

1 **Assessment of heritage rammed-earth buildings. The Alcázar of King Don**
2 **Pedro I (Spain).**

3 Jacinto Canivell^a *, Reyes Rodríguez-García^b, Ana González-Serrano^c, Ana
4 Romero-Girón^d

5 Prof. Jacinto Canivell. *Dept. Architectural Constructions II. Higher Technical School of*
6 *Building Engineering. Universidad de Sevilla. Av. Reina Mercedes 4a, 41012. Seville, Spain.*
7 *Orcid: 0000-0001-7636-102X. Email: jacanivell@us.es . Tel: +34 954556662. **
8 *Corresponding author.*

9 Prof. Reyes Rodríguez-García. *Dept. Architectural Constructions I. Higher Technical School*
10 *of Architecture. Universidad de Sevilla. Av. Reina Mercedes 2, 41012. Seville, Spain. Email:*
11 *rgarcia@us.es. Tel: +34 954557463*

12 Prof. Ana González-Serrano. *Dept. Architectural Constructions I. Higher Technical School of*
13 *Architecture. Universidad de Sevilla. Av. Reina Mercedes 2, 41012. Seville, Spain. Email:*
14 *gserrano@us.es. Tel: +34 954557463*

15 Ana Romero-Girón, PhD. *Dept. Architectural Constructions I. Higher Technical School of*
16 *Architecture. Universidad de Sevilla. Av. Reina Mercedes 2, 41012. Seville, Spain. Email:*
17 *anaromerogiron@gmail.com. Tel: +34 954557463*

18 **ABSTRACT**

19 The conservation and maintenance of earthen buildings is crucial, especially when dealing with
20 heritage sites. This normally involves considerable effort in preliminary studies, which must be
21 well-planned in order to efficiently manage any restoration. This case study proposes a
22 methodology to briefly assess the current state of a historical rammed-earth wall to bring to
23 light specific information regarding approaches for subsequent studies or decisions. This
24 methodology is based on the study of damage and risk as a tool to swiftly discern critical areas
25 or issues needing immediate attention. The procedure is illustrated on an outstanding heritage
26 building: the Alcázar of King Don Pedro I in Carmona (Seville, Spain). Our conclusions
27 confirm that this methodology constitutes an efficient and straightforward means to obtain not
28 only a preliminary assessment of rammed-earth walls, but also objective and useful criteria for
29 decision-makers.

30 Keywords: rammed earth, preliminary studies, damage, vulnerability, risk
31 assessment, preventive conservation.

32 **1. Introduction**

33 Earth has traditionally been used as a construction material by numerous countries and
34 communities in the past. This rich legacy is usually at a high risk of deterioration, largely due
35 to a lack of maintenance or to improper conservation techniques. This heritage is especially
36 abundant in the Iberian Peninsula, where a great number of fortresses were built using the
37 rammed-earth technique (Gil-Crespo, 2017). Although certain specific characteristics of this
38 technique depend on the historical period, all military rammed-earth (RE) constructions share
39 common features, such as the type of construction materials (presence of abundant gravel and
40 lime), a modulated height of the courses (85-90 cm), and the use of a continuous formwork,
41 which is normally replaced once each lift is finished.

42 The behaviour of earthen construction has been widely discussed, beginning with the
43 international research meeting first hosted by Icomos in 1972. The first authors on the topic
44 (Hughes, 1983; Viñuales, 1970) argued regarding the main weaknesses of earthen
45 constructions, and determined water, humidity, and erosion as the key factors involved in their
46 deterioration. Later, other authors proposed ways of conducting damage analysis (Illampas,
47 Ioannou, & Charmpis, 2013; Laurence Keefe, 2005; Monjo Carrió, Maldonado Ramos, Carrió,
48 & Ramos, 2001; Rotondaro, Monk, Ramos, & Rodrigo Ramos, 2002). Contributions of a more
49 specific nature strove to systematize the analysis by means of varying protocols and procedures
50 (Aktas & Türer, 2011; L Keefe, Watson, & Griffiths, 2001; Rodríguez, Monteagudo, Saroza,
51 Nolasco, & Castro, 2011). Nevertheless, those studies dealt with earthen construction and
52 techniques in general terms, rather than specifically with RE. Furthermore, the particular aim
53 of those cases was to catalogue prevailing failures and deterioration mechanisms and their
54 suitable repairs. Hence, these procedures provided a broad state of conservation. Nonetheless,

55 it was complex to prioritize actions in a timely manner since only damage and its causes were
56 classified.

57 Repair techniques for earthen construction have been proposed and discussed by many
58 authors (Ashurst & Ashurst, 1988; Fodde & Cooke, 2013; Graciani et al., 2012; Laurence
59 Keefe, 2005; Pearson, 1997; Vegas, Mileto, & Cristini, 2014). However, these measures have
60 been treated separately, and have never been integrated together with damage and risks in a
61 single assessment procedure.

62 During the last decade, the importance of vulnerability and risks and preventive
63 conservation has been highlighted when dealing with earthen architecture; since these factors
64 may constitute measurable parameters that would provide a more accurate explanation of the
65 state of conservation and the expected evolution of damage (ISCARSAH-ICOMOS, 2000;
66 Monjo Carrió, 2007). Although a number of applied methodologies have arisen that focus on
67 decision-making in heritage conservation issues (Kima et al., 2010; Ornelas, Guedes, & Breda-
68 Vázquez, 2018; Prieto et al., 2016; Ramos et al., 2018), especially when dealing with seismic
69 hazards (Barros et al., 2018), no procedure has yet been proposed to preliminary evaluate both
70 damage and risk in the case of earthen construction specifically for rammed earth (RE) heritage
71 construction.

72 Therefore, this paper proposes a methodology based on an expert evaluation to assess
73 the state of conservation of historical RE buildings and to aid in the decision-making concerning
74 which criteria or techniques are the most suitable for each situation. To this end, a procedure
75 based on qualitative parameters is proposed in order to indicate the main deterioration processes
76 and risks. As an outcome, an adapted technical criterion for conservation is suggested.

77 The proposed method is illustrated on one deteriorated area of the Alcázar of King Don
78 Pedro I (Fig. 1). Despite several historical refurbishments, the building remains almost in ruins.
79 The analysed sector corresponds to the west side of the inner perimeter wall (Fig. 1), which
80 dates from the 12th century. In the Iberian Peninsula, there are a great number of buildings

81 dating from this Almohadian period (12th-13th century), especially those regarding the territorial
82 defence, such as city walls, fortresses, castles and watchtowers. These military buildings
83 usually run a high risk of deterioration, due in part to certain factors related to the construction
84 materials, but mainly owing to the lack of maintenance. This case study was therefore selected
85 thanks to its construction representativeness and to its inclusion in a short-term restoration
86 program. The state of conservation of the selected building, which presents a variety of
87 significant damage and circumstances, is also of major interest, since the proposed analysis
88 could serve as an example for the reproduction of similar studies.

89 Fig. 1.

90 **2. Methodology**

91 The proposed methodology is based on the work of Canivell (2012) and is organized into two
92 different phases that corresponding to the work undertaken on site (Phase 1), and the subsequent
93 analysis results (Phase 2). Each phase is composed of several tasks (Table 1).

