Rammed Earth Conservation – Mileto, Vegas & Cristini (eds)
© 2012 Taylor & Francis Group, London, ISBN 978-0-415-62125-0

Characterization methodology to efficiently manage the conservation of historical rammed-earth buildings

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ABSTRACT: Over recent centuries, earthen-building techniques have been falling into disuse despite the long tradition of using earth as a building material. Rammed-earth walls have a rich heritage value in Spain. These structures are at high risk mainly due to a lack of maintenance. It is therefore necessary to underline their characteristics, often much less known, in order to ensure proper management of their conservation and maintenance. The management of a heritage object requires greater understanding for medium and long-term planning. To this end, a study of vulnerability and risk is introduced, as was alleged by several international organizations. Since no specific methodology has been developed to evaluate historical rammed-earth walls, this research is intended to indicate a new system of approach to any type of restoration or even facilitate the decision-making when managing a large heritage site.

1 INTRODUCTION

New initiatives related to the promotion and value of earth construction arose in the middle of the twentieth century. Hence, in recent decades, the research in this field has experienced a progressive development. As a result, a new network of knowledge has been generated, by means of a great number of individual contributions.

Initially, the lack of scientific and technological studies on earthen construction methods, and on their strategies of preservation and conservation led to the usage and adaptation of techniques from other systems without previous assessment of potential damages due to the incompatibility between materials. As a result, the random application of these techniques failed or aggravated the damage, especially where industrialized materials, such as cement, steel or certain chemical consolidants, are involved.

There is a lack of knowledge about historical rammed-earth walls. Nevertheless, despite the latest studies carried out on this field, it is still necessary to undertake some works/actions to provide convenient background for proper assessment and value enhancement strategies. Some research projects have already pointed out the main principles of this research line for historical rammed-earth technique, i.e. projects BIA 2004-1092 and BIA 2011-18921 (National Research Plan) or Terra Incognita project (project n° 2009-0758 of the European Programme "Culture 2007–2013").

This paper is aimed to study the main characteristics of historical rammed-earth walls, providing guidelines for intervention and helping in the decision-making, by means of assessment methodology based mainly on a comprehensive/proper understanding of the damaging process and vulnerability of these kinds of earthen walls. Likewise, the proposed methodology is part of a recent research work carried out by the current author (Canivell 2011).

2 CHARACTERIZATION METHODOLOGY

In general terms and regardless of the area of knowledge, a wide variety of diagnostic methodologies is currently available. Among other concerns, they may differ from each other according to the method of data collection, the typology of the data, and the level of conclusion that may be drawn (whether enhancement proposals may be included).

As for clinical diagnosis, the current methodology is based on a preliminary characterization, also known as an anamnesis. Before any diagnosis can be offered, it is necessary a prior step that enables the later collection of all the relevant information from the rammed-earth wall, related both to its material and to its state of conservation together with any weaknesses. Once a preliminary study is completed, it is not only feasible to give a diagnosis which determines the current state of decay, but also to suggest suitable conservation repairs.

Studies for the analysis of this kind of wall are mainly organoleptic and straightforward to be carriedy out through a visual inspection, although they may be completed by means of laboratory tests. The various aspects to be analyzed are as detailed:

– Constructive characterization. This encompasses all the studies related to the rammed-earth technique, its components and their proportions. It may be divided into several independent analyses as follows. Firstly, the Technical characterization that specifies the constructive system details and defines each kind of rammed-earth wall. Material characterization points out the chemical and physical properties of a rammed-earth wall. Finally, Measurement characterization focuses on the main magnitudes and proportions of a rammed-earth wall.
– Characterization of the state of conservation. The current damages of a wall are evaluated in order to determine their origin and the agents of the damage.
– Vulnerability and Risk characterization. Rammed-earth hazards are assessed as a complement to the damage evaluation.

