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VULNERABILITY STUDY OF EARTH WALLS IN URBAN FORTIFICATIONS USING CAUSE-EFFECT MATRIXES AND GIS: THE CASE OF SEVILLE, CARMONA AND ESTEPA DEFENSIVE FENCES

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ABSTRACT

The objective of this paper is to develop a new methodological model to assess the vulnerability of defensive remains in rammed earth walls in historical centers. To do this, the vulnerability index based on cause-effect matrix has been adapted for constructions which main component is rammed earth walls and combined with a Georeferenced Information System (GIS).

Medieval defensive fences have been studied in three historical centers in the province of Seville (Carmona, Estepa and Seville). 20 sections belonging to medieval rammed earth walls fortifications (10th -15th century) have been analysed. In the case of Carmona, the bases of the walls are from the Carthaginians period (3rd century BC). The sections were divided into 199 minimum units of analysis (MUA), with walls, towers, gates, shutters and fortresses. 2450 m of earth walls were studied in the three cities. The tools used to assess the vulnerability index were Leopold matrixes and cataloguing cards filled out after onsite inspection. As a result, a descriptive study of weathering forms that affect the structures and a vulnerability index that identifies the most vulnerable structures is presented. The information gathered is very useful in decision-making and prioritization of strategies in the preservation of urban heritage environments.

KEYWORDS: Historical centres, medieval fortifications, rammed earth walls, vulnerability, Georeferenced Information Systems.

1. INTRODUCTION

The assessment of vulnerability factors involved in Cultural Heritage requires an analysis from the point of view of risk management. In this sense, the development of studies and risk analysis models in recent years has been increasing.

According to UNESCO terminology, risk is the likelihood of extreme event that, in occurrence, may have negative impacts on the objectives (UNESCO, ICCROM, ICOMOS, 2014). This uncertainty may be defined by environmental threats (negative impacts) and by the vulnerability or ability of a building or structure to withstand its damaging effects (Ortiz et al., 2013).

Vulnerability analysis and risk assessment associated to preservation of historical buildings have increased in the last years. New technologies such as mathematical 3D models, infrared thermography and photogrammetry have been used by Elyamani (2018a, 2018b); structural studies were carried out by Altuntas (2017). New methodologies were developed (Liritzis & Korka, 2019) in order to achieve cultural heritage sustainability throughout archaeometry. Most of the studies are quantitative analysis methodologies for a single threat, such us the studies carried out by Ferreira (2013, 2019) and Maio (2018) towards the analysis of seismic danger in historical centres of Portugal and their environment, as well as those carried out by Di Salvo (2018) to quantify flood risk index in urban areas of Italy. From a landscape study approach, the methodology proposed by Agapiou (2016) (Cuca & Agapiou, 2018) for the evaluation of geotechnics and soil erosion processes in Cyprus and the studies developed by Elfadaly (2017, 2018) for the analysis of problems associated with urbanization and changes in land use in Luxor (Egypt) employed different vulnerability factors that influence Cultural Heritage conservation .

Regarding methodologies that allow a comprehensive management of all existing treats related to risk, the available literature is limited. A significant example of comprehensive risk and vulnerability studies are those carried out by Ortiz (2014a, 2014b, 2016a, 2016b, 2018) in risk and vulnerability of Cultural Heritage in Andalusia. The main objectives of these studies were developing risk maps, analysing weathering forms, evaluating materials behaviour against the existing threats and design and validate a diagnosis methodology for vulnerability analysis of monuments in historical centres. The methodological model proposed is based on the use of Leopold cause-effect matrixes and georeferenced information systems (GIS) applied to preventive conservation in Cultural Heritage in historical centres. Results obtained have been drawn in hazard and vulnerability maps in cities such as Seville, Cadiz and Ronda (Ortiz et al., 2013 ; Ortiz, 2014; Ortiz et al., 2016a; Ortiz et al., 2016b; Ortiz et al., 2018; Prieto et al. 2019).

The highest achievements were the systematization of factors and scores used through consultation by Delphi method to a multidisciplinary group of experts. The model has been designed taking into account all of the possible alteration factors and it can be applied in different contexts allowing interrelated results (Ortiz & Ortiz, 2016; Ortiz et al., 2018). The proposed tools can identify the main threats and risk that affect urban heritage, allow planning integral management proposals and facilitate decision-making regarding restoration interventions to be prioritized (Ortiz et al., 2014; Prieto et al. 2019).

Environmental threat assessment can be used in monuments of different materials; however, vulnerability studies are focused in stone and brick monuments, so it needs to be adapted to weathering forms related to earth rammed structures. For this, this paper revised the weathering forms and the environmental factors according to damages observed in rammed earth constructions studied.

Diagnosis and characterization methodology developed by Canivel (2011, 2019) for rammed earth fortifications in Macarena urban walls in Seville was studied. This methodology mixes threats and vulnerability factors. In this paper, the methodology separates vulnerability and threats, this is an advantage that allows the analysis of how the same threat affects to different constructions according to their vulnerability index. On the other hand, that methodology (Canivel, 2011, 2019) was used in rammed earth fortifications but it needs to be adapted to other fortifications because it is common to find stone and bricks being mixed with rammed earth in other fortifications. In this context, we have adapted our methodology to assess different types of structures: rammed earth walls, and earth walls mixed with stone and bricks.

Because of that, the objective of this study was to develop a new methodological model to assess the vulnerability of defensive remains in rammed earth walls in the historical centres of Seville, Carmona and Estepa. To achieve this main objective rammed earth weathering forms were recorded, the vulnerability factors presented were assessed and combined with a vulnerability map of each city.

2. MATERIALS AND METHODOLOGY

2.1. *Materials*

Medieval fortifications built in rammed earth have been studied in the historical centres of Seville, Carmona and Estepa (Seville Province, Spain). Seville has a historical centre of around 6,5 km2. The historical centre of Carmona (of around 2,45 km2) is a medium town, though in Estepa (of around. 50.000 m2) the fortification analysed is the outskirts of the historical centre of this town.

Seville is located in the Guadalquivir valley between the Aljarafe terraces (West) and the Alcores hills (East). The most ancient structure analysed in this town is the Royal Alcazares, its origins go back to the 10th century (Tabales, 2013). It is a complex of defensive elements and palaces. Its most ancient elements are from the Almohads period. When Seville was the Muslim capital this building was modified and afterwards was even expanded in Christian period (Almagro, 2007). Defensive walls were built in the Almoravids period. Sections conserved and studied corresponds with the Almohads ampliations of the 12th and 13th century. Some of these sections were demolished in the 19th century (Ramírez, 2014).

The town of Carmona is located in the Alcores hills in the Guadalquivir valley. These hills are made of calcarenite stone one of the main materials used in buildings and fortifications in this area. Sections of walls analysed in Carmona are from the 3rd century BC, these walls were modified repeatedly until the 15th century (Valor, 2014b). Don Pedro King Alcazar is a palace with concentric spaces built by the Omeyas (10th century) though conserved structures that are from Christian period around the 15th century (Valor, 2014b).

In Estepa all the fortifications analysed are in the San Cristóbal Hill that was in the past the historical centre of this town, while nowadays the town is on the hillside. Estepa is located in the Estepa mountain range with important quarries of Flint used in the roman period (Zoido, 2015). Archaeological studies show Turdetani walls (before the roman period) that is supposed a continuous settlement in this location. Today conserved walls are from the medieval period (14th and 15th century) (Valor, 1999c). During this medieval period Estepa was in the Muslim border (Valor, 1999c; Valor 2014b) this resulted in continuous restructuring due to defensive needs.

All the fortifications studied have rammed earth as their main constructive element. Rammed earth walls are built using a formwork with clay, sand and gravel that is rammed in different layers, where the wall is obtained adding up layers (Mileto et al., 2017). Sometimes pebbles are added to give more resistance to the defensive structure. According to Mileto et al. (2017) walls with more than 10% of lime can be called concrete earth rammed walls.