94 Table. 1.

95 The procedure described in this research shares only two aspects with the aforementioned
96 proposal. Although both methodologies deal with damage and risk assessment, Canivell (2012)
97 extends its evaluation to specific construction aspects of the RE military buildings, such as
98 dimensional and material features, and construction techniques. Regarding the damage analysis,
99 the parameters herein discussed have been adapted to match the singularities of the case study.
100 For instance, the failures related to the loss of cohesion have been divided into three categories
101 depending on the rate of damage. Other improvements concern the procedure of assessing the
102 risks, since the proposed methodology has changed the internal relations between the
103 parameters analysed. This issue is addressed in detail in Section 2.2.2. The common objective
104 is to reach a definition of level of risk by means of evaluating several risk factors. The current

105 analysis method uses a weighted sum based on a critical examination in order to obtain an
106 overall assessment of the risk factors (RFs), instead of obtaining radial plots as proposed by
107 Canivell (2012), which may involve certain inaccuracies when comparing different sectors.

108 **2.1. Phase 1: Data gathering**

109 The first phase deals with the gathering of singular wall features by means of on-site surveys.
110 The first task consists of obtaining the wall's dimensional parameters and roughly assessing the
111 mass loss. To this end, when the wall is highly eroded, it would be necessary not only to
112 represent each elevation but also to provide cross-sections as an essential tool to quantify how
113 the wall thickness is also affected.

114 For RE walls, each wall elevation is organized into several horizontal and vertical
115 sectors where failures and repairs may easily be located within a grid. Since horizontal joints
116 between courses usually mean a discontinuity, horizontal sectors correspond to a single course
117 of approximately 0.9 m in height. The span of the vertical sectors depends on the analytical
118 precision required and the concentration of the rate of failure. The grid designed for the case
119 study is shown in Figure 2.

120 Fig. 2.

121 The grid consists of nine horizontal sectors corresponding to each course, grouped in
122 sets of three (from Sector 1.1 to 3.3). Since, in this case, the failure concentration is high, the
123 vertical sectors cannot span a wide area, and they have therefore been set at four metres long
124 (from Sectors A to G). Since weathering can be considered a critical cause of damage for RE,
125 each façade (east and west) is analysed separately. Finally, 14 critical areas have been
126 identified, where failures are more intense. These are studied in detail by means of 14 cross-
127 sections. Figure 3 shows the most representative cross-sections, where the original hypothetical

128 profile is represented as a dotted line in order to assess the volume of RE lost. In addition, the
129 percentage of mass loss is determined from the original hypothetical profile.

130 Fig. 3.

131 For failure recognition (Task 1.2), each type of damage on the wall is identified. By
132 means of an elevation plan, each failure is located in the corresponding sector so that the overall
133 state may easily be highlighted. Damage has been organized according to its own nature and
134 the corrective measures that should be applied. The RE failures belong to three groups:
135 structural, material, and surface damage.

136 Structural failures include cracks and fissures (Ct-CI), whether they affect the entire
137 thickness or not. A crack may follow the longitudinal axis of the wall (longitudinal crack, CI)
138 or its cross-section (transverse crack, Ct). Only certain physical deformations, such as tilting
139 (T), have been considered since buckling is extremely rare thanks largely to the great
140 thicknesses of the walls.

141 Material failures are related to erosion and the cohesion of RE. In general, erosion is
142 caused by the combination of certain external agents (water, wind, and variations in
143 temperature). This kind of damage, usually repaired by filling with mortars, has been classified
144 into two types according to their repair, so that once damage is assessed, it is easy to propose
145 straightforward repair techniques. Water ponding damage (E1) is mainly caused by water
146 gathering in joints and putlog holes. Surface erosion (E2) involves slight erosion by water
147 runoff and weathering in which fine particles of soil are washed away, resulting in a very rough
148 surface. Additionally, damage directly related to mass cohesion has been classified depending
149 on the level of cohesion that remains and hence on the possible repair technique. Spalling and
150 flaking (LC1, LC2) implies loss of the mass in chunks or flakes that may come off easily. In
151 the case of disintegration (LC3), the loss is greater and implies an increase in porosity and hence
152 a considerable amount of RE, including coarse particles, can easily be brushed away. Finally,

153 sanding (LC4) is a result of the total lack of cohesion and a greater loss of material can easily
154 be removed. In contrast to erosion, material loss (ML) may involve a thicker replacement of
155 material. The classification ML2 indicates the restoration of entire or half RE boxes by means
156 of a system of formworks, whilst ML1 involves a depth of up to 25 cm, which could be repaired,
157 for example by consecutive layers of mortar.

158 Surface failure only refers to damage in the most external layer and no loss of material
159 is implied. Although its impact is relatively low, in the long term it may exponentially increase
160 the risk of developing further damage. As the first stage, dirt (D) consists of the accumulation
161 of fine particles in pores and voids, increased by capillary migration. When no cleaning has
162 been undertaken, a crust (C) occurs, normally involving fungus and lichen or even pollution
163 and intense cleaning may be required.

164 Damage characterization enables experts to ascertain the current state of conservation
165 and to propose corrective measures. Nevertheless, a step forward is needed when other
166 (preventive) actions must be additionally considered. In this regard, risk and vulnerability issues
167 are applied to state the possibility of damage occurring and to prioritize the various actions.

168 The purpose of Task 1.3 is to study and acknowledge RFs whose results are to be used
169 in Task 2.2 to carry out the entire risk management procedure. The aforementioned task is
170 shown on the left-hand side of Figure 5. Risk factors comprise the main causes of deterioration
171 of earthen construction. First, three categories of vulnerability are considered: (I) vulnerability
172 to water as the incapacity to withstand damage where the filtration within the wall or the
173 pounding of water on the wall is the main cause; (II) physical vulnerability; and (III) structural
174 vulnerability, as the weaknesses incurred from supporting damage from erosion and instability,
175 respectively. Each category concerns certain qualitative RFs that are deeply involved in the
176 durability of RE buildings (Table 2). After having set the mechanism to be analysed, RFs related
177 to each vulnerability are determined and classified as material (M), external (Ex), and anthropic
178 (A), whether they refer to concerns of the wall itself or not (see Table 2). The building is then

179 divided into sectors for their assessment in terms of risk. The assessment of these RFs may refer
180 to the same vertical division in sectors as that proposed for damage analysis. Each RF is given
181 a number that corresponds to the deficiency level; this is discussed in Task 2.2.

182 Table 2.

183 **2.2. Phase 2: Assessment**

184 This phase deals with the evaluation of all data gathered on-site, which is mainly related to
185 damage and RFs. First, the factors involved in the deterioration process are analysed and the
186 origin and causes of damage and potential risks are assessed. Depending on the damage and
187 risk, a number of corrective or preventive strategies may be proposed.

188 *2.2.1. Task 2.1: Failure analysis.*

189 Once damage is pinpointed in Task 1.2, it is necessary to link each failure with the
190 corresponding cause (see Table 3), and to indicate the worst deterioration processes (Task 2.1).
191 Since different failures are usually closely related, the prevailing order must be decided so that
192 the repair of the initial damage makes it easier to remove the remaining failures.