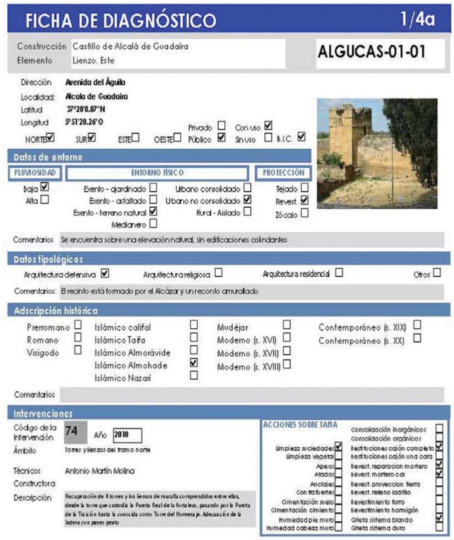
In order to perform this analysis, diagnosis data forms are proposed, gathering all those necessary parameters. These forms are used during a data-collection phase on the field. Their contents are managed by a database, not only to collect data, but also to create a comprehensive management tool for a heritage group of selected buildings. The database is designed to generate the following diagnosis data forms as reports, matching each part of the stated analysis:

Form 1 (Fig. 1). General data from the building and its rammed-earth wall are included indentifying the record by a unique alphanumeric code.

Form 2. Wall characteristics include all the physical and dimensional parameters needed from the rammed-earth wall, such as those of the rammed-earth box, putlocks and putlog holes. This data is structured according to the three aspects of constructive characterization: technical, material and dimensional.

Form 3. Pathological process. This third form is assigned to the study of current damage, its sources and causes, and it is focus on the development of a pre-diagnosis. Nevertheless, in order to facilitate the reading and completion of the form, it has been decided to gather all the damages into three general groups, (material, structural and surface damages). In addition, the form enables the decision-making regarding the more feasible causes and sources in the pathological process.

Form 4. Risk assessment. Risks and damage are evaluated in order to design a methodology which will allow a better understanding of feasible failures. In order to help the assignation of values to each risk factor, an auxiliary form is attached, which briefly holds all the criteria.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NORTE ☑ SUR ☑ ESTE ☐ OESTE ☐ Privado ☐ Público ☑ Con uso ☑ Sin uso ☐ B.I.C. ☑
Datos de entorno
PLUVIOSIDAD: Baja ☑ Alta ☐
ENTORNO FÍSICO: Exento - ajardinado ☐ Exento - asfaltado ☐ Exento - terreno natural ☑ Medianero ☐ Urbano consolidado ☐ Urbano no consolidado ☑ Rural - Aislado ☐
PROTECCIÓN: Tejado ☐ Revest. ☑ Zócalo ☐
Comentarios Se encuentra sobre una elevación natural, sin edificaciones colindantes
Datos tipológicos
Arquitectura defensiva ☑ Arquitectura religiosa ☐ Arquitectura residencial ☐ Otros ☐
Comentarios: El recinto está formado por el Alcázar y un reconto amuralado
Adscripción histórica
Prerromano ☐ Romano ☐ Visigodo ☐
Islámico califal ☐ Islámico Taifa ☐ Islámico Almorávide ☐ Islámico Almohade ☑ Islámico Nazarí ☐
Mudéjar ☐ Moderno (s. XVI) ☐ Moderno (s. XVII) ☐ Moderno (s. XVIII) ☐
Contemporáneo (s. XIX) ☐ Contemporáneo (s. XX) ☐
Comentarios
Intervenciones
Código de la Intervención 74 Año 2010
Ámbito Torres y lienzos del tramo norte
Técnicos Antonio Martín Molina
Constructora
Descripción Recuperación de 4 torres y los lienzos de muralla comprendidos entre ellas, desde la torre que custodia la Puerta Real de la fortaleza, pasando por la Puerta de la Traición hasta la conocida como Torre del Homenaje. Adecuación de la ladera con paseo peato
ACCIONES SOBRE TAPIA
Limpieza suciedades ☑ Limpieza vegetal ☐ Apeos ☐ Atados ☐ Anclajes ☐ Contrafuertes ☐ Cimentación suelo ☐ Cimentación cimiento ☐ Humedad pie muro ☐ Humedad cabeza muro ☐
Consolidación inorgánicos ☐ Consolidación orgánicos ☐ Restituciones cajón completo ☑ Restituciones cajón una cara ☐ Revest. reparacion mortero ☑ Revest. mortero cal ☑ Revest. proyeccion tierra ☐ Revest. relleno ladrillo ☐ Revestimiento forro ☐ Revestimiento hormigón ☐ Grieta sistema blando ☑ Grieta sistema duro ☐

Figure 1. Example of a diagnosis data form 1, regarding general information of a sample of historical rammed-earth wall.