Rammed earth structures analysed can be divided in two typologies: monolithic, where the homogeneous wall is built with earth and lime, and mixture walls that are reinforced with stone, brick and mortar (Martín del Río et al., 2019). These reinforced areas are located in roofs, basis and lined within the walls in the cases studied.

In Seville the almohades defences were mainly built adding bricks and lime to the earth rammed structure. Of all the analysed cases 89% are rammed earth structures while 11% are built in calcarenite stone (all of them located in the Alcazar). Minimum analysis unit (MUAs) of earth rammed are classified (table 1) in bare earth rammed (72%), lined with bricks (8%) and limed (9%).

Sections of urban rammed earth walls in Seville were built with merlons and battlements in the upper part. The walls are made of 2 to 5 levels of rammed earth. Sometimes they have been hollowed in arcs trying to improve urban mobility providing traffic access to the historical centre. The towers have solid chambers with rectangular form, except the Gold Tower that is twelve-sided and the White Tower with octagonal form. They are projected outside the walls and are attached to them trying to avoid structural damages such as collapse and giving the structure a defence without weak points.

In Carmona conserved fortifications have mixed earth rammed with stone from the Alcores quarries. This material is a calcarenite with a high percentage of fossils (Carmona Townhall, 2009). 54% of the structures are bare earth rammed while 37% is lined with calcarenite stone and 7% is limed (table 1). As in Seville, the towers have solid chambers with rectangular base except in Cordoba gate that there are two polygonal towers with six sides and the Alcazar with a semicircle base. They are projected outside the walls and attached to them avoiding interlocking.

Estepa present rammed earth reinforced with stone and limed as well as walls lined with stone. 85% of the structures are lined with stone whereas a 12% are bare rammed earth. Only a 3% is lined with bricks and it is found in the eight-sided tower (table 1). Some of the structures lined with stone corresponds with medieval interventions in order to repair bare earth rammed decayed (Gurriagan, 2016). The Homenaje tower is the only case of an interlocking earth rammed structure. All of them have limestone from Estepa quarries, which main component is calcite ($CaCO_3$) with less than 1% (SiO_2) (Ortiz et al., 1995). This limestone is homogeneous, compact and with low absorption that provides medium-high resistance.

Moreover, most fortifications analysed have been restored using different materials and constructive techniques.

Table 1: Relative Frequency of constructive techniques in Seville, Carmona and Estepa defensive fences.

Type	Constructive technique	Seville	Carmona	Estepa
Earth rammed	Bare earth Rammed	72%	56%	12%
	Lined with bricks	8%	0%	3%
	Lined with stones	0%	37%	85%
	Limed	9%	7%	0%
Stone	Masonry	11%	0%	0%

Location of fortifications in the historical centres has conditioned their maintenance, as some of them were broken into pieces as in the case of Seville and Carmona, due to the expansion of the cities. Actually, these structures are preserved by Cultural Heritage laws and urban planning protection but in the 1960s a lot of sections of these walls were knocked down or added to buildings in order to modernize and urbanize historical centres (Instituto del Patrimonio Cultural Español, 2015; Graciani & Canivell, 2019).

Fortifications analysed have been declared Assets of Cultural Interest and are protected by Spanish Cultural Heritage Law (Law 16/1985) and Andalusian Cultural Heritage Law (Law 14/2007). Following the recommendations of these laws, General Urban plannings have protected these monuments throughout Special Protection Planning in Historical Centres in the case of Seville and Carmona. In the case of Estepa this document is nowadays drawing up. It is highlighted that the Royal Alcazar, the Indias Archive and the Cathedral of Seville are part of the UNESCO World Heritage list.

Though these fortifications had defensive use in the past nowadays some of them have new uses not always according to their legal protection requirements (table 2). The majority are museums and sightseeing spaces but in Seville and Carmona, some structures are dedicated to traffic accesses, as they maintain their functionality as gates. In Seville there are two cases of car parks within the defensive walls.

Table 2: Relative Frequency according to actual uses

Actual uses	Seville	Carmona	Estepa
Sightseeing space	38%	17%	94%
Museum spaces	44%	74%	6%
Enclosure of car parks	13%	0%	0%
Traffic access	5%	9%	0%

2.2. *Data collection*

Analysed structures have been standardized using the classification of the International Centre of Fortification Studies and Logistical Support (CIEFAL) depending of the International Council of Monuments and Sites (ICOMOS) adapted by the Spanish Cultural Heritage Institute in the National Plan of Defensive Architecture (Instituto del Patrimonio Cultural Español, 2015).

According to the National Plan of Defensive Architecture, military architecture is the collection of structures and constructions built throughout history towards the defence and control of a stablished territory, belonging as part of the territory as a whole.

Functional and usable variables have been used to classify defensive constructions. According to this a military construction is the union of fortifications (defensive walls, towers, castles, alcazars), logistical spaces (quarters, academies, boatyards, harbours, weapons factories) and control and command spaces (quarters, bunkers…) and commemorative spaces (monuments, battle fields….). The sum of the different military constructions would form the defensive set and the strategies developed between different defensive sets would be considered defensive systems.

In order to collect data, only fortifications in public areas have been analysed. Boatyards, control or command and commemorative spaces have a structure apart from fortifications, so they were not considered in this paper, as well as the structures that were reused as inner walls in new constructions and those located in private spaces or those buried in the subsoil.

The fortifications usually have been conserved in a unique and continuous way but in urban areas this is not common due to some sections were demolished in the 20th century. So for the cases analysed sections walls have been taken into account as units of study.

For data collection six fortifications have been studied (Alcazars and urban walls), they were separated into 20 sections and 199 MUAs. Data of each MUA was collected in cataloguing cards in order to assess vulnerability index. Tables 3-5 show the list of fortifications and sections analysed in Carmona, Seville and Estepa.

The MUA was understood as the main minimal entity analysed in this study, was defined from the elemental architectonic units (wall, tower and gate) that the fortifications presented. Risk management implies working with a lot of data at the same time, while MUAs allows a fast data collection, periodical reviews and data updating.

Cataloguing cards were carried out on on-site inspection to analyses the vulnerability variables. The model of these cards includes different information such as cadastre data, historical, bibliographic, architectonic and urban planning data. Collected information is allocated in the following paragraphs:

1. Acronyms was used in order to name fortifications. Acronyms have three letters corresponding to the section or fortification analysed and a number corresponding to each MUA (for example: MUS_JVA_0001 means section 0001 of Gardens of Valle walls in Urban wall of Seville).
2. Location: includes the name and number of the street and the latitude and longitude using WGS84 references.
3. Urban protection and present use: include Spanish Cultural Heritage type protection, cataloguing level and present uses according to urban planning. Urban protection is included in the cataloguing card with pictures of urban planning that shows the level of protection and the allowed uses according to Cultural Heritage Laws.
4. Chronology and historical uses: include a brief summary of researches and published studies.
5. Materials and constructive techniques: include the type of rammed earth wall, the type of formwork, the type of gravel, the presence of lime and the type of the lining (brick, stone, etc..). Materials and constructive techniques have been described following Graciani and Tabales methodology with a simplified model taking into account constructive types, materials and metric (Graciani, 2009). It was included interlocking in brick or stone, the type of formworks, the presence of lime or lining with stone and brick in accordance with Canivel studies (2011).
6. Structure description, archaeological studies and restorations: includes a brief summary of researches and published studies.
7. Quantification of magnitude and frequency of weathering forms and diagnosis of the state of conservation: includes a summary of damages such as deposits, fractures, cracks, deformations, discoloration, missing parts and biological colonization, their quantification assessment and the analysis of the causes. Leopold cause-effect matrixes were used in order to quantify the magnitude and frequency of weathering forms observed in the inspections.

