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Climate change impacts on cultural heritage building foundations in Western Andalusia

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ABSTRACT: The purpose of this study is to present the consequences of climate change, especially temperature increase, drought, sea-level rise, and coastal flooding or earthquake increase, in the foundations of four heritage buildings in Andalusia, to enhance the importance of risk assessments of heritage to contribute to disaster resilience.

The climate-related hazard that may thrive as climatic stressors on outdoor cultural heritage have been studied, as the decrease in soil moisture leads to a subsidence and shrinkage effect of the surface clays affecting such important heritage buildings as the Church of the Sagrario, next to the cathedral of Seville. Other hazards analyzed in the study cases include a slight rise in sea level at the mouth of the Guadalquivir and the recent erosion of coastal buildings such as the Chipiona Castle or the castle of Utrera, all of them placed on Western Andalusia.

1 IMPACTS OF GRADUAL CLIMATE CHANGES ON OUTDOOR CULTURAL HERITAGE

Climate change has been proved to be one of the major underlying causes for the increasing vulnerability of cultural heritage. Their continued preservation requires understanding these impacts to elaborate a response. Concern over this issue has led international organizations to identify climate change as a threat to cultural heritage and to encourage the implementation of measures to mitigate its effects. In 2007 UNESCO World Heritage Centre adopted its “Strategy for Reducing Risks at World Heritage Properties”, to improve the World Heritage site’s protection from natural hazards. In 2020 ICOMOS Climate and Ecological Emergency Statement calls for urgent action to safeguard cultural heritage from the potential impacts of climate change and cultural heritage risk assessment.

This document reviews the damage to four historic buildings located in Andalusia that are directly related to climate change. Climate parameters, risk factors, and identified impact reviewed in this paper are summarized in table 1.

Some of these physical impacts on cultural heritage have been analyzed in four very significant buildings located in Andalusia, such as the walls of Sevilla or the Chipiona and Utrera castles.

2 THE WALLS OF SEVILLA

The walls of Sevilla, whose origin is debated between the 12th and 13th centuries AD, was one of the largest fortified urban enclosures in the Middle Ages in Spain, is one of the most important rammed-earth buildings in Andalusia. From 2020 onwards, some interventions are being carried out in the sector of the Macarena Wall, which have allowed the study of its materials, and more accurately, the influence of water, either as an external weathering agent or as the moisture content in the material,

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Table 1. Parameters of climate change and physical impacts.

Parameters	Climate Change Risk	Impacts on cultural heritage
Rise in temperature	– Warmer temperatures – Stronger heat waves – Melting of the Polar Ice Caps – Thermoclastism	– Flooding of coastal areas. – Loss of marshlands due to the occupation of saltwater.
Variations in precipitation patterns	– Decrease in annual rainfall. – Greater drought. – Concentration of dunes.	– Decrease in the water table. – Subsidence in sandy soils leading to settling. – Decrease in soil moisture and shrinkage in clay soils. – Occasional instabilities due to heavy rainfall affecting slopes. failure of retaining structures due to insufficient drainage in retaining structures – Salt crystallization cycles
Wind	– More dangerous hurricanes. – Winds with higher speeds.	– Increased horizontal stresses and moments in foundations due to hurricanes and winds in general with higher speeds
Earthquakes	– Fracking application	– Increase in small earthquakes

has been analyzed for mechanical properties, durability or within the cycles crystallization of salts in rammed earth. The test run in some of these works has proven that water plays an important role in weathering processes, as salts migrate when dissolved in water, from the inside to the surface, where they crystallize. Different impacts are analyzed below.

2.1 *Thermoclastism*

Thermoclastism results from the expansion and contraction of surface mineral grains due to thermal variations caused by seasonal variations and diurnal changes in air temperature and direct insolation (Germinario, Andriani, y Laviano 2015).