3 CONSTRUCTIVE CHARACTERIZATION

With the purpose of describing a rammed-earth wall, it is necessary to review its constructive process. Hence, we become familiar with the materials, the auxiliary resources and processes that should be used, when restoration work is needed. Constructive analysis is divided into three parts corresponding to three main aspects of any constructive system, gathered on diagnosis data form 2.

3.1 *Technical characterization*

Firstly the generic construction system of a traditional rammed-earth wall is analyzed, although it is already described by other authors.

Facing the constructive analysis, the chrono-typological classification of Graciani and Tabales (2008) is proposed, together with the addition of fields deduced through the study of the selected walls. Therefore, a definition is obtained, in terms of the complexity of the constructive system, from the simple monolithic rammed-earth wall, to the more complex "fraga" type, which consists on a wall reinforced with inner columns and courses, usually made of stones or fired bricks.

According to the constructive process studied, certain aspects considered for the preliminary studies have been proposed on diagnosis data form 2. Hence, for instance, it is possible to identify the type of constructive rammed-earth blocks, (in the form of single blocks or of long blocks), or the rhythm of the putlocks, which describes interesting characteristics to take into account in any evaluation.

3.2 *Material characterization*

The first aspect that may be highlighted is the great diversity in the dosage for the rammed-earth mass, and hence it is impossible to attain general models or rules, and each case should be studied independently. Nevertheless, it is viable to identify the variety of materials normally used.

The main aim is to register the basic components through a visual inspection, which could be confirmed later by means of laboratory analysis. To this end, several parameters are designed in order to help towards the characterization: ranging from the estimated lime content and the aggregate maximum size or their shape (round or coarse shape) and even to other kinds of foreign materials in a rammed-earth wall, such as boulders and ceramic rubble. All these parameters are classified on diagnosis data form 3. Some outstanding parameters are detailed below:

- Soil content. Usually this is the basic component for this kind of wall and its nature will depend directly on the nature of the soil of the extraction site.
- Lime content. Depending on the hardness or the strength of the wall and on the abundant presence of lime nodules, a preliminary assessment may be made.
- Maximum size of the gravel. The gravel is an important part of the mass, especially in military rammed-earth walls. Knowledge of the gravel content may be useful for the design of repair material that matches properly with the eroded wall.
- Type of coarse aggregate. Based on the nature of the extraction site, either sharp or rounded aggregate can be found in a wall.
- Presence of stone blocks or ceramic rubble. Considerable quantities of these materials sometimes used to strengthen the wall, to take advantage of spare materials, and also to speed up the building process.

Moreover, laboratory tests may be ran once this organoleptic evaluation is over. These tests are useful in the identification of the soil and of its suitability in earthen buildings. Some of these proposals are based on a critical review carried out within the project BIA-2004.1092 (Graciani, et al., 2005), as well as in earthen-building manuals (Ontiveros et al., 2006).

3.3 *Dimensional characterization*

In order to complete the constructive characterization of a rammed-earth wall, it is necessary to analyze the dimensional parameters, both those related to the whole wall and those to each of its auxiliary items. For this reason the analysis is split into three parts, each one related to a different concern, such as the rammed-earth blocks, the shuttering (tapial), and the putlocks. It should be pointed out that the relationship between the dimensions of a wall and its historical period has yet to be exactly determined. Hence, the following parameters have been chosen:

- The rammed-earth box. This may be considered as the essential constructive unit of a wall, in the same way as a fired brick is to brickwork. Although it is not always feasible to define it as a unit of the wall, it is sometimes possible to register its three dimensions: the height, the length, and the width. The heights are summed up in just three types: short module (≤80 cm), high module (85–95 cm) (Graciani & Tabales 2008:137), and special module (≥100 cm). It is always feasible to measure the length of the box whenever the wall is built with short blocks of rammed earth. Otherwise the wall would show some slanting joints instead of vertical joints.
- The formwork. This should be the most useful parameter for the characterization of a rammed-earth wall, but unfortunately there are no formworks remaining. There only remain some prints on the surfaces showing their dimensions and the number of wooden planks that formed the shuttering. These marks are, to a certain point, more constant than the measures from the rammed-earth box.
- The putlocks (or, in their absence, the putlog holes), are very specific items of any rammed-earth wall. Certain tendencies in the use of several types of putlocks may be registered, which are mainly made of a tough wood. The shape may vary from a circular or semi-circular timber to square o rectangular sections, usually of about 3×7 cm (Martín 2005). The gaps between consecutive putlocks and their rhythm may be used as a rough parameter of characterization.

4 CHARACTERIZATION OF THE STATE OF CONSERVATION

The goal is to determine the origin of the pathologies so that strategy for suitable intervention may be planned. It must be borne in mind that there is no singular cause for any failure. Normally several types of damage can be linked, since the diagnosis becomes more complex when determining which is the original area of damage is necessary.

The diagnosis Data Form 3 groups all the damage into three groups according to their nature. The first group is material damage which is related to the erosion, although at some extend they could affect structural stability. This one is normally caused by weathering agents such as water, rain, ice, wind, thermal changes, and chemical attacks.

The next group concerns structural damage, which occurs when the limits of strength and tension in the rammed-earth wall are exceeded. The last group represents the surface damage, which, although it may be similar to material damage in some ways, is treated separately since this damage only affects the external face of the wall or its coating, and, in contrast to material damage, no loss of material has to occur. Dirtiness, efflorescence, and all pathologies with regarding the coating, are examples of this kind of damage.

The first step in the pathological analysis is to arrange the data according to the type of damage and discuss about their feasible causes. Hence, the agents and causes are classified according to their nature. Firstly, mechanical causes are those which lead to structural tension in the wall. They usually lead to cracking, bending, distortions, and a slanting of the wall. In the other hand, physical causes concerning the group of atmospheric agents, and therefore are practically unavoidable; thereby it is only possible to take measures in order to mitigate their effects. Chemical causes involve any chemical substance that may react to the components of the wall and cause unexpected effects. Urban pollution, efflorescence, fungus and lichen attacks are common examples.

The causes can also be classified as direct or indirect. When the causes are external and they do not belong to the wall itself, they are called direct causes, since they may generate damages whenever they appear. Any cause can be considered as indirect if they are part of the characteristics of the rammed-earth wall. Furthermore, could happen that no indication of deterioration will arise unless a specific external circumstance appears. For instance, low quality rammed earth may remain in good condition until dampness arises.

5 VULNERABILITY AND RISK CHARACTERIZATION

In order to assess the risks, it is essential to thoroughly know how rammed earth functions and also its pathological response in order to obtain a better base for decision-making. If solely current damages are considered, only corrective measures can be applied. Nevertheless, the management of a heritage object requires greater understanding for medium and long-term planning. To this end, a study of vulnerability and risks has been introduced, as claimed by several international organizations (Iscarsah 2000).

5.1 *Concepts involved in risk assessment*

First of all, in order to properly comprehend the whole evaluation process an introduction of the main terms and issues related to risk assessment is needed.

Risk factor and risk level. Risk and hazard are separate terms that are commonly confused. Hazard refers to the inherent capacity of a circumstance to generate damage, whereas risk is the combination of the probability of a defined hazard and the magnitude of the consequences of damage. For instance, weathering is always a hazardous circumstance for rammed-earth buildings; however the chance of damage occurring (risk) might be low or null. Risk factor is a condition from the object or the environment that helps towards the evolution of new damage, or aggravates damage. The Risk Level (NR) is the parameter that measures the rate of risk.

Vulnerability and Vulnerability Level. Vulnerability for a rammed-earth wall is defined as its incapability to be adjusted by itself to a certain change in the environment, due to the influence of certain risk factors (Wilches-Chaux 1993). In addition, Vulnerability is always linked to an aspect. The concept of Vulnerability does not exist alone. By analyzing the failure process, the main weaknesses of this kind of wall may be concluded, and so the aspects the vulnerability that is joined to. The vulnerability level is a measure of this concept, in order to describe the state of the wall. Therefore, the weakness of a wall can be characterized by the Vulnerability level (NV) and the Risk level (NR), among other parameters.