193 In order to accomplish Task 2.1, the failures surveyed in Task 1.2 need to be represented
194 on an elevation plan in accordance with the stated classification (Fig. 4). In addition, failures
195 are arranged in a table according to their corresponding sector along with the probable causes
196 of damage (see Table 3). In Figure 4, only one vertical sector is represented, which is where the
197 damage is the most highly concentrated, although the analysis has been carried out for the whole
198 length of the wall. In Section 2.1, which corresponds to the data-gathering task, every incidence
199 of damage and its corresponding code are discussed. Figure 4 together with Table 3 explained
200 in detail in Section 3, where prevailing damage is ascertained and the corresponding causes are
201 proposed for all the sectors analysed. Nevertheless, it should be noted that, in such cases, the

202 damage is rated in one of two categories (low and high) depending on the development and
203 intensity of the surveyed failure. For instance, Figure 4 represents two sectors, where sector Aw
204 is considered as high-damage, and Ae as low-damage, since the former sector presents failures
205 that are more critical and more widely spread (loss of mass, LM2). In Section 3, Table 3 shows
206 the results of the damage survey and the category of each sector depending on the rate of
207 damage.

208 Fig. 4.

209 2.2.2. *Task 2.2: Risk assessment*

210 The procedure used in Task 2.2 (see Fig. 5), which is based on similar proposals to those of
211 Canivell (2012), allows specialists to identify and assess the RFs involved in deterioration by
212 establishing certain levels of risk corresponding to a specific vulnerability. Thus, critical sectors
213 can be prioritized and interventions can become more efficient.

214 Fig. 5.

215 The prior evaluation of RFs carried out in Task 1.3 is used as a first step in the current
216 task, as can be observed on the left-hand side of Figure 5. Task 2.2 deals with the evaluation of
217 the RFs introduced in the phase (Task 1.3) and is explained on the right-hand side of the
218 aforementioned figure. Nonetheless, the details and implications of this assessment are
219 discussed in detail in Section 3. Depending on the vulnerability considered, the level of
220 deficiency (LD) is obtained for each RF through criticality analysis (see Table 2). Criticality
221 analysis involves the assessment of both the determinism and the scope of the possible damage
222 in order to establish the weight of each RF: ranging from null-RF to key-RF. The weighted sum
223 of all LD is equal to the total LD, namely LD^t , for the sector and the vulnerability considered.
224 At this point, pairs of parameters are crossed in predesigned matrices of risk in order to obtain,
225 in the first place, the level of probability (LP), with LD^t and the level of exposure (LE), and

226 secondly the level of risk (LR), with the LP and the level of consequences (LC). This level of
227 exposure is determined through a risk matrix and considers the frequency and severity of
228 possible damage. The level of consequences is obtained by means of an evaluation of four
229 anthropic RFs: heritage value, economic value, human damage, role in building. Since three
230 vulnerabilities have been considered for risk assessment, the LR is detailed in terms of the
231 hazard upon water (LR-W), physical erosion (LR-Ph), and structural stability (LR-St).

232 A scale of five numbers (from 1 to 5) has been established to assess LD, LP, LC and
233 LR. For instance, the highest number in the case of LR determines a higher risk, and therefore
234 a greater chance of damage occurrence. Even the LD for each RF is evaluated within the same
235 scale, thereby associating each number with a predesigned situation. Once the types of failures,
236 their causes, and their risks are established (Tasks 1.2, 1.3, 2.1, 2.2), the corresponding
237 diagnostic may be developed (Task 2.3), according to damage and LR.

238 **3. Results and discussion**

239 With regards to Tasks 1.1, 1.2, and 2.1, the failures have been surveyed, arranged in sectors,
240 and graphically represented for the whole wall. As an example of the results, Table 3
241 summarizes the failures for each sector and Figure 4 represents the damage in an elevation plan
242 of two representative sectors (Aw, Ae) and the most common failures found. The code of the
243 cross-sections represented in Table 3 corresponds to the profiles shown in Figure 3. The
244 categories of the failures (low-high) in the terms discussed in Section 2.2 are also detailed in
245 Table 3 for each sector.

246 Table 3.

247 In terms of structural stability, the failures are not serious, although several sectors (A,
248 B, C, and F) present significant cracks and loss of mass (ML1, ML2, mainly in the west façade)
249 that will probably involve a partial collapse in the medium- or long-term. Structural stability
250 would be compromised since sectors A and B are undermined and have lost almost 40% of the

251 original wall thickness (see Figure 3). Although sector F has lost 50% of the original mass, the
252 section is more stable than sectors A and B.

253 Material failure represents the main cause of the damage process. Washing erosion (E1)
254 is mainly present at the top of the wall, on top of the footing of the west façade, and in the
255 horizontal joints. Surface erosion (E2) is more critical on the west face at lower levels, in
256 contrast to the opposite face, where the surfaces remain slightly smoother. With regards to
257 mass cohesion, disintegration (LC3) has been extensively surveyed mainly in holes and cracks
258 in the lower courses. Finally, spalling, flaking (LC1, LC2), and sanding (LC4) occur in very
259 specific areas with low impact on the state of conservation. Surface damage such as dirt (D) is
260 spread all over both sides of the wall. The west face stands out since crusts (C) are extensive
261 on the top courses. Herbaceous vegetation (V) can be found in some areas at the top and on
262 lower courses of the west façade due to the greater presence of water ponding and debris from
263 the upper surfaces. Table 3 shows the prevailing causes of damage. The weathering and greater
264 exposure to rain and wind on the west face, together with the lack of maintenance, are the most
265 common origins of the damage in the RE wall.

266 The main contribution of the proposed diagnosis of failures lies in the procedure to
267 connect the arrangement of sectors to the types of damage and their qualitative categorization
268 in order to ease comprehension of the behaviour of the building and facilitate straightforward
269 decision-making. Since the damage conditions and the construction features of the case study
270 are common within this kind of built heritage, the authors believe that this procedure for the
271 evaluation of damage can easily be implemented in a wide range of cases.

272 Table 4.

273 The LD risk assessments corresponding to all the sectors are depicted in Table 4, and
274 arranged into the three vulnerabilities as reported in Section 2.2.2. These levels of deficiency
275 have been compensated by the criticality analysis, through which different weights are assigned
276 to each RF, as detailed in Figure 4 and discussed in Section 2.2. Considering the three categories

277 established for the vulnerability, it may be highlighted that, in Table 4, LDs related to wall
278 parameters (material RFs) are higher than those from external sources (external and anthropic
279 RFs).