On the other hand, salts migrate when dissolved in water, from the inside to the surface, where they crystallize. This process usually leads to a higher concentration of salts on the surface, where the increase in volume by crystallization internally stresses the pores of the material, causing its fracture. Weathering, sandblasting and disintegration of the outer layers are usually the result of this loss of cohesion (Martín-del-Rio et al. 2021).

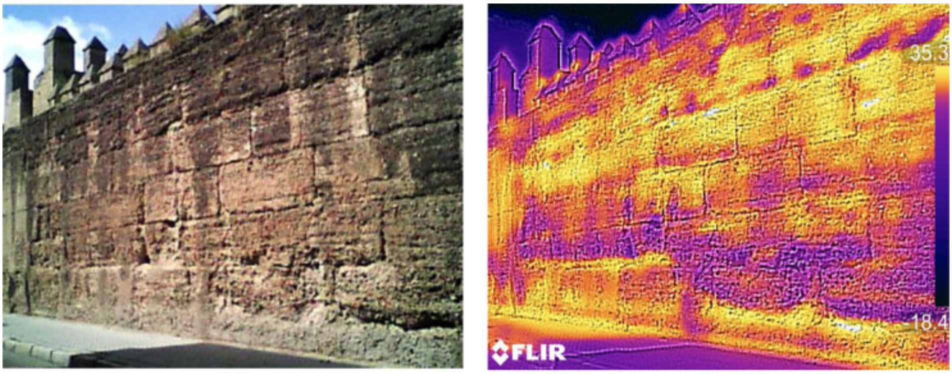
2.2 *Biological degradation*

Changes in humidity influence the growth of microorganisms in stone and wooden heritage materials. The growth of small plants can contribute to the biodegradation of these elements. The photograph above shows the growth of small plants in the battlements and several stains of humidity on the wall. Loss of mass is also quite significant in certain areas, as can be seen in the photograph (Figure 1).

2.3 *Salt crystallization cycles*

It can be established that the main cause of the degradation of the wall of Seville is the loss of material and physical-chemical weathering. The cause does not lie in the material composition or poor performance of the original materials, but rather in the presence of water in the walls, its transport, and the crystallization cycles of the salts. This effect worsens when the hygrothermal behaviour is altered, mainly due to climate changes. The following images show the different temperatures on the surface of the wall due to the humidity of the rammed earth (Figure 2).

Figure 1. Biological degradation in the Macarena wall.



(a) (b)

Figure 2. Thermographic image (b) and real image (a) of the external face of the wall generated by a Flir T420bx model camera (images taken on 4/9/2019 at 4:33 p.m.)

3 THE CASTLE OF CHIPIONA

This castle is located in Chipiona, province of Cadiz, in the south of Andalusia. Its origin, although some authors establish in the thirteenth century, should be placed in the mid-fifteenth century as a result of the rapid economic growth suffered by the locality with the exploitation of the vineyard and the constant incursions of Turkish, Berber and French pirates on the coast of Cádiz, which would certainly oblige Rodrigo Ponce de León, lord of these lands, to build the castle as a defensive element of the closest sector of the municipality to the estuary of the Guadalquivir River.

Different pathologies that have affected the building throughout its history and some of them are briefly described in this document.

3.1 *Sea level rise*

Rising sea level (SLR) poses a significant threat to cultural heritage situated within coastal areas; 19% of UNESCO World Heritage Sites (WHS) globally could be lost to inundation (Marzeion y Levermann 2014).

To date, studies in Europe on this topic have focused on the Mediterranean region. (Reimann et al. 2018) investigated the potential risk of flooding due to SLR in this region and Ravanelli et al. (2019) focused on the archaeological site of Motya in Sicily (Reimann et al. 2018). Investigating similar scenarios in other areas, (García Sánchez, García Sánchez, y Ribalaygua 2020) mentioned that SLR is threatening coastal fortifications in the Canary Islands.

SLR will also increase the frequency of extreme events, such as storm surges that result in higher waves, and affect the balance of sediments in coastal regions and the stability of underwater archaeological sites and monuments (Wright 2016).

