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

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ABSTRACT

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

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

1. Introduction

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

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

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

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

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

The proposed method is illustrated on one deteriorated area of the Alcázar of King Don Pedro I (Fig. 1). Despite several historical refurbishments, the building remains almost in ruins. The analysed sector corresponds to the west side of the inner perimeter wall (Fig. 1), which dates from the 12th century. In the Iberian Peninsula, there are a great number of buildings dating from this Almohadian period (12th-13th century), especially those regarding the territorial defence, such as city walls, fortresses, castles and watchtowers. These military buildings usually run a high risk of deterioration, due in part to certain factors related to the construction materials, but mainly owing to the lack of maintenance. This case study was therefore selected thanks to its construction representativeness and to its inclusion in a short-term restoration program. The state of conservation of the selected building, which presents a variety of significant damage and circumstances, is also of major interest, since the proposed analysis could serve as an example for the reproduction of similar studies.

Fig. 1.

2. Methodology

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

Table. 1.

The procedure described in this research shares only two aspects with the aforementioned proposal. Although both methodologies deal with damage and risk assessment, Canivell (2012) extends its evaluation to specific construction aspects of the RE military buildings, such as dimensional and material features, and construction techniques. Regarding the damage analysis, the parameters herein discussed have been adapted to match the singularities of the case study. For instance, the failures related to the loss of cohesion have been divided into three categories depending on the rate of damage. Other improvements concern the procedure of assessing the risks, since the proposed methodology has changed the internal relations between the parameters analysed. This issue is addressed in detail in Section 2.2.2. The common objective is to reach a definition of level of risk by means of evaluating several risk factors. The current analysis method uses a weighted sum based on a critical examination in order to obtain an overall assessment of the risk factors (RFs), instead of obtaining radial plots as proposed by Canivell (2012), which may involve certain inaccuracies when comparing different sectors.

2.1. Phase 1: Data gathering

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

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

Fig. 2.

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

Fig. 3.

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

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

Material failures are related to erosion and the cohesion of RE. In general, erosion is caused by the combination of certain external agents (water, wind, and variations in temperature). This kind of damage, usually repaired by filling with mortars, has been classified into two types according to their repair, so that once damage is assessed, it is easy to propose straightforward repair techniques. Water ponding damage (E1) is mainly caused by water gathering in joints and putlog holes. Surface erosion (E2) involves slight erosion by water runoff and weathering in which fine particles of soil are washed away, resulting in a very rough surface. Additionally, damage directly related to mass cohesion has been classified depending on the level of cohesion that remains and hence on the possible repair technique. Spalling and flaking (LC1, LC2) implies loss of the mass in chunks or flakes that may come off easily. In the case of disintegration (LC3), the loss is greater and implies an increase in porosity and hence a considerable amount of RE, including coarse particles, can easily be brushed away. Finally, sanding (LC4) is a result of the total lack of cohesion and a greater loss of material can easily be removed. In contrast to erosion, material loss (ML) may involve a thicker replacement of material. The classification ML2 indicates the restoration of entire or half RE boxes by means of a system of formworks, whilst ML1 involves a depth of up to 25 cm, which could be repaired, for example by consecutive layers of mortar.

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

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

The purpose of Task 1.3 is to study and acknowledge RFs whose results are to be used in Task 2.2 to carry out the entire risk management procedure. The aforementioned task is shown on the left-hand side of Figure 5. Risk factors comprise the main causes of deterioration of earthen construction. First, three categories of vulnerability are considered: (I) vulnerability to water as the incapacity to withstand damage where the filtration within the wall or the pounding of water on the wall is the main cause; (II) physical vulnerability; and (III) structural vulnerability, as the weaknesses incurred from supporting damage from erosion and instability, respectively. Each category concerns certain qualitative RFs that are deeply involved in the durability of RE buildings (Table 2). After having set the mechanism to be analysed, RFs related to each vulnerability are determined and classified as material (M), external (Ex), and anthropic (A), whether they refer to concerns of the wall itself or not (see Table 2). The building is then divided into sectors for their assessment in terms of risk. The assessment of these RFs may refer to the same vertical division in sectors as that proposed for damage analysis. Each RF is given a number that corresponds to the deficiency level; this is discussed in Task 2.2.