280 Therefore, the origin of probable damage lies with the wall's characteristics. As detailed
281 in Table 4, LDs for external factors have low to moderate values with the exception of
282 topography (E8), and exposure (E9), and spatial configuration (E11), when dealing with
283 physical and structural vulnerability, respectively. As a consequence, since LC-W, LC-Ph, and
284 LC-St are all high, all RFs could also reach adverse LR. In fact, according to Table 5, the risk
285 of physical erosion (LR-Ph) is critical, mainly due to the high exposure and disintegration of
286 the material. This case study is located on the most elevated area of the city of Carmona with
287 no physical obstacles protecting it from prevailing winds. In fact, this is one reason why western
288 sectors show more LP-Ph. This implies that the probability of decay is high and the
289 consequences are serious in the short term. As depicted in Table 5, the LR for structural
290 vulnerability (LR-St) is also high in certain sectors (Aw, Bw, Cw, and Fw), although structural
291 damage remains moderate, mainly due to undermining and loss of cohesion on the western
292 façade. Nonetheless, according to the moderate LR-W (see Table 5), serious damage related to
293 water and humidity is unlikely to occur, although a more detailed study should be undertaken
294 in order to distinguish between the different types of damage: rising damp or infiltration.

295 Table 5.

296 **3.1. Correlation between damage and risk**

297 Damage and risk assessment are considered as complementary procedures in establishing which
298 repairs are to be tackled (whether they be corrective or preventive), when they should be
299 implemented, and also in establishing the recommended detail of development of the
300 aforementioned measures. In order to ease the decision-making procedure, Table 6 shows the

301 correlation between both types of assessment (damage and risk) and their relationship to the
302 measures. One of the main objectives of the risk assessment is to establish when and how to
303 implement the perceptive measures. In this regard, LR is employed to determine the urgency of
304 application either corrective or preventive measures. Hence, the greater the level linked to LR
305 (from 1 to 5, as proposed), the sooner the measures are to be tackled. Three classes of period
306 are considered for the implementation of the repairs, namely long-term, medium-term, and
307 short-term periods, whereby the third implies the greatest urgency.

308 As discussed earlier, LD^t is related to the rate of deficiencies, whether it be an external
309 or intrinsic characteristic external or intrinsic characteristics of the wall. In terms of complexity,
310 a degree of detail is therefore proposed for each solution, depending on the corresponding LD^t ,
311 whereby basic measures correspond to low LD^t , while advanced or more complex solutions are
312 associated to higher LD^t . Examples of these categories are depicted in Section 3, Table 7.

313 Since LD^t is simultaneously linked to deficiencies or failures of the wall and to external
314 circumstances, it is infeasible to apply this parameter to suggest where to carry out the repairs.
315 Therefore, both proposed categories of damage (low/high), established in Section 2.2.1, are
316 employed to decide the prevailing location of the repairs. If damage is rated high, then the
317 measures would be aimed at the wall itself and would also be designed to eliminate the
318 pathology. In contrast, measures dealing with outer conditions would be related to a low-
319 damage situation (see Table 6), and would therefore be aimed at simply controlling or limiting
320 the incidence of the damage. Alternatively, the distribution of LD between the three established
321 categories (material, external, and anthropic, depicted in Table 4) may be used with similar
322 results. Whenever the LDs of the external RFs (M1 to M14) are greater than the corresponding
323 LDs of the material RFs, then the condition of the sector indicates that the measures should be
324 aimed towards controlling an outer situation. For instance, regarding the physical vulnerability
325 shown in Table 4, the anthropic risk factor A4 (animal activity) is extreme and predominant in

326 the east façade since birds are profusely nesting. Hence, preventive measures should be
327 introduced in order to prevent further physical erosion.

328 Table 6. Classification of measures according to the results of the damage and risk
329 assessment.

330 In the case of earthen buildings, the procedure for the evaluation of risk may be put into
331 practice in other cases since the categories of the selected RFs can be directly applied under any
332 circumstances. Likewise, similar relations between the parameters discussed (LD, LP, LR) may
333 be established in order to achieve a detailed diagnosis of the behaviour of the building given
334 the probability of damage occurring.

335 **3.2. *Diagnosis and preliminary proposal of measures***

336 In general, as analysed in the previous section, weathering and the lack of maintenance
337 have led the wall to its current state of deterioration, and have considerably increased the risk
338 of further damage. Once all this input data is available, it is therefore feasible to design various
339 strategies to deal with current and potential problems. In this regard, corrective repairs are
340 proposed in relation to current damage (Task 2.1), which take into account the scale of LD,
341 from moderate to extreme (Task 2.2). Concerning the corrective aim, measures should be
342 undertaken when the failure analysis indicates highly damaged areas. Depending on the causes
343 (see Table 3) related to each failure, it would then be possible to decide, in a more precise way,
344 which corrective repair is the most appropriate.

345 With regards to material failures represented in Table 3, erosion is widespread as are
346 spalling (LC1), flaking (LC2), and loss of mass (PM1). Although these failures are not critical,
347 certain corrective measures must be implemented. On the other hand, the combination of
348 significant disintegration (LC3), in the vertical sectors A, B, and F and in the dovecote (sectors
349 De, Ee, and Fe), and heavy loss of mass in the west façade (sectors Aw, Bw, Cw, and Fw),
350 determines a major risk that should be countered by means of repairs of a more serious nature.

351 In comparison to physical failures, surface damage is less relevant since this type of
352 failure seldom affects the core of the RE and hence seldom affects its stability. Furthermore, as
353 established in Table 6, a high-damage sector would demand corrective measures to be
354 implemented in the wall, instead of simply modifying outer conditions. Hence, in sectors Aw,
355 Bw, and Fw (categorized as highly damaged), crust and dirt should be removed by directly
356 treating the wall. In relation to low-damage sectors (see Table 3), since the situation is less
357 critical, measures addressing dirt, crust, and vegetation may be designed not to completely
358 eliminate the damage, but instead to control it. In this respect, surface failures in high-damage
359 sectors should be solved by dry brushing to improve the aesthetic appearance of the wall,
360 whereas in low-damage sectors, in order to prevent any increase in erosion, a protection on the
361 top of the wall would be needed.

362 Structural failures are not critical since no tilting has been recorded (see Table 3), but
363 the probability of collapse (see Table 5 LR-St) is high mainly due to undermining of the
364 construction. In order to ensure structural stability, since LD^t-St is moderate (see Table 5), the
365 repair of cracks may be tackled by means of basic strategies (see relations stated in Table 6)
366 and, according to the high-damage category of the sector, the proposed solution should directly
367 focus on the failure. For example, the proposed solution may be soft stitching (see Table 7, code
368 C7.2), which is a basic and direct type of repair that consists of simply filling a gap with a
369 compatible material.

370 With regards to risk, LD^t-W, LD^t-Ph, and LD^t-St (see Table 5) are moderate parameters,
371 with the exception of sectors Aw, Bw, and Fw when dealing with erosion issues (LD^t-Ph). This
372 matches the evaluation made of material failures, since those sectors are designated as critical
373 areas (see Table 3). The LDs related to material RFs in the case of physical vulnerability (see
374 Table 4) are much higher than external or anthropic RFs, hence measures are designed to mainly
375 solve inherent causes of damage to the wall in order to control the erosion damage in sectors
376 Aw, Bw, and Fw.