The effect of SLR has been studied in the coastal area of Chipiona. Chipiona Castle has been suffering the consequences of the SLR during the last few years, and some of the foundation has been removed by the water. Marked with an ellipse is shown the castle position. The front area of the castle has nearly disappeared due to recent strong tides; in the last 5 years, large holes have appeared under the north retaining wall because of rising tides and waves.

This event could be related to the ice melting at the poles, the water from the melted streams flows out of the glacier contributing to the sea level rise. In Andalusia, the sea level will rise from 0.50 m to 1.0 m. At least 20 to 50 cm of sea level will rise on the coast of Cadiz and Huelva. Because of this rise, species such as the Iberian lynx will become extinct from their natural habitat in the marshes of the Coto de Doñana and the main impacts on coastal areas will be temporary or permanent flooding, increased erosion, loss of wetlands and brackish water intrusion. The images below show the results of these on the walls of the castle of Chipiona (Figure 3).

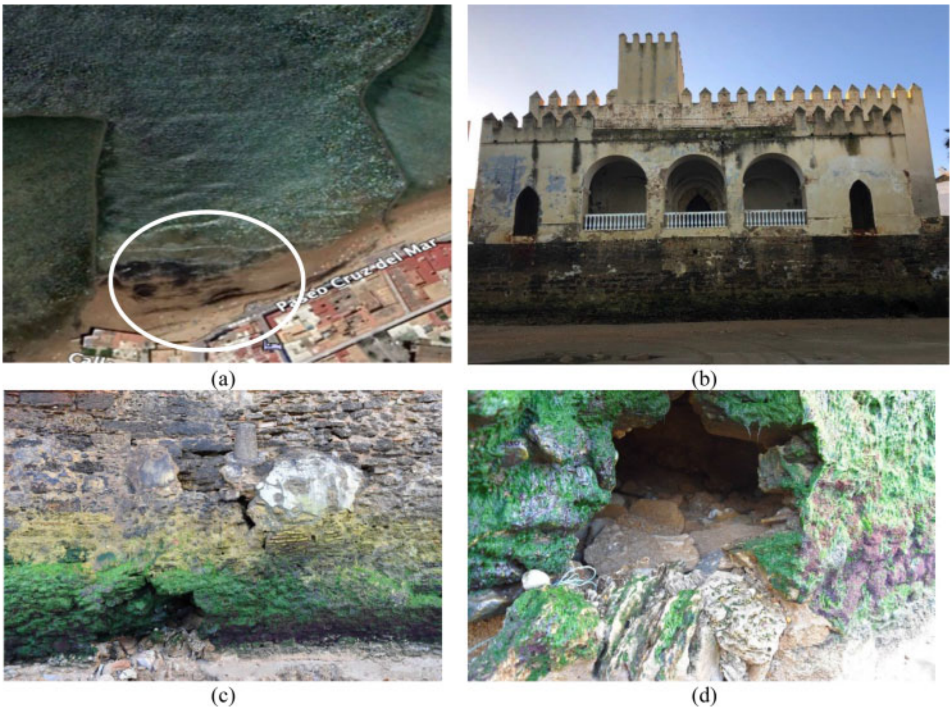
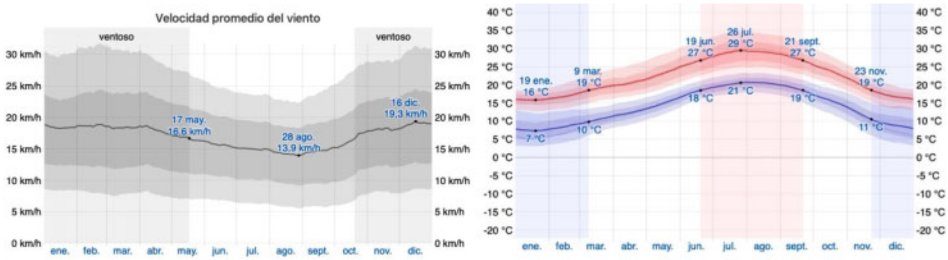


Figure 3. Chipiona Castle: Location (a) and a general view from 2021 (b). Hole under the foundation in two different scales (c and d).