Table 2.

2.2. Phase 2: Assessment

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

2.2.1. *Task 2.1: Failure analysis.*

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

In order to accomplish Task 2.1, the failures surveyed in Task 1.2 need to be represented on an elevation plan in accordance with the stated classification (Fig. 4). In addition, failures are arranged in a table according to their corresponding sector along with the probable causes of damage (see Table 3). In Figure 4, only one vertical sector is represented, which is where the damage is the most highly concentrated, although the analysis has been carried out for the whole length of the wall. In Section 2.1, which corresponds to the data-gathering task, every incidence of damage and its corresponding code are discussed. Figure 4 together with Table 3 explained in detail in Section 3, where prevailing damage is ascertained and the corresponding causes are proposed for all the sectors analysed. Nevertheless, it should be noted that, in such cases, the damage is rated in one of two categories (low and high) depending on the development and intensity of the surveyed failure. For instance, Figure 4 represents two sectors, where sector Aw is considered as high-damage, and Ae as low-damage, since the former sector presents failures that are more critical and more widely spread (loss of mass, LM2). In Section 3, Table 3 shows the results of the damage survey and the category of each sector depending on the rate of damage.

Fig. 4.

2.2.2. *Task 2.2: Risk assessment*

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

Fig. 5.

The prior evaluation of RFs carried out in Task 1.3 is used as a first step in the current task, as can be observed on the left-hand side of Figure 5. Task 2.2 deals with the evaluation of the RFs introduced in the phase (Task 1.3) and is explained on the right-hand side of the aforementioned figure. Nonetheless, the details and implications of this assessment are discussed in detail in Section 3. Depending on the vulnerability considered, the level of deficiency (LD) is obtained for each RF through criticality analysis (see Table 2). Criticality analysis involves the assessment of both the determinism and the scope of the possible damage in order to establish the weight of each RF: ranging from null-RF to key-RF. The weighted sum of all LD is equal to the total LD, namely LD^t, for the sector and the vulnerability considered. At this point, pairs of parameters are crossed in predesigned matrices of risk in order to obtain, in the first place, the level of probability (LP), with LD^t and the level of exposure (LE), and secondly the level of risk (LR), with the LP and the level of consequences (LC). This level of exposure is determined through a risk matrix and considers the frequency and severity of possible damage. The level of consequences is obtained by means of an evaluation of four anthropic RFs: heritage value, economic value, human damage, role in building. Since three vulnerabilities have been considered for risk assessment, the LR is detailed in terms of the hazard upon water (LR-W), physical erosion (LR-Ph), and structural stability (LR-St).

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

3. Results and discussion

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

Table 3.

In terms of structural stability, the failures are not serious, although several sectors (A, B, C, and F) present significant cracks and loss of mass (ML1, ML2, mainly in the west façade) that will probably involve a partial collapse in the medium- or long-term. Structural stability would be compromised since sectors A and B are undermined and have lost almost 40% of the original wall thickness (see Figure 3). Although sector F has lost 50% of the original mass, the section is more stable than sectors A and B.

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

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

Table 4.

The LD risk assessments corresponding to all the sectors are depicted in Table 4, and arranged into the three vulnerabilities as reported in Section 2.2.2. These levels of deficiency have been compensated by the criticality analysis, through which different weights are assigned to each RF, as detailed in Figure 4 and discussed in Section 2.2. Considering the three categories established for the vulnerability, it may be highlighted that, in Table 4, LDs related to wall parameters (material RFs) are higher than those from external sources (external and anthropic RFs).

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

Table 5.