377 In terms of time, the decision regarding how to organize corrective and preventive
378 measures relies on how LR is distributed, as stated in Section 3.1 (see Table 6). Therefore,
379 preventive and corrective measures should be urgently taken on high-rated LR sectors (levels
380 4-5), which correspond to a short-term period, as stated in Tables 5 and 6. As LR-Ph and LR-
381 St reach high levels in the west façade (see Table 5), preventive and corrective repairs should
382 be undertaken within a short-term period to prevent erosion and collapse and to improve
383 hardness by increasing surface cohesion with suitable materials. Likewise, as LD^t-St is high in
384 sectors Aw, Bw and Fw (Table 5), advanced repairs should be undertaken, and since damage is
385 highly rated in these cases, the solutions should directly address the problem. Additionally,
386 since LR-St is high in those sectors, preventive and corrective actions should be considered in
387 the short-term period. Therefore, in these critical sectors, one-side replacement of mass (see
388 Table 7, code C5.1) should be proposed to directly deal with the stability and should be aimed
389 in those horizontal sectors where the loss of mass is higher (horizontal sectors 1.3, 2.1, and 2.2,
390 as can be observed in Figure 2). Nevertheless, regarding these sectors, other basic measures,
391 such as intense cleaning (code C1, Table 7), consolidation (code C4.2, Table 7), and protection
392 at the top (code P2.1-P2.2, Table 7), may be implemented to deal with high values of LD^t-Ph,
393 LR-Ph, and the high-damage category of failures.

394 In other sectors, if the damage in the wall is moderate (LD is usually moderate to low),
395 and LR is high to extreme, then preventive actions should be put ahead of corrective actions.
396 This is the case of sectors Cw, Dw, and Ew, which are considered as a low-damage category of
397 damage (Table 3), with a moderate LD^t-Ph (value 3, Table 5). However, since LR-Ph is high
398 (LP and LC are high, see Table 5), preventive measures, such as the protection at the top of the
399 wall (code P2, Table 7), are to be tackled before any corrective measure.

400 Several of the most common repair techniques for RE walls and those used in the
401 restoration work of the Alcázar are depicted in Table 7 and correspond to their degree of detail
402 (basic/advanced as proposed in Section 3.1), the related failures and risk. However, this repair

403 must be considered as an example since the literature suggests a wider range of solutions
404 (Viñuales, 1970; Keefe, 2005; Illampas et al., 2013; Fodde & Cooke, 2013; Ashurst & Ashurst,
405 1988; IPCE, 2017). The list of failures in Table 7 is discussed in Section 2.1. The repairs are
406 classified as either corrective or preventive measures. However, corrective techniques, apart
407 from yielding solutions for the associated failures, may also be used as preventive measures
408 against the incidence of other types of damage. For instance, consolidation is needed to harden
409 disintegrated material, but it could additionally prevent erosion or even the build-up of crust or
410 dirt.

411 Table 7.

412 As a guide for decision-makers, it is possible to select suitable repair techniques,
413 whether they be preventive or corrective, once risk and damage have first been assessed for
414 every sector. Risk analysis is employed to decide when and how to undertake corrective
415 measures and whether it is necessary to have a preventive aim. When dealing with the
416 assessment of a number of sectors, if LR reaches at least a high level (level 4 and 5, for example
417 in western sectors), then preventive and corrective repairs should be undertaken in a short-term
418 period. In contrast, when LR is moderate to low (1-3) there is no urgent need to carry out any
419 actions, so actions may be undertaken in a medium- to long-term period.

420 In Table 7, the failures discussed are associated to the repair techniques, and hence once
421 the diagnostic of the current state of conservation is carried out, suitable intervention measures
422 can easily be designated. Moreover, once the LD^t and hence the required degree of detail of the
423 measures (basic or advanced) have been determined, the selection of the repair technique in
424 Table 7 is more precise. When the risk assessment is finished, a higher LR may establish the
425 need for preventive measures. To this end, the three types of LR (LR-W, LR-Ph, and LR-St)
426 are represented in Table 7, so that in the case of a prevailing LR, the most suitable preventive
427 technique may be selected. For instance, soft stitching would be advisable when LR-Ph or LR-

428 St are greater, although hard stitching, which implies using connectors, would only be needed
429 if the structural stability is critical, in other words, when the LR-St is predominant.

430 Figure 6 shows several parts of the wall before and after the restoration work. Sector
431 Aw illustrated in Figure 6, which requires measures to prevent erosion and improve structural
432 stability, has been restored by means of a sloped lime mortar bed and a one-side replacement
433 of mass (Fig. 6, parts (a) and (d)). The high LR-St in sector Fw has been addressed with the
434 aforementioned solution for mass loss, but focused on lower horizontal sectors where the
435 undermining was critical (Fig. 6, parts (b) and (e)). Finally, the mass loss (failure ML1) due to
436 the presence of a dovetail was repaired through mortar filling executed in several layers (Fig.
437 6, parts (c) and (f)).

438 Fig. 6.

439 **4. Conclusions**

440 This case study presents similar construction features to those of other medieval fortresses from
441 the same group whose construction dates back to the 11th and 12th centuries. For instance, as
442 mentioned earlier, the rammed-earth technique is based on courses that are 90 cm in height,
443 which is the standard dimension for this type of medieval building in Spain. Hence, since the
444 arrangement of the sectors has been shown to be suitable in this case, the procedure may be
445 adapted for analogous buildings. Depending on the detail of the required evaluation, vertical
446 and horizontal sectors may be expanded or shrunk to reach the desired size. In general terms,
447 the authors recommend that the more widely spread and developed the damage is, the more
448 precise and concise the vertical sector should be.

449 Since the proposed method uses straightforward parameters and simple qualitative
450 indices, it is feasible that it can be put into practice by technicians that are less than highly
451 qualified. Likewise, its outcome can provide information useful for decision-making. In fact,

452 the preventive and corrective measures finally carried out for the restoration in the case study
453 followed the main principles provided in this research.

454 The proposed methodology involves a simple procedure for the evaluation of historical
455 RE walls, and can be adapted to other construction techniques. The implementation in the
456 Alcázar has illustrated the adaptability and reliability of the tool, since its response matches the
457 expectations according to the real state of conservation of the wall. When dealing with rammed-
458 earth buildings, the way of arranging horizontal and vertical sectors has demonstrated itself to
459 be flexible and in accordance with their construction features and damage distribution. With
460 minimum effort and resources, a preliminary analysis can establish critical areas through
461 quality-ranked RFs. Therefore, subsequent quantitative analysis of a more specific nature can
462 focus on these critical zones instead of wasting valuable resources and time on non-critical
463 zones. Furthermore, this methodology can be put into practice in a larger case study, and hence
464 the management of a greater number of sectors could easily be achieved.

465 The assessment of both damage and risk is complementary. The current damage
466 provides an orientation towards corrective repairs. The classification of failures is designed to
467 match the state of conservation of the case study. However, since damage is widely spread and
468 diverse, the proposed failures may serve as a guide for other evaluations in rammed-earth
469 buildings.

470 Vulnerability and risk, since they are related to probability, call for an intervention plan
471 based on a criticality index (LR). The results regarding the risk evaluation lead to several
472 conclusions. The higher the LR, the sooner the corrective or preventive repairs must be
473 undertaken. Additionally, when an LD of the material RFs reaches a critical point, corrective
474 repairs should be carried out since they are directly related to damage. In contrast, preventive
475 repairs should be targeted when LR is high or the assessment of external RFs is adverse. Hence,
476 risk assessment is a procedure for the organisation of repairs into a hierarchy, which determines
477 the most critical areas where decision-makers should focus resources. Furthermore, since the

478 risk evaluation is more closely related to the cause analysis, it provides a better way to manage
479 a predictive conservation plan.

