenario and earthen typology

Scenarios	INT VII		INT VII-VIII		INT VIII	
Typologies	DBA min	DBA max	DBA min	DBA max	DBA min	DBA max
SRE	8%	34%	14%	50%	24%	67%
RRE	8%	24%	14%	38%	24%	55%

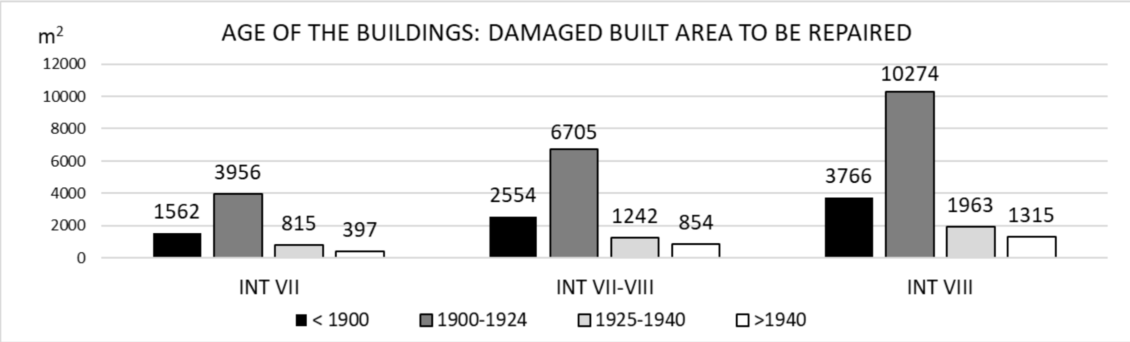


Figure 18. Damaged built area to be repaired in sqm for the three scenarios considering the age.

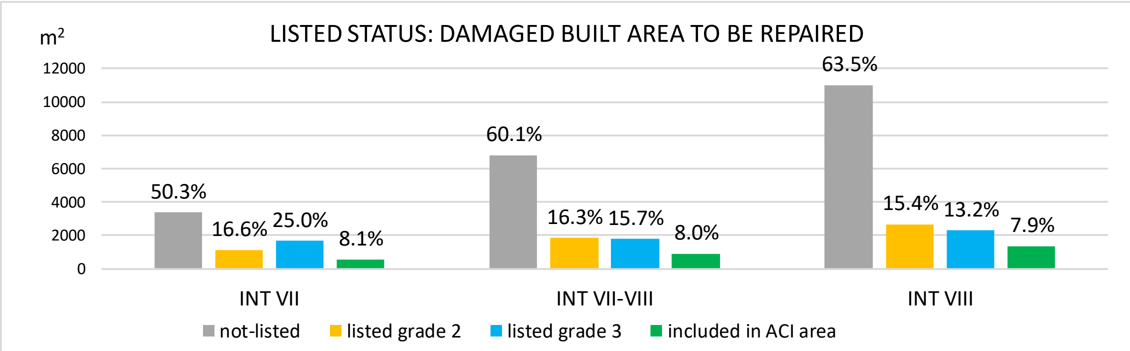


Figure 19. Damaged built area to be repaired in sqm for the three scenarios considering the listed status.

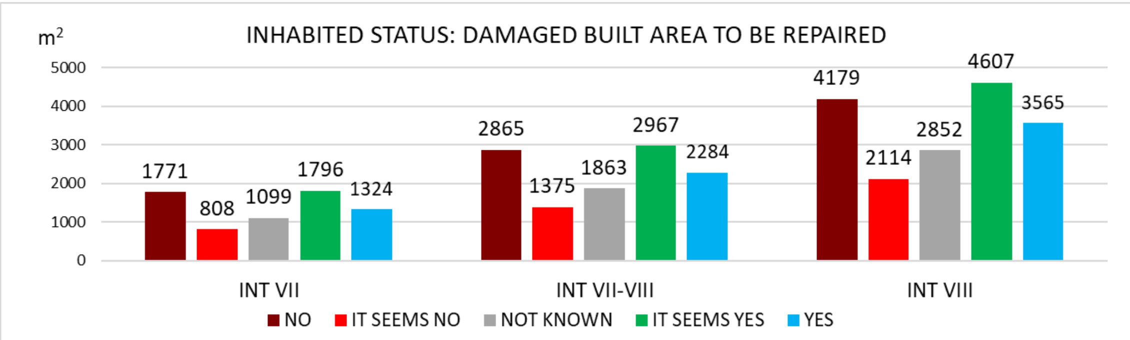


Figure 20. Damaged built area to be repaired in sqm for the three scenarios considering the inhabited status.

Figure 21. Rammed earth building being demolished. Source: The authors 2021

6. Conclusions

Earth as a building material has been widely employed for residential buildings in the Mediterranean area and beyond. Being part of their landscape and cultural heritage, to preserve these constructions is a must, therefore seismic vulnerability assessment methodologies should include the specificities of earthen typologies.

The field study of this research has revealed the presence of a significant number of humble rammed earth residential dwellings in the old city centre of Mula. These buildings will have gone unnoticed until abandon and decay of the renderings showed the real nature of the structural walls. It is quite likely that this number will increase when including the earthen buildings that have not been identified due to their good state of maintenance.

The seismic vulnerability of the identified rammed earth residential buildings in Mula has been evaluated using the L1-Risk-UE VIM, proposing new values for the initial vulnerability index and the modifiers, tailored to the specific features of the analysed building stock. Then, the geographical distribution of the seismic vulnerability and of the predicted damage for each earthquake scenario have been represented with a Geographic Information System (GIS).

The obtained data, maps and graphs show that the seismic vulnerability of Mula's rammed earth minor heritage is quite high, being the seismic risk relevant, affecting a non-negligible amount of the built area. It must be pointed out that a great part of these affected sqm correspond to listed buildings with different protection grades.

The assessment has shown that, with a proper state of maintenance, the considered structural typologies (SRE or REE) are not relevant in the value of the seismic vulnerability index or the expected losses.

Despite being the Region of Murcia a seismically active area, the presence of quoins, as aseismic devices, is only anecdotal (unless there are more unidentified quoins under the coatings) and their influence in the seismic behaviour of the analysed elements, negligible.

Due to the singularity of the rammed earth buildings, and the difficulty to obtain a market price for the reconstruction of such structural typology, the seismic risk has been estimated calculating the heritage losses in terms of damage-built area (DBA) for three probable seismic scenarios: int VII, int VII-VIII and int VIII.

In view of the results of this study, assessing the seismic vulnerability of the building stock before starting any rehabilitation action is a must. Criteria for optimally allocating resources must be established, selecting the most urgent area or dwellings to intervene in.

ACKNOWLEDGMENTS

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