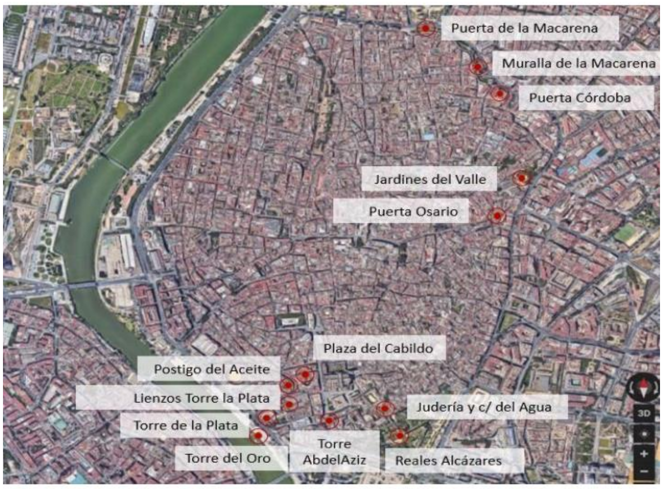
All the data was drawn in GIS using ETRS89 coordinates system.

Table 3: Fortifications walls divided in sections in Seville, Carmona and Estepa (Google Maps, 2019).

Carmona

Estepa

Seville



**Defensive fences have been divided in MUAs (sections, towers and gates)*

Table 4: Urban Walls: fortifications and sections studied in Seville, Carmona and Estepa.

Seville		Carmona		Estepa
Fortification	**Sections**	**Fortification**	**Section**	**Fortification /Section**
MUS: Seville Urban Wall	MAC: Macarena Section Wall 	MUC: Carmona Urban Wall	ESM: Section wall in San Mateo Street 	VIE: Estepa ancient village 
	JAV: Garden of Valle Section Wall 		RCE: Ronda Cenicero 	
	PMS: Macarena Gate 		PSC: Seville Gate 	
	PCS: Cordoba Gate 		PCC: Cordoba Gate 	
	PAS: Oil Shutter Gate 			

Table 5: Alcazars, fortifications and section walls studied in Seville, Carmona and Estepa.

Seville			Carmona		Estepa
Fortification	**Sections Wall**		**Fortification**	**Section Wall**	**Fortification /Section**
ALS: Royal Alcazar	ERA: Main entrance to the Royal Alcazar 	PLA: Wall section joint to the Silver tower 	ALC: Don Pedro King Alcazar	ALC: Don Pedro King Alcazar 	ALE: Estepa Alcazar 
	JUD: Section Wall in the Juderia Street 	TOS: Gold Tower 			
	AGU: Section Wall in the Agua Street 	TPL: Silver Tower 			

	 CAB: Section Wall in the Cabildo Square	TAZ: AbdelAziz Tower 			

2.3. *Vulnerability analysis*

Vulnerability index assessment of wall sections have been carried out using methodology based on cause-effect matrixes developed by Galán et al. (2006) that was adapted to archaeological sites by Ortiz et al (2014). This methodology includes three types of Leopold matrixes: identification matrix, characterization matrix and assessment matrix.

Identification matrix, according to cause-effect matrixes developed by Galán et al. (2006), records the relationship between threats and the main features of the earth walls related to the materials: physical-chemical characteristics and texture/structure and structure of the defensive element: foundation, building structure and construction.

Characterization matrix records the weathering forms found on the on-site inspection in the identification matrix. Characterization matrixes allows us to relate the action of the different hazards existing in the environment with the registered weathering forms and the main features of earth walls. The characterization matrix is based on the one developed by Ortiz & Ortiz (2016b).

Assessment matrixes quantifies the weathering forms and their frequency. This matrix includes a list of 26 weathering forms rated with magnitude and frequency of damage. Weathering forms follow ICOMOS glossary in stone (Vergès-Belmin, 2008) but adapted to earth walls. Differential alteration has been included in relationship with layers of rammed earth and deformation in the base of fortification due to rain (Mileto et al, 2014).

The magnitude applied to weathering forms follows Fitzner (2007) model, that quantify the damage associated to each weathering form, the variables goes from 1 (very low damage) to 5 (very high damage). Fragmentation has special score 10 because implies two pathologies breakage and displacement (Ortiz et al., 2014).

Frequency indicates how often this weathering form appears in a MUA. Frequency goes from 1 to 3 where 1 means that it is difficult to find the indicator; 2 if it is easy to find the weathering form and 3 when this pathology is abundant. Only the section of MUAs accessible to the public were studied.

Table 6 shows the relationship between frequency and magnitude. The intensity of the damage is obtained by the following equation $Ii = Mi + (Fi-1)$ where I is the intensity, M is the magnitude and F is the frequency.

The Assessment matrix determines vulnerability index (VI) dividing the intensity of the sum of all the weathering forms found in a fortification (Vx) according to the characterization matrix by the sum of all the possible weathering forms (∑vdp) in the worst condition (frequency damages values (f) = 3).

$$VI = \frac{\text{Vx}}{\sum vdp} x100$$
$$f = 3$$

Vulnerability index results of fortifications are classified in five groups according to Galan el at (2006).

Table 6: Intensity of weathering forms (Ortiz & Ortiz, 2016a).

Magnitude	Low frequency (1)	Medium frequency (2)	High frequency (3)
Very low (1)	1	2	3
Low (2)	2	3	4
Moderate (3)	3	4	5
High (4)	4	5	6
Very High (5)	5	6	7

Results obtained of vulnerability index through Leopold matrixes have been drawn in an information georeferenced system using ArcGis software in order to build a vulnerability index map of the monuments analysed.

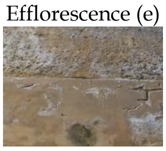
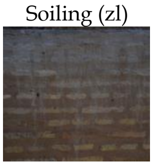
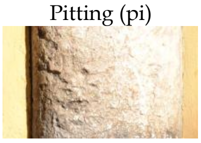
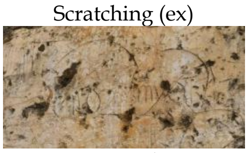
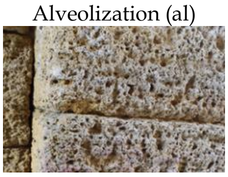
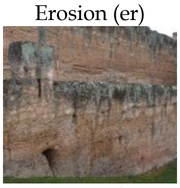
3. RESULTS

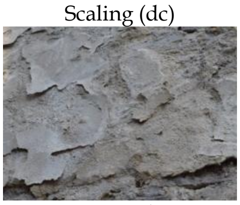
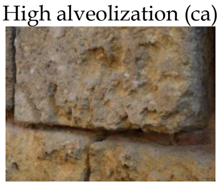
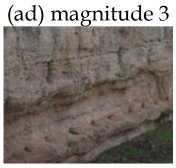
Thanks to on-site inspections of 199 MUAs, weathering forms were collected and were recorded. Main agents that cause these weathering forms were analysed in characterization matrixes. Data obtained allow obtain us vulnerability index of each structure studied.

3.1. *Weathering forms*

The on-site inspections allow the recording of the frequency and intensity of the weathering forms presented by each of the MUA analysed. Table 7 shows weathering forms follow ICOMOS glossary (Vergès-Belmin, 2008) and adapted to earth walls according to Mileto et al. (2014) and their magnitude. To facilitate rapid identification, the weathering forms have been structured into four groups: discoloration and deposits; fractures, detachments and losses and biological colonization (Table 7).

Table 7: Weathering forms in earth walls.