480 However, the results, as either intervention criteria or specific techniques, should only
481 be considered as an aid to decision-makers since many other crucial factors have been excluded,
482 such as economic, aesthetic, and social issues.

483 Finally, the analysis of risk has been oriented according to three general issues:
484 humidity, erosion, and stability. This is therefore a broad-based initial approach to assessing
485 conservation. Instead of studying the stated vulnerabilities, it would be more efficient to analyse
486 the vulnerability of specific damage so that the proposed measures would specifically target the
487 real damage. However, this implies a more detailed study on which factors are linked to each
488 type of damage and in which way they are related to the deterioration process.

489 **ACKNOWLEDGEMENTS**

490 We would like to thank Pablo Díaz and Geocisa S.A. for considering our expertise for the
491 assessment of the Alcázar, as well as Anfora S.L. and Gares S.L. for their collaboration. This
492 work was supported by the research project 68/83 (number PRJ201201606), and is likewise a
493 consequence of the National Research Project BIA 2004-1092, entitled “Proposals for
494 maintenance, assessment and restoration of historical rammed-earth walls in the province of
495 Seville”.

496 **Data availability statement**

497 Some or all data, models, or code generated or used during the study are available from the
498 corresponding author by request (Spreadsheets for risk analysis).

499

500 **Disclosure statement**

501 No potential conflict of interest was reported by the authors

502 **References**

- 503 Aktas, Y. D., & Türer, A. (2011). A General Procedure for the Structural Condition Assessment
504 of Historic Earthen Masonry Structures through Structural Identification and Monitoring.
505 In *Terra 2008. 10th International Conference on the Study and Conservation of Earthen*
506 *Architecture* (Vol. Mali, pp. 352–356). Los Angeles: The Getty Conservation Institute.
- 507 Ashurst, J., & Ashurst, N. (1988). *Practical building conservation: English Heritage technical*
508 *handbook*. Aldershot: Gower.
- 509 Barros, R., Rodrigues, H., Varum, H., Costa, A., & Correia, M. (2018). Seismic Analysis of a
510 Portuguese Vernacular Building. *Journal of Architectural Engineering*, 24(1), 05017010.
511 [https://doi.org/10.1061/\(ASCE\)AE.1943-5568.0000258](https://doi.org/10.1061/(ASCE)AE.1943-5568.0000258)
- 512 Canivell, J. (2012). Characterization methodology to efficiently manage the conservation of
513 historical rammed-earth buildings. In C. Mileto, F. Vegas, & V. Cristini (Eds.), *Rammed*
514 *Earth Conservation* (pp. 283–288). London: Taylor & Francis Group.
- 515 Fodde, E., & Cooke, L. (2013). Structural consolidation of mud brick masonry. *Journal of*
516 *Architectural Conservation*, 19(3), 265–281.
517 <https://doi.org/http://dx.doi.org/10.1080/13556207.2014.858296>
- 518 Gil-Crespo, I.-J. (2017). Late Medieval Castles Built with Rammed Earth in Castile, Spain.
519 *Journal of Architectural Engineering*, 23(3), 04017013.
520 [https://doi.org/10.1061/\(ASCE\)AE.1943-5568.0000259](https://doi.org/10.1061/(ASCE)AE.1943-5568.0000259)
- 521 Graciani, A., Martín del Río, J. J., Mora, G. M., Alexandre, F. J., Canivell, J., del Río, J. J., ...
522 Canivell, J. (2012). Preliminary studies for intervention, interpretation and value
523 enhancement of Tower of Don Fadrique (Albaida, Seville, Spain). In *Rammed Earth*
524 *Conservation* (pp. 345–350). London: Taylor & Francis Group.
- 525 Hughes, R. (1983). Material and structural behaviour of soil constructed walls. *Monumentum*,
526 26(2–3), 176–188.
- 527 Illampas, R., Ioannou, I., & Charmpis, D. C. (2013). Overview of the pathology, repair and
528 strengthening of adobe structures. *International Journal of Architectural Heritage*, 7(2),
529 165–188. <https://doi.org/10.1080/15583058.2011.624254>
- 530 IPCE. (2017). *Proyecto COREMANS: Criterios de Intervención en la arquitectura de tierra.*
531 *C.Mileto y F.Vegas (Coord.)*. IPCE.
- 532 ISCARSAH-ICOMOS. (2000). *Declaration of Assasi* (Vol. Declaratio). Assasi: International
533 Council on Monuments and Sites.
- 534 Keefe, L. (2005). *Earth building: methods and materials, repair and conservation*. London:
535 Taylor & Francis.
- 536 Keefe, L., Watson, L., & Griffiths, R. (2001). A proposed diagnostic survey procedure for cob
537 walls. *Proceedings of the Institution of Civil Engineers. Structures & Buildings*, 146(1),
538 57–65.
- 539 Kima, C.-J., Yoob, W.-S., Leec, U.-K., Songd, K.-J., Kange, K.-I., & Chof, H. (2010). An
540 experience curve-based decision support model for prioritizing restoration needs of
541 cultural heritage. *Journal of Cultural Heritage*, 11, 430–437.
- 542 Monjo Carrió, J. (2007). Durabilidad vs vulnerabilidad. *Informes de La Construcción*, 59(507),
543 43–58.

- 544 Monjo Carrió, J., Maldonado Ramos, L., Carrió, J. M., & Ramos, L. M. (2001). *Patología y*
545 *técnicas de intervención en estructuras arquitectónicas*. Madrid: Munilla Lería.
- 546 Ornelas, C., Guedes, J. M., & Breda-Vázquez, I. (2018). Integrated Built Heritage Assessment:
547 Development of MAPEH. *Journal of Architectural Engineering*, 24(1).
548 [https://doi.org/10.1061/\(ASCE\)AE.1943-5568.0000287](https://doi.org/10.1061/(ASCE)AE.1943-5568.0000287)
- 549 Pearson, G. T. (1997). *Conservation of Clay and Chalk Buildings*. London: Donhead
550 Publishing.
- 551 Prieto Ibáñez, A. J., Macías Bernal, J. M., Chávez de Diego, M. J., & Alejandro Sánchez, F. J.
552 (2016). Expert system for predicting buildings service life under ISO 31000 standard.
553 Application in architectural heritage. *Journal of Cultural Heritage*, 18, 209–218.
554 <https://doi.org/10.1016/j.culher.2015.10.006>
- 555 Ramos, L., Masciotta, M., Morais, M., Azenha, M., Ferreira, T., Pereira, E., & Lourenco, P.
556 (2018). HeritageCARE: Preventive conservation of built cultural heritage in the South-
557 West Europe. In *Innovative Built Heritage Models: Edited contributions to the*
558 *International Conference on Innovative Built Heritage Models and Preventive Systems*
559 *(CHANGES 2017), February 6-8, 2017, Leuven, Belgium*. CRC Press. Taylor & Francis
560 group.
- 561 Rodríguez, M. A., Monteagudo, I., Saroza, B., Nolasco, P., & Castro, Y. (2011). Aproximación
562 a la patología presentada en las construcciones de tierra. Algunas recomendaciones de
563 intervención. *Informes de La Construcción*, 63(523), 10–97.
564 <https://doi.org/10.3989/ic.09.007>
- 565 Rotondaro, R., Monk, F., Ramos, A. R., & Rodrigo Ramos, A. (2002). Patrimonio y
566 arquitectura de tierra del noroeste argentino. Metodología para el estudio comparativo de
567 patologías constructivas. In *Memoria 1º seminario Consorcio Terra cono Sur. “La tierra*
568 *cruda en la construcción del habitat” (CD) (Vol. San Miguel)*. FAU-UNT.
- 569 Vegas, F., Mileto, C., & Cristini, V. (2014). Constructive features and preservation work of
570 rammed earth architecture: the Islamic tower of Bofilla (Valencia). *Journal of*
571 *Architectural Conservation*, 20(1), 28–42.
572 <https://doi.org/http://dx.doi.org/10.1080/13556207.2014.886377>
- 573 Viñuales, G. M. (1970). *Restauración de arquitecturas de tierra*. Tucumán: Instituto Argentino
574 de Investigaciones de Historia de la Arquitectura y del Urbanismo.
575