Durability. This concern is strongly bound to Vulnerability. Monjo (2007) defines it as proportionally inverse to vulnerability. Therefore, the more vulnerable a wall is, the less durability it shows. The objective is to achieve the greatest Durability.

Risk map. This is a graphical tool that represents and classifies risk factors in order to determine patterns and trends in wall behaviour. Likewise, risk maps constitute the last step to a more accurately description of some of the measurement parameters described above.

5.2 *Risk assessment methodology*

Since Vulnerability is always linked to something, it had been selected three aspects that any rammed-earth wall is vulnerable to: vulnerability to water, to erosion and to structural instability.

In order to carry out this risk assessment, it has been developed a tool which focuses both on the risks of the wall and on the current damage. This tool aims to plan preventive actions to avoid new pathological processes from occurring. Likewise, it is intended to design corrective actions to repair the current damage, and also to bring up to date or to enhance the conditions of maintenance.

Therefore, an improvement in durability may be achieved by identifying and limiting any weaknesses. As a conceptual model, a risk assessment method is applied. More precisely the NTP-330: A simplified method for risk assessment in accidents (Bestraten & Pareja 1994) it is used as a support and layout. This simplified method enables the identification of conventional risk situations (risk level) through minimum resources, so that the designation of a suitable preventive and corrective action can be made. Broadly speaking, the method outlined is based on setting the probability of damage (accidents) and the consequences (material, intangible, and personal) that this would involve.

Therefore, the risk level (NR) of an element is established based on the probability of damage (NP) and on the consequences (NC) of this damage. Likewise, the probability of the damage occurring (NP) depends on the deficiency level (ND) of the risk under analysis and on the exposure rate (NE) for the assessed risk.

Next, the evaluation process is to be briefly described.

5.2.1 *Determining vulnerabilities and risk factors*

First of all, three types of vulnerabilities should be studied and characterized, corresponding to those stated weak aspects of rammed earth: vulnerability to water, physical vulnerability (erosion) and structural vulnerability (structural instability). Each type of vulnerability depends on several risk factors that must be determined and classified in order to identify any weaknesses of the rammed-earth wall. Therefore, according to their nature all the risk factors, for each type of vulnerability, are organised into the three groups detailed below:

- Material risk factors. Those refer to characteristics of the rammed earth itself.
- External risk factors. These risks do not depend directly on the rammed-earth wall, but on the environment where it is found.
- Anthropic risk factors. Those are also external risks, but their origin is related to human activities.

5.2.2 *Risk factor assessment*

The next step involves the assessment of each risk factor by assigning exposure levels (NE). Exposure levels are used in an effort to measure how the wall is affected by a specific circumstance that may generate damage. Each exposure level is designed within a range, in this case it consists on five consecutive levels. In order to work with these levels, each range has been assigned a numbered scale, whereby 10 corresponds to the highest level of exposure. These ranges are inserted into diagnosis data form 4, and also into the data base. Each risk factor is assessed according with the pre-designed rules and criteria.

5.2.3 *Setting the probability of damage*

Not all risk factors are of the same significance in the generation of pathological processes. High exposure levels of certain risk factors might induce a greater possibility of damage than others. However, in order to carry out a suitable classification, a simple criticality analysis of risk factors is used (Canivell 2011). It consists on a scale of three types of risk factors: key, moderate factors and secondary factors, which are applied directly to each exposure level (NE) in order to obtain probability levels (NP) for each risk factor.

5.2.4 *Characterization of the vulnerability*

Once Probability levels (NP) are characterized for each factor, their global evaluation is then sought in order to achieve a parameter which measures a general state of risk. To this end, risk maps are used since they allow both the plotting of a chart and the characterization of the state of levels of selected risk factors.

Radial chart is the selected representation for risk maps (Figure 2), where each axis represents a probability level (NP) for certain vulnerability. Through the reading of these maps, it is possible to deduce trends, prevailing values, certain parallels, and/or differences between measurements.