Weathering form				
Group	**Name and magnitude (1 to 5)***			
Discoloration and deposits	 Coloration or discoloration (ac) magnitude 1	Efflorescence (e)  magnitude 3	Pigeon droppings (g)  magnitude 2	Moist area (ac)  magnitude 3
	Concretion (cc)  magnitude 3	Soiling (zl)  magnitude 1	Iron-rich patina (ac)  magnitude 2	Surface deposit (d)  magnitude 1
	 Black Crust (c) magnitude 2			
Fractures and deformations	 Crack (fi) magnitude 2	 Fracture (frc) magnitude 5	Fragmentation (frg)  magnitude 10	Deformation (abo)  magnitude (3)
Losses of material and detachment	 Sanding (ar) magnitude 3	Pitting (pi)  magnitude 2	Missing part (pm) magnitude 5 	
	Scratching (ex)  magnitude 2	Alveolization (al)  magnitude 3	Erosion (er)  magnitude 3	

	Scaling (dc)  magnitude 2	High alveolization (ca)  magnitude 4	Blistering (am)  magnitude 2	
	Detachment (ds)  magnitude 3	Differential alteration (ad) magnitude 3 		
Biological colonization	 Biological colonization (b) magnitude 2	Plants (v)  magnitude 3		
Other	Building works (i)  magnitude 3			

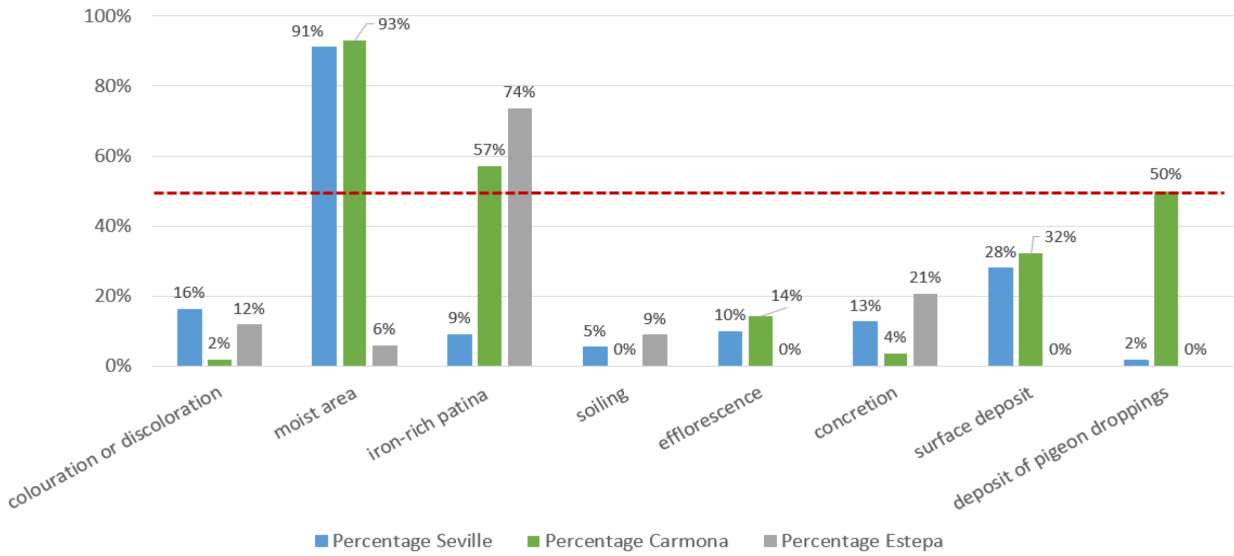


Figure 1: Total relative frequency of decoloration and deposits weathering forms.

Related to discoloration and deposits weathering forms: moist areas and iron rich appear in more than 50% of the studied fortifications (Fig. 1).

91% of MUAs in Seville present moist areas, 93% of analysed structures in Carmona and 6% in Estepa (fig. 2). In Seville and Carmona, it affects equally to rammed earth and to mixed rammed earth fortifications reinforced with stone and brick. The durability of Estepa limestone and geotechnique conditions may be the causes of this difference in percentage.

In towers, moist areas can raise 2,5 m of the walls. According to Canivel (2011), this process depends on the internal structure of the walls and the external conditions, for instance if there are gardens, traffic roads or natural ground in the surroundings.

Thickness of structures and missing parts may generate problems of destabilization of the walls. Those with stones bases (6%) are less vulnerable to the effects of water, and erosion processes are less frequent in the base of the walls than in bare rammed earth walls. Nevertheless, the biocalcarenite used in this construction also shows deterioration associated with the presence of water. Alveolization (14%) or high alveolization (19%) are two weathering forms generated by the mechanical action of water and wind that have been identified in all the stone walls analysed.

Iron-rich patina affects 9% of MUAs in Seville, 57% in Carmona and 74% in Estepa. Although iron-rich patina has been identified in rammed earth structures in Seville, it is usually associated to stone bases or reinforcements. It appears more frequently in the biocalcarenite of Seville and Carmona walls rather than in the limestone of Estepa walls.

Superficial deposits appear in 28% of MUAs in Seville and in 32% in Carmona. It is associated to its location in urban spaces related to traffic and historical fires. Fortifications in Estepa are in the outskirts of the town, because of that this weathering form does not appear in this city. Although stone bases seem to be especially sensitive to this type of pathology, bare rammed earth walls commonly present these deposits at those points where vehicles pass just a few meters from the structure. Deposits identified in the Royal Alcazar in Seville may be related to historical fires rather than the presence of pollutant gases.

Pigeon deposits only appear in 2% of MUAs in Seville while this percentage increases in Carmona to 50%. Hidden areas in defensive structures in Carmona bring on bird nesting. Gates and wind protected areas are the most affected.

Concretions and efflorescences appear with low frequency and are related to the use of Clinker cement in mortars.

Figure 2 shows the weathering forms due to loads, the most common weathering forms are fractures that affects 48% of the structures of Seville, 45% in Carmona and 29% in Estepa. There are vertical fractures located in weak points, wall unions and battlements systems. In Carmona it is important to know that in the past great part of urban walls fell down due to geotechnique problems. These structures have high risk of loss.

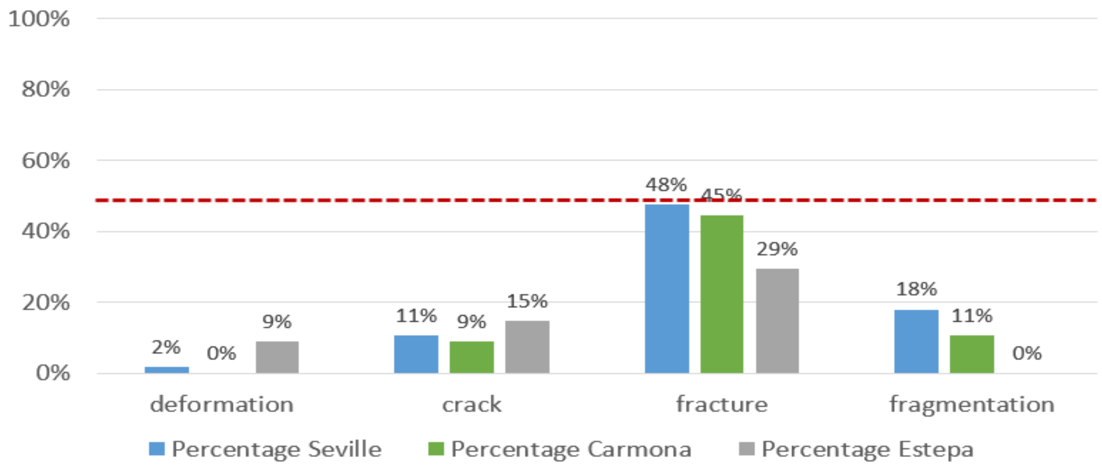


Figure 2: Total relative frequency of fractures and deformations weathering forms.

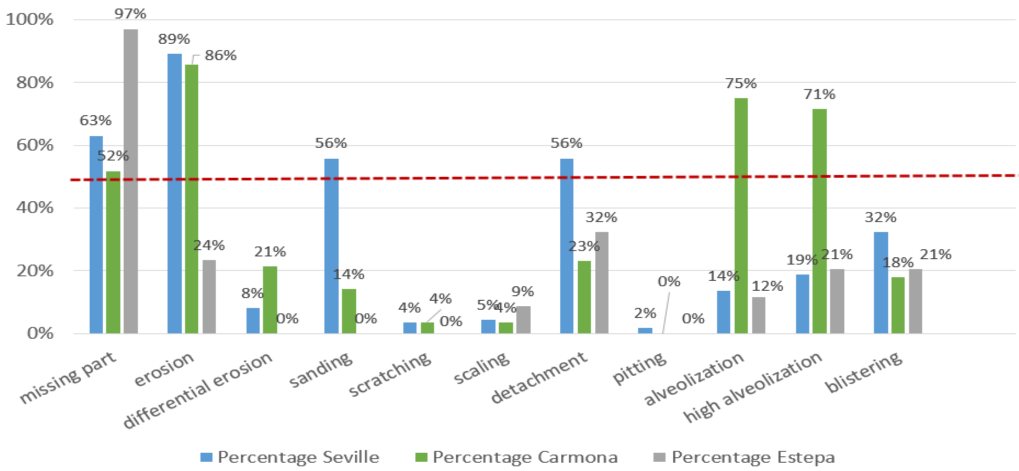


*Figure SEQ Figura * ARABIC 4: Total relative frequency of fractures weathering forms.*

Only 2% and 9% of MUAs in Seville and Estepa present respectively deformation, that is an indicator of severe damage in earth architecture. They usually appear in massive structures such as towers that have lost their roof or upper part and therefore are especially vulnerable to the effects of rainwater. When the coronation of the structure does not impede the access of water, the water drags particles of earth towards the lower areas that are progressively swelling.