The waves are washing away the castle’s foundation blocks and leaving large holes of more than 3 meters wide and deep, which may affect the stability of the stone walls in the medium and long term. The climatic conditions regarding temperature and wind in the year 2020 are likely to corroborate these hypotheses (Figure 4).



(a) (b)

Figure 4. Average wind speed in Chipiona (a). The average temperature in Chipiona in 2020 (b).

Around 50% of the surface area of Malaga’s coastal neighbourhoods such as Sacaba Beach, San Carlos, Torre del Rio and San Andres are exposed to sea flooding (Gil-Guirado et al. 2022). The Chipiona Castle is being affected by recent strong tides. In the last 5 years, large holes have appeared under the north retaining wall due to the effect of rising tides and waves. Quantifying uncertainty in shoreline projections can be crucial and it is necessary for heritage building management and its adaptation at long-term time scales. The analysis of coastal impacts is essential in order to assess climate-related risks in heritage located in coastal areas (Alvarez-Cuesta, Toimil, y Losada 2021).

4 THE CASTLE OF UTRERA

Utrera is a municipality in the province of Seville, Andalusia. The construction of the castle has been dated around 1398, and there are documents about repair and improvement work in 1420 and 1444 on the external elements of the tower of homage.

From the 16th century onward and after the loss of value of the site as a military site, it fell into a process of abandonment and decadence. The tower of the tribute, attached to the castle walls, has been restored and is in a quite acceptable condition, although it is exposed to the inclement weather of the area. As for the materials used for its construction, the walls are made of rammed earth and the corners of the tower are built with stone masonry. This building has been introduced in this paper due to its pathologies, which are directly related to SLR, the temperature increase and the effect of the wind on the damaged walls.

4.1 *Warmer temperatures. Stronger heat waves*

In 2021 we have already had temperatures over 40° in Seville in June. An increase of 1°C degree in the average temperature in Seville this summer had been predicted. The average temperature of the planet has increased only 0.85°C since the beginning of the industrial revolution. In Seville for instance, we reach sometimes, fortunately only occasionally, 46° in the month of July. However, studies have informed us that if strong measures are not taken, we will rise to 50° in July in 2100. At the very least, the temperature will rise by 2°C, reaching 48°C in July. According to an ongoing temperature analysis conducted by scientists at NASA’s Goddard Institute for Space Studies (GISS), the average global temperature on Earth has increased by a little more than 1° Celsius (2° Fahrenheit) since 1880. Two-thirds of the warming has occurred since 1975, at a rate of approximately 0.15–0.20°C per decade. High temperatures are also causing the sandblasting of mortars, masonry walls, and slopes (Figure 5).

Figure 5. Sandblasting of the surface of the Utrera Castle.

4.2 *More intense storms*

Analyzing the data from the Spanish Meteorological Agency, and after plotting a chart with the linear regression of annual rainfall, a decrease in the average over the last 65 years can be noted, every year the average is 2.1 to 2.3 liters of precipitation less, so decrease in rainfall is happening.

Regarding the annual data, we consider a second step in the treatment of the data using the Fast Fourier Transform (FFT), as shown in the figure above (Figure 6). The main frequency is 0.149. This means that the recurrence period of heavy rains is approximately 6.7 years, with a second period with a very similar amplitude of 0.125, a period of heavy rains every 8 years.

4.3 *Shrinkage of expansive soil*

Shrink–swell is the volume change that occurs due to changes in the moisture content of clay-rich soils. These soils can absorb large amounts of water after a rainfall, causing swelling. On the contrary, they can also become very hard when they are dry, resulting in shrinkage and cracking of the ground.