3.1. Correlation between damage and risk

Damage and risk assessment are considered as complementary procedures in establishing which repairs are to be tackled (whether they be corrective o preventive), when they should be implemented, and also in establishing the recommended detail of development of the aforementioned measures. In order to ease the decision-making procedure, Table 6 shows the correlation between both types of assessment (damage and risk) and their relationship to the measures. One of the main objectives of the risk assessment is to establish when and how to implement the perceptive measures. In this regard, LR is employed to determine the urgency of application either corrective or preventive measures. Hence, the greater the level linked to LR (from 1 to 5, as proposed), the sooner the measures are to be tackled. Three classes of period are considered for the implementation of the repairs, namely long-term, medium-term, and short-term periods, whereby the third implies the greatest urgency.

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

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

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

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

3.2. Diagnosis and preliminary proposal of measures

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

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

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

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

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

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

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

Several of the most common repair techniques for RE walls and those used in the restoration work of the Alcázar are depicted in Table 7 and correspond to their degree of detail (basic/advanced as proposed in Section 3.1), the related failures and risk. However, this repair must be considered as an example since the literature suggests a wider range of solutions (Viñuales, 1970; Keefe, 2005; Illampas et al., 2013; Fodde & Cooke, 2013; Ashurst & Ashurst, 1988; IPCE, 2017). The list of failures in Table 7 is discussed in Section 2.1. The repairs are classified as either corrective or preventive measures. However, corrective techniques, apart from yielding solutions for the associated failures, may also be used as preventive measures against the incidence of other types of damage. For instance, consolidation is needed to harden disintegrated material, but it could additionally prevent erosion or even the build-up of crust or dirt.

Table 7.

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

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

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

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

Fig. 6.

4. Conclusions

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

Since the proposed method uses straightforward parameters and simple qualitative indices, it is feasible that it can be put into practice by technicians that are less than highly qualified. Likewise, its outcome can provide information useful for decision-making. In fact, the preventive and corrective measures finally carried out for the restoration in the case study followed the main principles provided in this research.

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

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

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

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

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

ACKNOWLEDGEMENTS

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

Data availability statement

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

Disclosure statement

No potential conflict of interest was reported by the authors

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WORD COUNT: 7160 WORDS

LIST OF FIGURE CAPTIONS:

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

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

Fig. 3. Representative cross-sections.

Fig. 4. Failures represented in two elevations (a), and cross-sectionS1 of vertical sector A (b).

Fig. 5. Procedure to assess risk and vulnerability.

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

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

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

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

	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

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

				Material								**Surface**			**Structural**		
Façade	**Sector**	**Category**	**Cross-sections**	**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	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	
			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	
			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)														

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)

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

Façade	Vertical Sector	LD^t –W	LD^t -Ph	LD^t -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

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

			Classification of measures			
			Corrective		**Preventive**	
			Where		**Where**	
	Risk	**Level**	**Low damage**	**High damage**	**Low damage**	**High damage**
How	**LD_t**	**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	