If the wall is made up of stone or brick in the external part, the structure is more rigid, and this deformation can cause the loss of pieces of those materials and makes the rammed earth structure also weaker. Once the rammed earth wall is exposed, the erosion is quicker and ends up falling off (Mileto & Vegas, 2012). The remains analysed in Estepa presented a situation of abandonment and prolonged state of ruin shown that seems to be related to this pathology.

In the group of losses of material and detachment (Fig. 3), missing parts and erosion are very common in Seville and Carmona in more than 50% of fortifications, while erosion is medium in Estepa (≈25%).

Missing parts affect to 63% of MUAs in Seville, 52% of the fortifications in Carmona and 97% in Estepa. This weathering form in Seville and Carmona specially affects roofs, battlements and the upper part of towers. In Estepa, missing parts affect to stones that fell down.

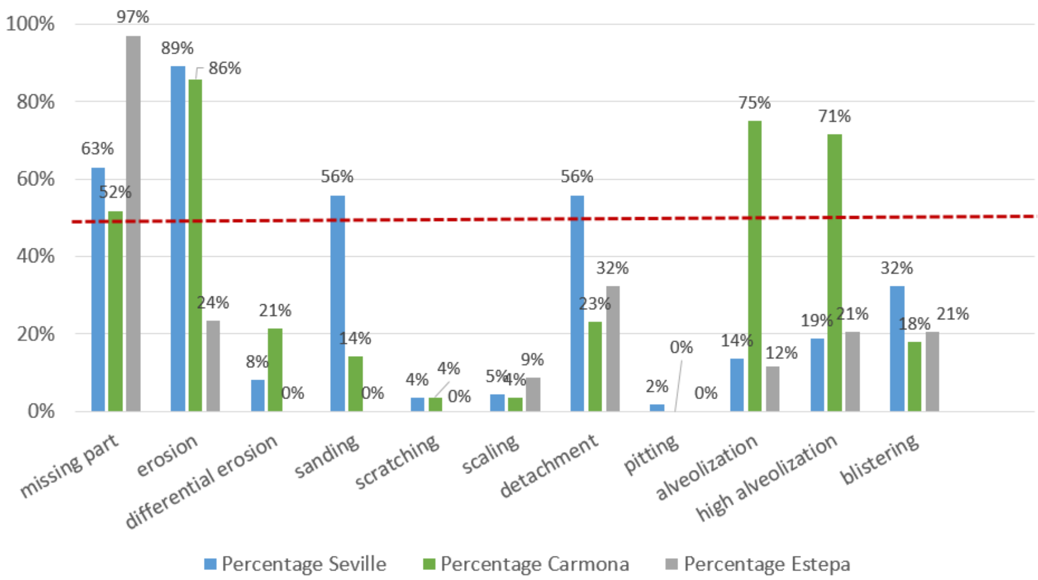


Figure 3: Total relative frequency of losses of material and detachment weathering forms.

Erosion processes appears in 89% of MUAs in Seville, 86% in Carmona and 24% in Estepa. This pathology has the higher frequency in bare rammed earth walls. Biocalcarenite reinforcements in Seville and Carmona also have erosion as weathering form although with lower frequency. Limestone walls respond better to erosive processes.

Sanding and detachments appear mainly in MUAs in Seville in the base of the restored structures with earth and earth-lime mortars. These weathering forms are associated to moist areas due to ground water in bare walls.

Alveolization and high alveolization only affect stone reinforcements, with a higher presence in Carmona due to its use in the base of walls. These weathering forms appear more frequently in biocalcarenite than in limestone (Estepa), as it is associated to stone texture and moist areas due to underground water.

In the group of biological colonization and others (Fig. 4), the affectation with this weathering form is high in the MUAs in the three historical centres. Biological colonization with 95% in Seville is highlighted while in Estepa plants appear more frequently (91%).

Building works appear in 72% of MUAs in Seville, while it is 54% in Carmona and it is 85% in Estepa (Fig. 4). Most of ancient and modern interventions have compatibility problems. In Seville the use of Clinker cement promotes concretions, efflorescences and fractures while the use of lime goes to sanding and detachment and those MUAs repaired with mud show sanding. The same problems are observed in Carmona, where geotechnique features have also caused fractures and fragmentation. In Estepa, there are concretions due to the use of clinker cement and loss of cultural value caused by lack of documentation and respect to different historical periods. Table 8 shows the frequency of problems due to interventions, and it is mainly low or medium in Seville and Carmona, while problems due to interventions have a high occurrence in MUAs of Estepa.

Most of the interventions works tried to repair structural damages and give stability to the structures because of the erosion of rammed earth. Resistance obtained compacting with formwork only in one side of the structure seems insufficient at the base of the wall (Mileto, 2017).

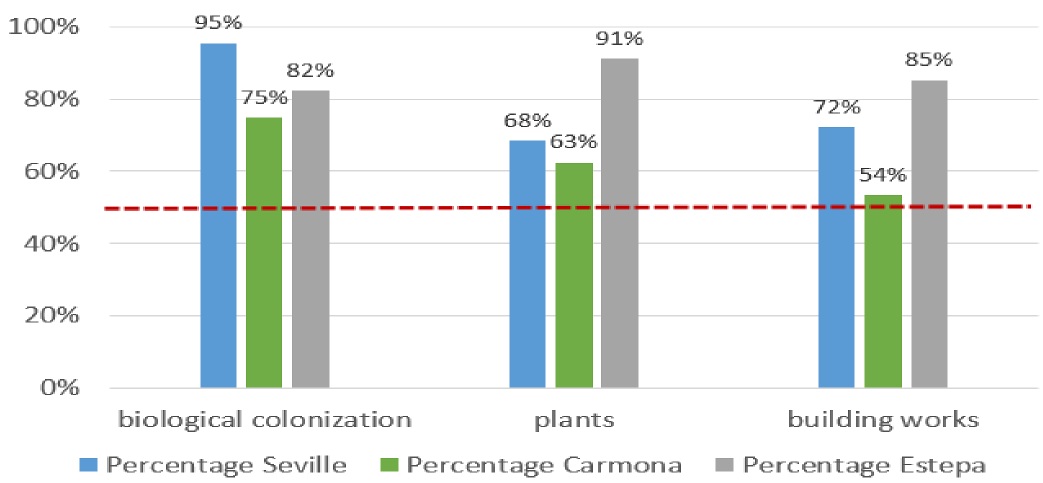


Figure 4: Total relative frequency of biological colonization and others weathering forms.

Table 8: Relative frequency of MUAs with problems due to interventions

	Low (1)	Medium (2)	High (3)	Total
Seville	40%	32%	0%	72%
Carmona	31%	16%	7%	54%
Estepa	15%	70%	0%	85%

3.2. Characterization matrixes

The characterization matrixes is based on the diagnosis, and allow us to identify the main agents that cause the weathering process. The environmental factors have great influence in the conservation of outdoor structures, and in the majority UMAs without protection roof. Within them, water is the main threat especially in the base of walls and at the top, that are the most affected areas.

As Figure 5 shows in Seville, the factors that have the most influence in the development of weathering forms are: the presence of aquifers that is majority associated with the development of moist areas, detachments in three quarters of the analysed sections, sanding and blistering in more than a half of the analysed sections, high alveolization and alveolization in a third part of them; wind and rain is associated to erosion processes in three quarters of all; while disuse is associated to missing parts and erosion, inappropriate interventions carried out and vandalism associated with chromatic alterations appears in more than a half of the cases studied.