576 **WORD COUNT: 7160 WORDS**

577 **LIST OF FIGURE CAPTIONS:**

578 Fig. 1. General plan of the Alcázar (b) with location of the studied area (1). View of the wall
579 from the east (a).

580 Fig. 2. Eastern elevation of the rammed-earth wall. Sectors and location of cross-sections.

581 Fig. 3. Representative cross-sections.

582 Fig. 4. Failures represented in two elevations (a), and cross-section S1 of vertical sector A (b).

583 Fig. 5. Procedure to assess risk and vulnerability.

584 Fig. 6. Several prevailing failures (a, b, and c), and their corresponding repairs (d, e, and f).

585 **List of tables**

586 Table. 1. Phases and tasks proposed for the methodology.

587

PHASE 1 Data-gathering	TASK 1.1	Data-gathering of physical parameters
	TASK 1.2	Checking state of conservation
	TASK 1.3	Recognition of RFs
PHASE 2 Assessment	TASK 2.1	Failure analysis
	TASK 2.2	Risk management
	TASK 2.3	Diagnosis and Proposal of corrective/preventive repairs

588

589

590 Table 2. Classification of RFs used in the evaluation of each vulnerability considered.

591

	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	Ex1	Ex2	Ex3	Ex4	Ex5	Ex6	Ex7	Ex8	Ex9	Ex10	Ex11	Ex12	A1	A2	A3	A4	A5	A6
W*	3	3	3	1	2	1	3	2	2	-	-	-	-	-	1	1	2	1	1	1	3	1	-	-	-	-	2	1	-	-	-	-
Ph*	-	-	-	-	1	3	3	-	2	-	-	-	-	-	-	-	-	-	1	-	3	-	3	-	-	-	-	-	2	2	-	-
St*	3	-	-	-	-	-	3	2	-	-	3	3	3	3	-	-	-	-	-	-	-	-	-	3	3	2	-	-	-	-	2	3

* W: Vulnerability to water; Ph: Physical vulnerability; St: Structural vulnerability

Note 1: Criticality analysis: (-) null; (1) secondary risk factor; (2) moderate risk factor; (3) key risk factor

Note 2: Risk factor codes:

Material RFs: M1 - Foundation; M2 - Wall footing; M3 - Water barrier; M4 - Drainage; M5 - Wall transpiration; M6 - Coating; M7 - Cohesion-toughness; M8 - Retaining wall; M9 - Roof-covering; M10 - Dirt; M11 - Wall reinforcements; M12 - Wall slenderness; M13 - Cracking; M14 - Degree of erosion.

External RFs: Ex1 - Orientation, sun exposure; Ex2 - Rainfall rate; Ex3 - Ventilation; Ex4 - Close vegetation; Ex5 - Vegetation on the wall; Ex6 - Proximity of water course; Ex7 - Ground transpiration; Ex8 - Topography; Ex9 - Exposure to rain/wind; Ex10 - Seismic danger; Ex11 - Spatial configuration; Ex12 - Permanent loads.

Anthropic RFs: A1 - Incorrect repair (lining); A2 - Water installation; A3 - Human activity; A4 - Animal activity; A5 - Overloads; A6 - Structural alterations

592

593

594 Table 3. Summary of failures and prevailing causes for each vertical sector.

Façade	Sector	Category	Cross-sections	Material								Surface			Structural		
				E1	E2	LC1	LC2	LC3	LC4	ML1	ML2	D	C	V	Ct	Cl	T
West	Aw	High	S1,2	X	X	X	X	X	X		X	X		X	X		
	Bw	High	S3, 4, 5, 6	X	X	X	X	X		X	X	X	X	X		X	
	Cw	High	S7, 8, 9	X	X	X	X	X		X	X	X	X	X	X		
	Dw	Low	S10	X	X		X			X		X		X	X		
	Ew	Low	S11	X	X		X			X		X		X			
	Fw	High	S12, 13, 14	X	X		X		X	X	X	X			X	X	
East	Ae	Low	S1,2	X	X	X		X	X		X			X	X		
	Be	Low	S3, 4, 5, 6	X	X	X	X	X		X		X		X		X	
	Ce	Low	S7, 8, 9	X	X	X	X	X		X		X					
	De	Low	S10	X	X	X	X	X	X		X			X	X		
	Ee	High	S11	X	X		X		X	X		X		X			
	Fe	High	S12, 13, 14	X	X	X	X	X	X	X		X		X	X	X	X
		Prevailing causes		E1	E2	LC1	LC2	LC3	LC4	ML1	ML2	D	C	V	Cl	Ct	T
		Weathering	X	X	X	X	X	X	X	X	X	X	X		X	X	
		Water ponding		X	X	X	X	X	X			X	X	X	X		
		Water runoff	X									X					
		Animal activity						X	X								
		Fungus											X				
		Shrinkage													X	X	
		Note: Types of failures: Erosion (E1, E2); Loss of cohesion (LC1-LC4); Material loss (ML1, ML2); Failures on the surface (D-dirt, C-crust, V-vegetation); Structural (Ct-Transverse crack, Cl- Longitudinal crack, T-Tilting)															