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

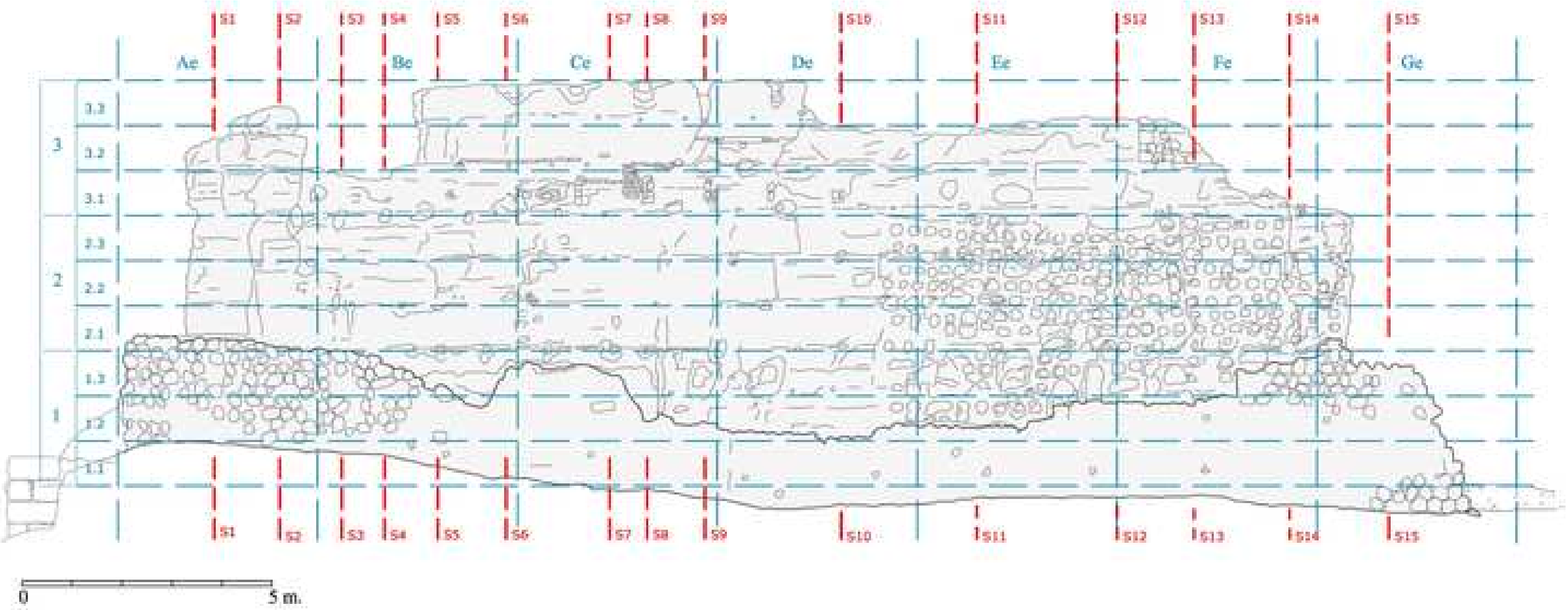
			Material								Surface			Structural			Risk		
Code *	**Detail ****	**Repairs for rammed-earth walls**	**E1**	**E2**	**LC1**	**LC2**	**LC3**	**LC4**	**ML1**	**ML2**	**D**	**C**	**V**	**Ct**	**Cl**	**T**	**LR-W**	**LR-Ph**	**LR-St**
C1	B	**Intense cleaning**			X	X				X								**x**	**x**
C2	Ad	**Vegetation removal**											X					**x**	
C3.1	B	**Dirt cleaning**: Dry brushing					X	X		X	X			X	X			**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							**x**		
P1.2	B	**At the bottom**: Outward ground slopes	X	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					**x**		
P2.2	Ad	**At the top**: wall coping overhang	X	X	X	X	X	X	X	X	X	X					**x**	**x**	
P3.1	B	**Renders**: Limewash	X	X	X	X	X	X			X	X					**x**	**x**	
P3.2	Ad	**Renders**: 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 1

Figure 2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2.1
1
1.3
1.2
1.1
0
5 m.