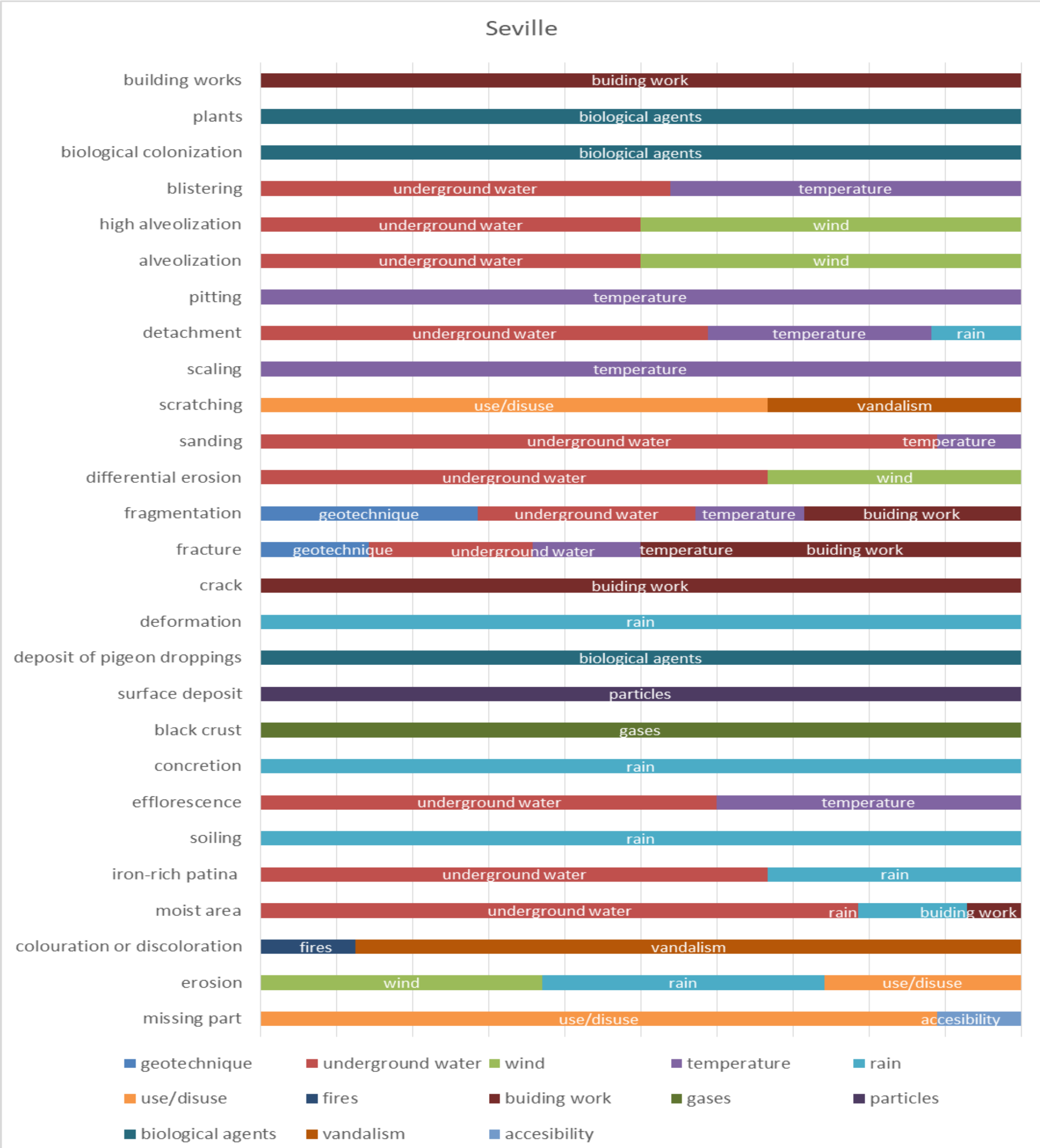


Figure 5: Relationship between weathering agents and weathering forms in Seville defensive fences.

In Carmona (Fig. 6), the main weathering agents are: geotechnique conditions that favour the development of fractures and fragmentation in more than 80% of the analysed sections; the presence of aquifers that is associated with the development of detachments, high alveolization and alveolization and also missing part associated to disuse appears in more than three quarters of the sections; in a half of them show moist areas and iron-rich patinas; wind is associated to erosion processes and the disuse is associated with missing parts and finally interventions have caused compatibility problems.

Its location in the Alcores hill and geotecnique conditions with clays are high threats to the fortifications analysed. Calcarenite blocks move over clay. These displacements are frequent in all the historical centre except in the west side, the higher intensity of movements processes area in the South and North sides of the city (Carmona Townhall, 2009).

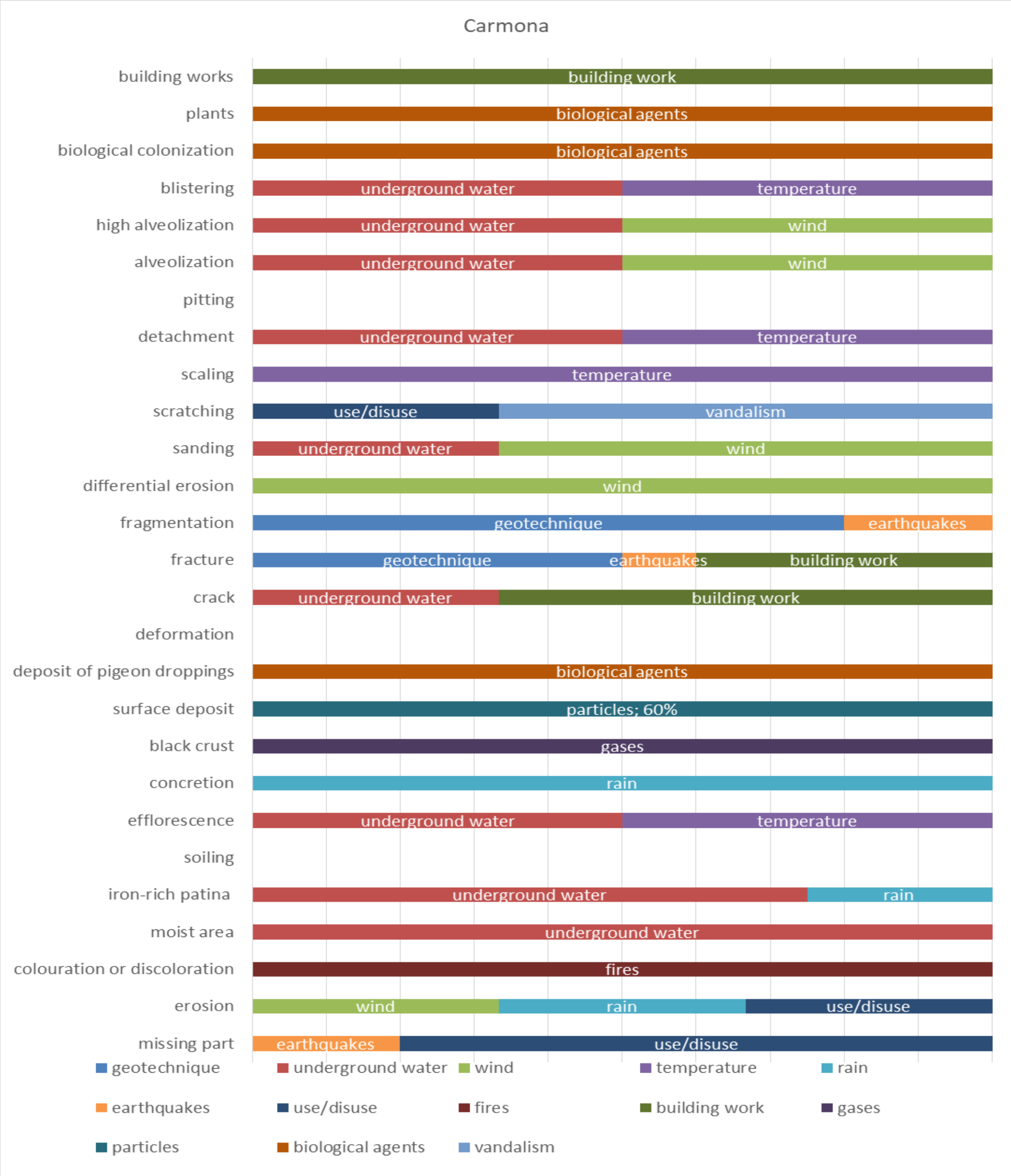


Figure 6: Relationship between weathering factors types and weathering forms in Carmona defensive fences.