595

596

597 Table 4. Levels of deficiency (LD) corresponding to each vulnerability considered.

	Façade	Vertical Sector	M1	M2	M3	M4	M5	M6	M7	M8	M9	M10	M11	M12	M13	M14	Ex1	Ex2	Ex3	Ex4	Ex5	Ex6	Ex7	Ex8	Ex9	Ex10	Ex11	Ex12	A1	A2	A3	A4	A5	A6			
Vulnerability to water	West	Aw	3	3	5	3	1	4	5	2	5						2	2	1	2	1	1	1	3					1	1							
		Bw	3	3	5	3	1	4	5	2	5							2	2	1	2	2	1	1	3					1	1						
		Cw	3	3	5	3	1	3	5	1	5								2	2	1	2	1	1	1	3					1	1					
		Dw	3	3	5	4	1	4	5	1	5								2	2	1	2	1	1	1	4					1	1					
		Ew	3	3	5	4	2	4	4	1	5								2	2	1	2	2	1	1	4					1	1					
		Fw	3	3	5	4	2	4	3	1	5								2	2	1	3	2	1	5	3					1	1					
	East	Ae	3	3	5	4	3	4	5	2	5							2	2	1	2	1	1	1	4					1	1						
		Be	3	3	5	4	3	4	3	2	5								2	2	1	2	2	1	1	4					1	1					
		Ce	3	4	5	3	3	4	4	1	5								2	2	1	2	2	1	1	3					1	1					
		De	3	4	5	3	2	4	4	1	5								2	2	1	2	1	1	1	3					1	1					
		Ee	3	3	5	3	2	4	5	1	5								2	2	1	2	2	1	1	3					1	1					
		Fe	3	3	5	3	2	4	5	1	5								2	2	1	2	1	1	1	3					1	1					
Physical vulnerability	West	Aw					1	5	5	5												1	1	5								1	3				
		Bw					1	4	5	5													2	1	5								1	5			
		Cw					1	4	5	5														1	1	5								1	5		
		Dw					1	5	5	5														1	1	5								1	3		
		Ew					2	5	4	5														2	1	5								1	3		
		Fw					2	5	3	5														2	5	5								1	3		
	East	Ae					3	5	5	5													1	1	3								2	3			
		Be					3	5	3	5														2	1	3								2	4		
		Ce					3	5	4	5														2	1	3								2	5		
		De					2	5	4	5														1	1	3								2	5		
		Ee					2	5	5	5														2	1	3								2	5		
		Fe					2	5	5	5														1	1	3								2	5		
Structural vulnerability	West	Aw						5	2					4	5	2	5											3	4	1					1	2	
		Bw						5	2					4	3	2	5											3	4	1					1	2	
		Cw						5	1					4	3	2	5											3	4	1					1	2	
		Dw						5	1					4	5	2	5												3	4	1					1	2
		Ew						4	1					4	3	2	5												3	4	1					1	2
		Fw						3	1					4	3	5	5												3	4	1					1	2
	East	Ae						5	2					4	5	5	4												3	4	1					1	2
		Be						5	2					4	3	5	5												3	4	1					1	2
		Ce						4	1					4	3	5	3												3	4	1					1	2
		De						4	1					4	3	2	3												3	4	1					1	2
		Ee						5	1					4	3	2	5												3	4	1					1	3
		Fe						5	1					4	3	5	5												3	4	1					1	3

Notes:
Codes of Risk Factors are described in Table 2. Material: M1-M9; External: E1-E8; Anthropic: A1-A2
Values of LD: Extreme (5); High (4); Moderate (3); Low (2); Very low (1)

598

599

600

601

602

603

604

605 Table 5. Consequence, vulnerability, and risk levels for each sector.

Façade	Vertical Sector	LD'-W	LD'-Ph	LD'-St	LP-W	LP-Ph	LP-St	LC-W	LC-Ph	LC-St	LR-W	LR-Ph	LR-St
West	Aw	3	4	3	3	5	4	4	4	4	3	5	4
	Bw	3	4	3	3	5	4	4	4	4	3	5	4
	Cw	3	3	3	3	4	4	4	4	4	3	4	4
	Dw	3	3	3	3	4	3	4	4	4	3	4	3
	Ew	3	3	3	3	4	3	4	4	4	3	4	3
	Fw	3	4	3	3	5	4	4	4	4	3	5	4
East	Ae	3	3	3	3	3	3	4	4	4	3	3	3
	Be	3	3	3	3	3	3	4	4	4	3	3	3
	Ce	3	3	3	3	3	3	4	4	4	3	3	3
	De	3	3	3	3	3	3	4	4	4	3	3	3
	Ee	3	3	3	3	3	3	4	4	4	3	3	3
	Fe	3	3	3	3	3	3	4	4	4	3	3	3

Note:
 Values of each level: Extreme (5); High (4); Moderate (3); Low (2); Very low (1)
 Suffix: W: vulnerability to water; Ph: Physical vulnerability; St: Structural vulnerability

606

607

608 Table 6. Classification of measures according to the results of the damage and risk
 609 assessment.

Classification of measures						
			Corrective		Preventive	
			Where		Where	
	Risk	Level	Low damage	High damage	Low damage	High damage
How	LDt	1-3	Outer/Basic	Wall/Basic	Outer/Basic	Wall/Basic
		4-5	Outer/Advanced	Wall/Advanced	Outer/Advanced	Wall/Advanced
When	LR	1-2	Long-term		Long-term	
		3	Medium-term		Medium-term	
		4-5	Short-term		Short-term	

610

611

Table 7. Proposal of repairs according to LR and extant failures

Code *	Detail **	Repairs for rammed-earth walls	Material						Surface			Structural			Risk			
			E1	E2	LC1	LC2	LC3	LC4	ML1	ML2	D	C	V	Ct	Cl	T	LR-W	LR-Ph
C1	B	Intense cleaning			X	X			X								x	x
C2	Ad	Vegetation removal									X						x	
C3.1	B	Dirt cleaning: Dry brushing					X	X	X			X	X				x	
C3.2	B	Dirt cleaning: Wet brushing								X	X						x	
C4.1	Ad	Consolidation: Mineral consolidant		X	X	X	X	X	X								x	x
C4.2	B	Consolidation: Thick limewash		X	X	X	X	X				X	X				x	x
C4.3	Ad	Consolidation: Lime mortar			X	X	X	X				X	X				x	x
C5.1	B	Replacement of mass: One-sided replacement							X								x	x
C5.2	Ad	Replacement of mass: Two-sided replacement							X									x
C6	Ad	Mortar filling: By layers	X					X									x	x
C7.1	B	Crack repairs: Soft stitching										X	X				x	x
C7.2	Ad	Crack repairs: Hard stitching										X	X	X				x
P1.1	Ad	At the bottom: Drainage	X		X	X	X	X	X								x	
P1.2	B	At the bottom: Outward ground slopes	X	X				X	X			X	X	X			x	x
P2.1	B	At the top: Outward sloped mortar bed	X	X	X	X	X	X	X	X	X						x	
P2.2	Ad	At the top: wall coping overhang	X	X	X	X	X	X	X	X	X						x	x
P3.1	B	Renderers: Limewash	X	X	X	X	X	X		X	X						x	x
P3.2	Ad	Renderers: Lime mortar	X	X	X	X	X	X		X	X						x	x
P4	Ad	Stabilization, shoring											X					x

* Code: C- Corrective repair, P- Preventive repair
** Detail of repairs: B- Basic repair, Ad: Advanced repair

Note:
Types of failures: Erosion (E1, E2); Loss of cohesion (LC1-LC4); Material loss (ML1, ML2); Failures on the surface (D-dirt, C-crust, V-vegetation); Structural (Ct-Transverse crack, Cl-Longitudinal crack, T-Tilting).



Figure 2