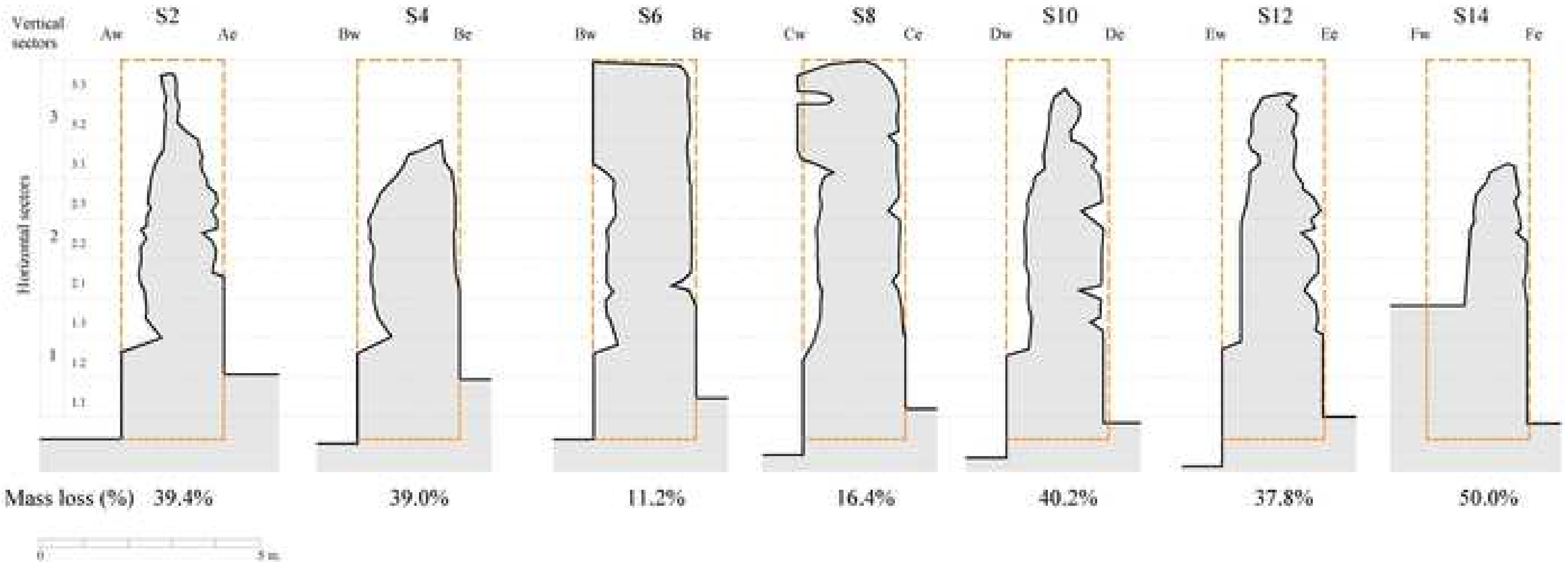
Vertical sectors
S2
Aw
Ae
S4
Bw
Be
S6
Bw
Be
S8
Cw
Ce
S10
Dw
De
S12
Ew
Ee
S14
Fw
Fe
Horizontal sectors
3
2
1
3.3
3.2
3.1
2.3
2.2
2.1
1.3
1.2
1.1
Mass loss (%)
39.4%
39.0%
11.2%
16.4%
40.2%
37.8%
50.0%
0
5 m.