In Estepa (Fig. 7), wind and underground water are the main causes of alveolization and high alveolization; underground water an rain caused iron-rich patina; while temperatures and building works are related to fractures and cracks; colouration and discolouration is associated to use and vandalism; rain caused detachment in bare rammed earth structures and temperature cause it in the rest of the analysed sections.

Thermal expansion coefficients are very different in stone and bare rammed earth. Complex structures mixing stone, brick and rammed earth are more vulnerable accelerating the appearance of weathering forms. The contractions due to expansions cause fractures and detachment and is why the stone fell dawn in the case of Estepa. Cracks are mainly caused by drying of the walls.

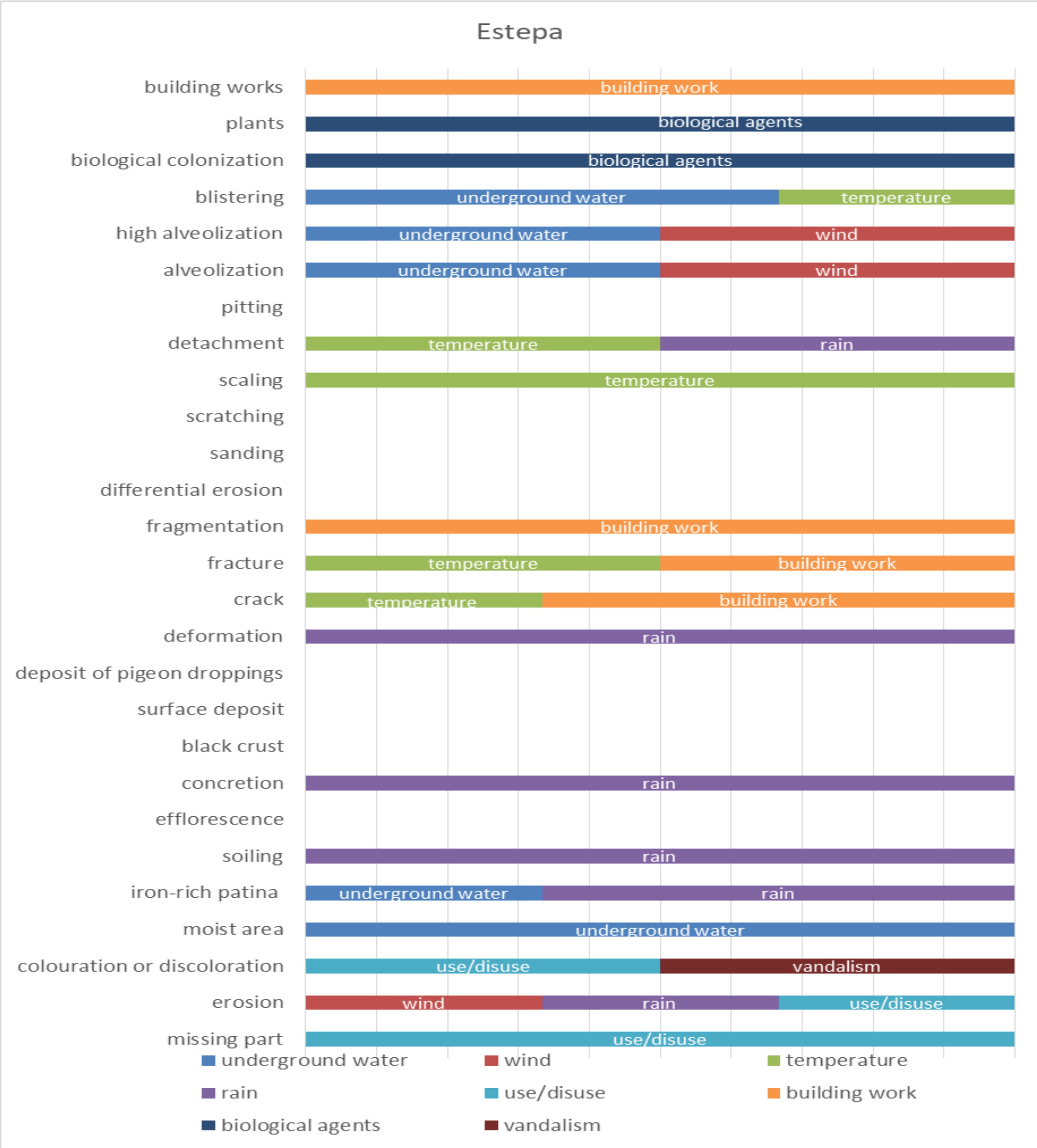


Figure 7: Relationship between weathering agents and weathering forms in Estepa defensive fences.

In summary, weathering forms related to water presence (rain or underground water), wind, interventions, the abandon and biological agents are pathologies with high influence in the state of conservation of the fortifications studied.

Vandalism is only a problem in Seville perhaps because of the size of this town in comparison with the others. Carmona has important pathologies caused by geotecnique conditions while Estepa presents weathering forms related to temperature and compatibility of structures lined with stone. When, the stones fell down, rammed earth inside deteriorate rapidly.

Finally, the results obtained in the characterization matrix allows agents being associated with weathering forms and know which parts of the fortifications in rammed earth are affected.

3.3. Vulnerability index

The results of vulnerability index allow us to know the state of conservation of defensive fortifications analysed and obtain a ranking list in order to prioritize interventions and restorations in the near future.

Figure 8 shows the vulnerability index of all the fortifications analysed in Carmona, Estepa and Seville. Using this data, a vulnerability map of each historical centre has been drawn using GIS (Figs. 9, 10 and 11).

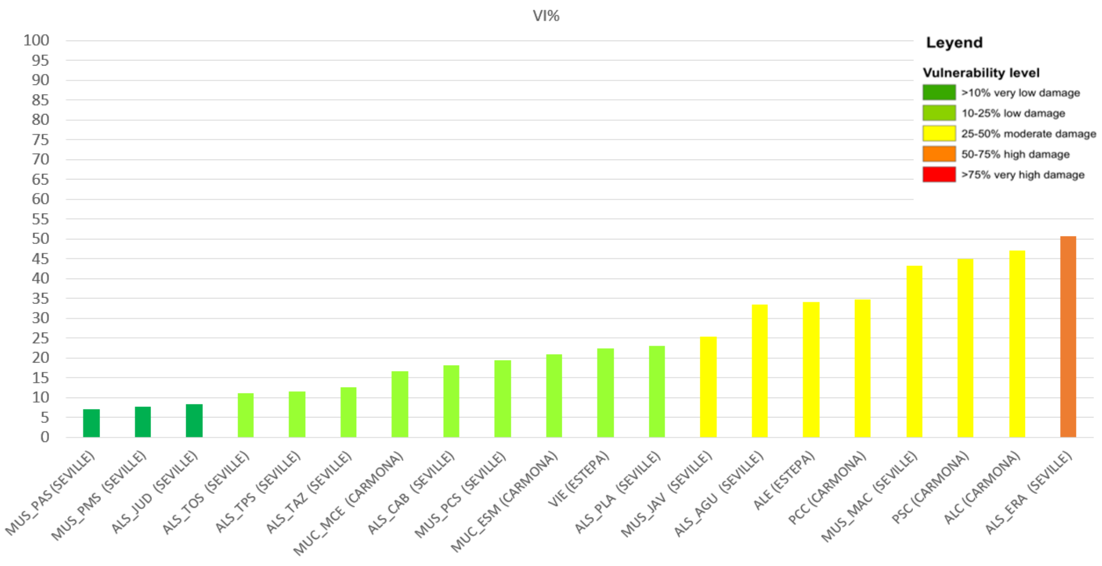


Figure 8: Vulnerability index of defensive fences in Seville Carmona and Estepa.