In Andalusia, shrinkage –swell damage far exceeds earthquake damage. The church of The Sagrario, placed next to the cathedral of Seville has had to be underpinned due to the settling (shrinkage) that has mainly affected the corner of the Avenida de la Constitución (Figure 7). The Columbus Library of the Cathedral of Seville has also had to be reinforced due to ground movements.

The movement of the soil of several decimeters was measured in a layer of clay 3–4 m thick (Diz-Mellado et al. 2021). In addition to the problem, the process is slow, but not uniform throughout the foundation, and is usually greater at the border of the building because the perimeter soil dries out faster than the soil under it, given that the building itself prevents the water from evaporation.

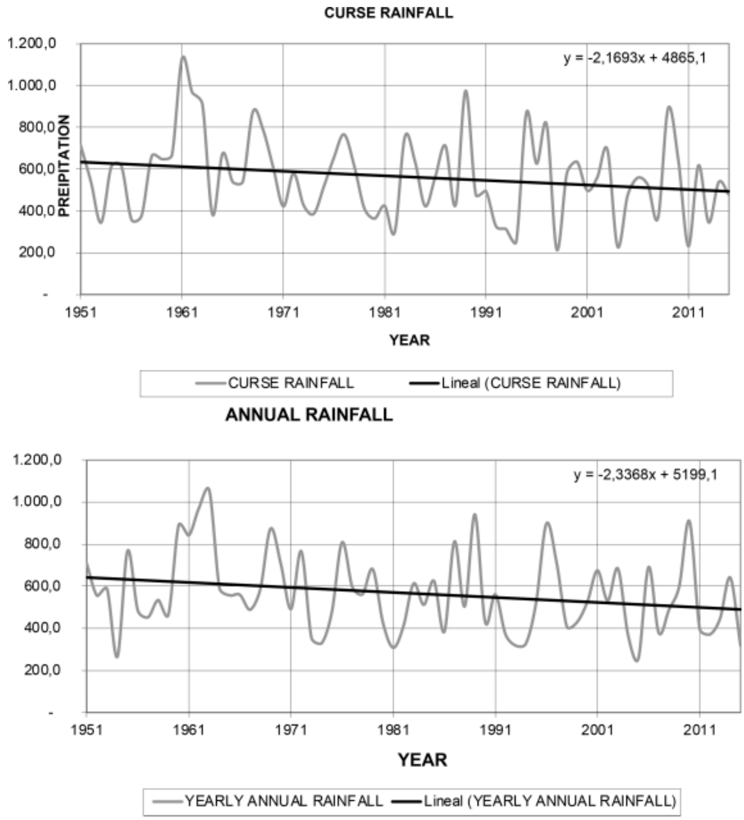


Figure 6. Precipitation regimen in Utrera.

(a) (b)

Figure 7. Settlement at the corner of the building due to soil shrinkage (a). Detail with topography mark installed on the building during the year 2021 (b).

Figure 8. Seville ramparts could be affected by the earthquakes.

4.4 *Increase in earthquakes*

The incidence of glacial earthquakes is increasing, especially in the summer months when glacial ice melts faster. (Ekström G 2006). The loss of glacial compression causes an increase of up to twice as many earthquakes of magnitude up to 5.1 on the Richter scale.

The fall of large blocks of glaciers when they melt and fall into the sea is causing a considerable increase in tsunamis in nearby coastal areas, although, fortunately, of small magnitude.

On the other hand, fuel prices are making it profitable to obtain oil and gas from the ground using the "fracking" technique. The installation of several extraction wells is underway less than

10 km from Seville in the town of La Rinconada. The “fracking” system will most likely produce earthquakes, even if they are of small magnitude, but they can damage heritage buildings through their foundations (Sun et al. 2019).

One of the monuments that may be most affected will be the Almohad Wall of Seville in the Macarena area since it is composed of the earth as a construction material. There is no masonry foundation, and it is simply buried 2 meters into the ground. The location of the Almohad wall of the Macarena is just north of the city centre and the closest to the Rinconada (Figure 8).

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