Figure 4

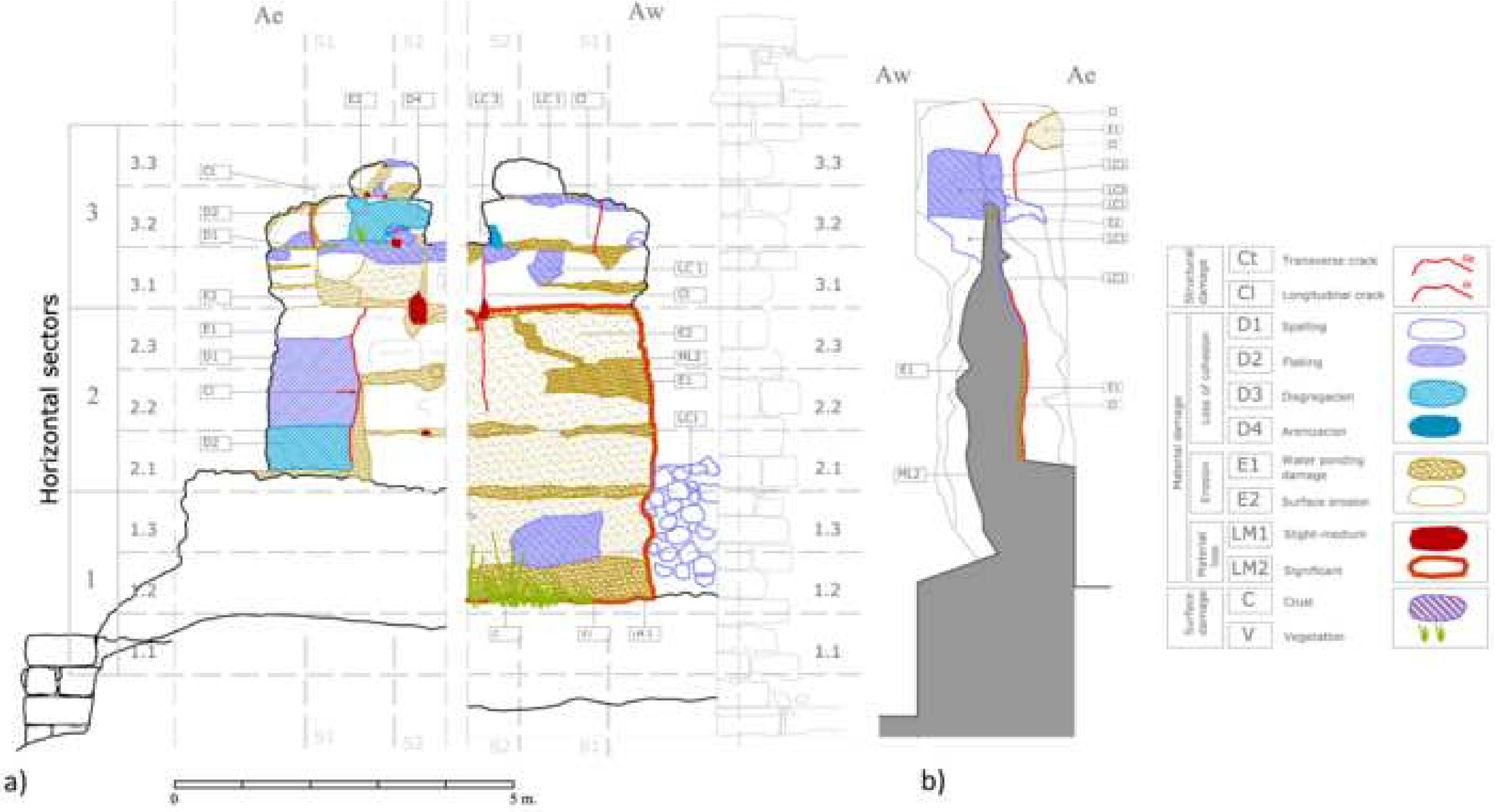
Ac
Aw
Horizontal sectors
3
2
1
3.3
3.2
3.1
2.3
2.2
2.1
1.3
1.2
1.1
S1
S2
0
5 m.
a)
Aw
Ac
b)
Structural damage
Ct
Transverse crack
Cl
Longitudinal crack
Material damage
Loss of cohesion
D1
Spalling
D2
Flaking
D3
Disgregation
D4
Arenization
Erosion
E1
Water ponding damage
E2
Surface erosion
Material loss
LM1
Slight-medium
LM2
Significant
Surface damage
C
Crust
V
Vegetation