Twelve of the structures studied have low or very low vulnerability index due to periodic restoration and conservations works. Meanwhile eight of the fortifications have moderate or high vulnerability index. These sections with higher vulnerability indexes correspond with the Alcazars because of their constructive complexity versus urban walls. Different materials, constructive systems mixed together have compatibility problems and this increase fragmentations and fractures.

Different sections in a fortification can have different vulnerability index according to their conservation state. This is the case of the Royal Alcazar in Seville with high vulnerability index (50%) in the main entrance, moderate vulnerability index in the section in Agua Street, low vulnerability index in the AbdelAziz Tower, the Silver Tower, the Gold Tower and the Cabildo Square and very low in Juderia Street.

Bare rammed earth structures present higher vulnerability indexes than those limed or lined with bricks or stones. Special care should be taken in the Silver Tower in Seville due to the use of clinker cement in the restorations carried out in the past.

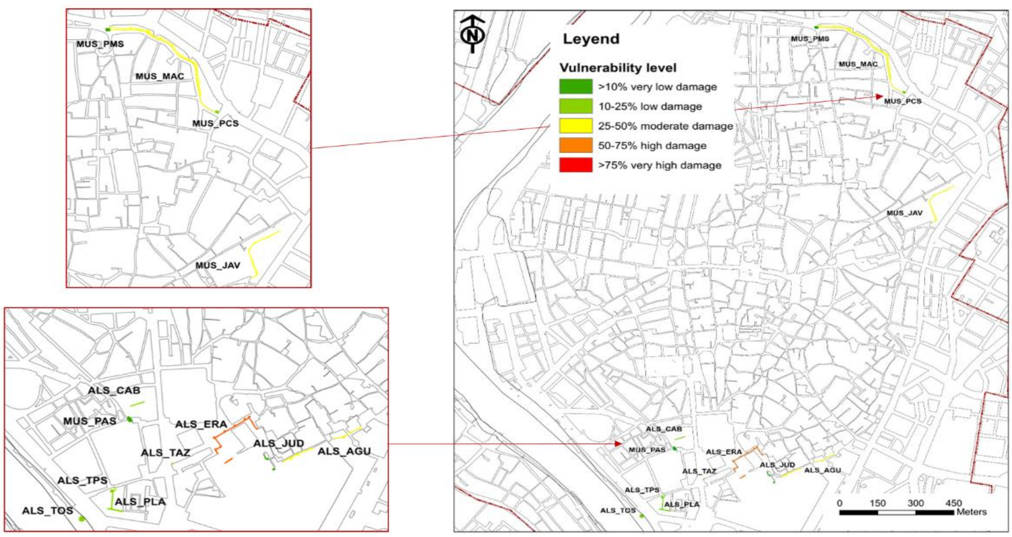


Figure 9: Vulnerability index Map of defensive fences in Seville.

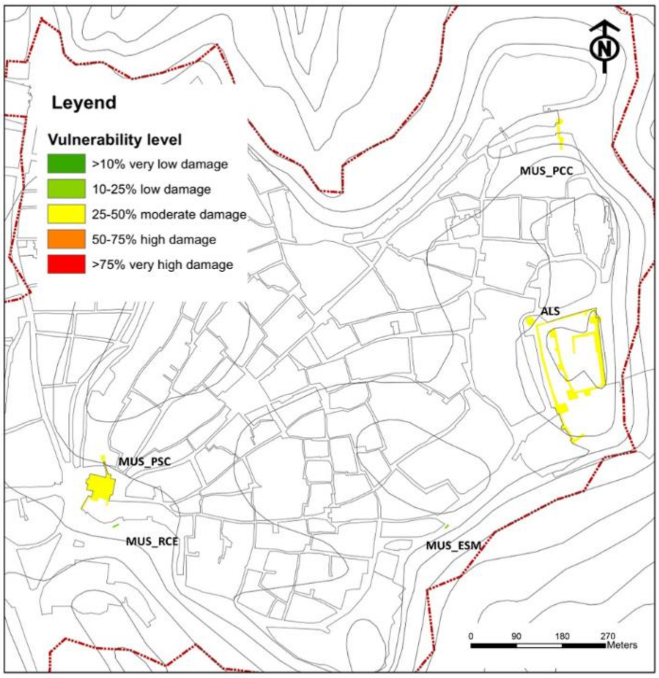


Figure 10: Vulnerability index Map of defensive fences in Carmona.

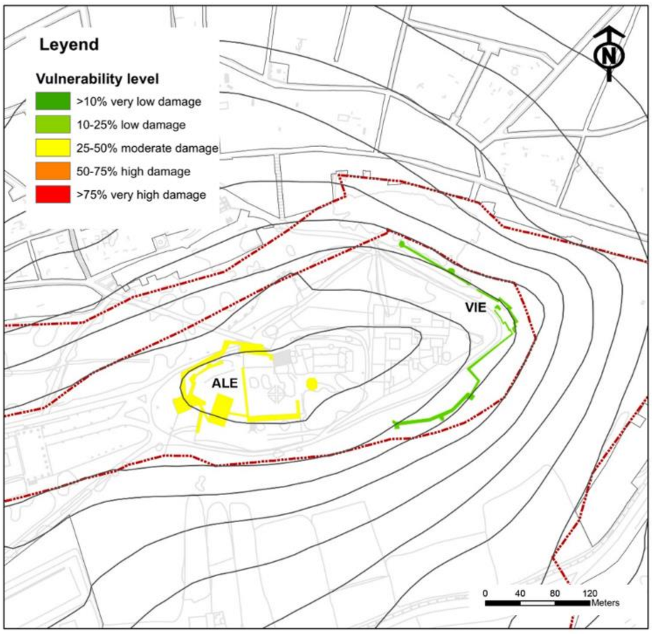


Figure 11: Vulnerability index Map of defensive fences in Estepa.

4. CONCLUSIONS

The methodology employed for assessing the vulnerability of rammed earth fortifications located in historical centres is useful and low-cost, allowing us a quick and efficient way to study their main threats and their state of conservation. It was necessary to divide and classify urban fortifications in small units that could be analysed, in this case the classification of UAMs was designed according to the criteria of the Spanish Plan of Defensive Architecture.

For the first time, vulnerability matrixes we adapted to carry out the diagnosis in rammed earth fortifications in bare or mixed walls, and represented by Georeferenced Information System (GIS). Vulnerability index maps are useful for urban development policies and risk mitigation strategies.

The main weathering forms found in the three cities were related to environment (underground water or rainwater), constructive techniques or the use of non-compatible materials in restorations, and in lower percentage wind, temperatures, disuse or biological colonization.

Different constructive typologies such us bare rammed earth, lime and lined with brick and stone were recorded, as well as the use of stone and brick as reinforcements. These materials minimize the occurrence of sanding and detachment associated to underground water but using stone appear other weathering forms such as iron-rich patina, alveolization and high alveolization that affect the reinforcements. Structures with different materials are more complex and the most vulnerable, followed by the earth rammed structures. The lined and lime structures are the least vulnerable.

The current uses and the conservation of these fortifications show a complex scenario, where a preventive conservation plan as a whole system is recommendable. Moreover, those zones with high vulnerability index (>50%) need further studies to be carried out by expert technicians before a year, while preventive conservation and maintenance measures carried out periodically, are recommended for the units with moderate vulnerability degree. Finally, inspections and monitoring are advisable for units with low or very low vulnerability index which are well preserved. Further studies would be interesting to incorporate 3D models and IR thermography in the process of analysis and surveillance.

Finally, most fortifications analysed have been restored using different materials and constructive techniques. It is recommendable to use compatible materials and techniques due to problems and weathering forms observed.

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