Figure 5

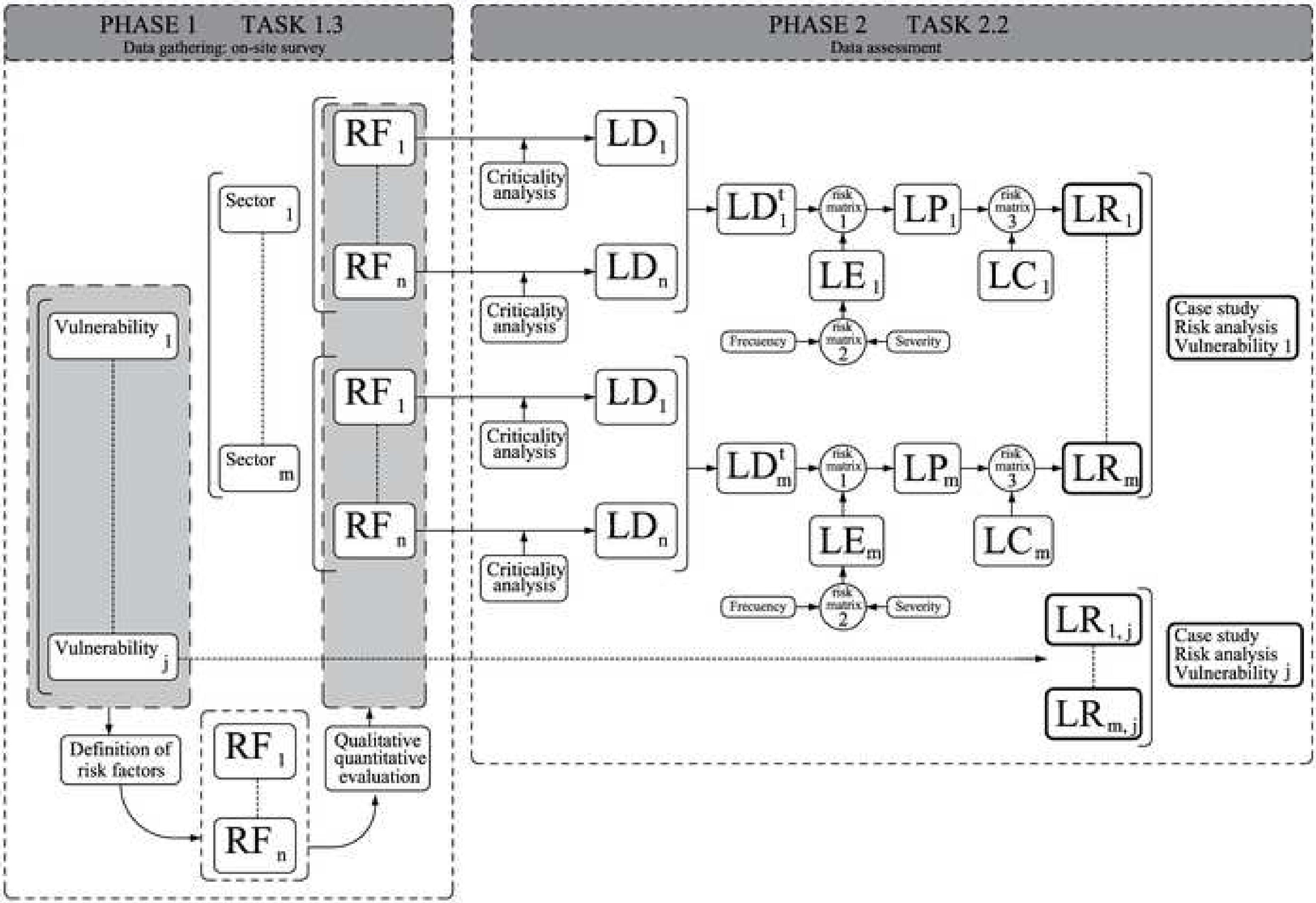
PHASE 1 TASK 1.3
Data gathering: on-site survey
PHASE 2 TASK 2.2
Data assessment
Vulnerability 1
Vulnerability j
Sector 1
Sector m
RF 1
RF n
RF 1
RF n
Criticality analysis
Criticality analysis
Criticality analysis
Criticality analysis
LD 1
LD n
LD 1
LD n
LD$^t_1$
LD^t_m
risk matrix 1
risk matrix 3
risk matrix 2
LP 1
LP m
LR 1
LR m
LE 1
LE m
LC 1
LC m
Frecuency
Severity
Case study
Risk analysis
Vulnerability 1
LR 1, j
LR m, j
Case study
Risk analysis
Vulnerability j
Definition of risk factors
RF 1
RF n
Qualitative quantitative evaluation

Figure 6