The area or the perimeter of the charts characterizes the Vulnerability levels (NV) of each rammed-earth wall: vulnerability to water (NV-HID), physical vulnerability (NV-FIS), and structural vulnerability (NV-EST).

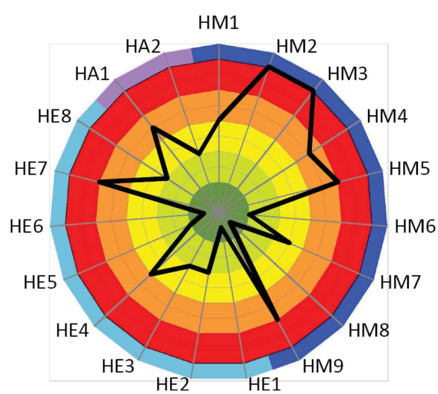

Figure 2. Example of a Water risk map. Polygonal chart which sets out risk factors for water vulnerability.

WATER RISK LEVEL (NR-HID) WATER INTERVENTION LEVEL (NI-HID)		CONSEQUENCE LEVEL (NC)				
		59-48 Very high	48-37 High	37-26 Moderate	26-15 Low	15-0 Very low
WATER VULNERABILITY LEVEL (NV)	309-225 VH	V	V	V	IV	III
	225-135 H	V	V	IV	IV	III
	135-65 M	IV	IV	III	III	II
	65 - 20 L	III	II	II	II	I
	20 - 0 VL	II	I	I	I	I

Figure 3. Example of matrix for water vulnerability.

5.2.5 *Characterization of risk and decision making*

According to NTP-330 methodology, the impact of both the potential material and potential personal damage must be assessed. As stated before, risk level depends on the impact of the feasible damages on the wall. The parameter which measures this impact is the consequence level (NC) and it is obtained through a similar procedure as vulnerability level, but antrophic risk factor are used instead.

Through risk matrix (Figure 3), whose usage is widespread in risk evaluation, vulnerability and consequence levels (NV, NC) are crossed in order to obtain the risk level (NR). One specific risk matrix has been built for each vulnerability, hence, as an outcome, three kinds of risk level will be obtained. Risk levels are scaled in a range of five steps, from trivial risk level to unbearable risk level. As it is shown in Figure 3, a five-step colour scale also matches each risk level.

Once risk level (NR) is known, it is possible to determine a suitable set of actions, which is regarded as intervention level (NI). Each state of risk (NR) matches an Intervention level (NI) for which preventive, corrective and maintenance actions are designed. The higher the risk level becomes, the more urgently the actions (preventive, corrective and maintenance) should be taken. There are five intervention levels for each type of vulnerability, ranging from low Intervention to urgent Intervention level. This is created just to help the decision-making, when actions are to be taken in order to reduce vulnerability and maximize durability of rammed-earth walls.

6 CONCLUSION

A complete anamnesis is necessary in order to carry out a proper wall diagnoses that may lead to effective treatments. The anamnesis must include the full history of the rammed-earth wall, by considering carefully its constructive and pathologic aspects plus its risk factors.

The diagnostic system should be considered as a tool for guiding and supporting during the decision-making. It does not offer automatically a closed and definite solution, but a synthesis of the essential aspects required to design an adequate treatment, either for maintenance or prevention.

The organoleptic analysis represents the first stage in data collection. However, when detailed laboratory tests are not feasible or available, the parametric evaluation here proposed points out the main aspects to consider in order to diagnose and design a treatment.

The damage evaluation proposed in diagnosis data Form 3 represents the current conservation state of the construction, being thus useful for the proposal of corrective action on the walls. On the other hand, the tool for the evaluation of vulnerability puts together risk factors, probable damage evolution and the seriousness of their consequences, which makes it more suitable for the design of maintenance and preventative measures.

REFERENCES

Bestratén, M. & Pareja, F. 1994. NTP 330: Sistema simplificado de evaluación de riesgos de accidente. *Instituto Nacional de Seguridad e Higiene en el Trabajo*. Madrid: INSHT.

Canivell, J. 2011. *Methodology of diagnosis and characterization of historical rammed-earth walls*. PhD Thesis. Seville: Departament of Architectural Constructions 2. University of Seville.

Graciani, A. et al. 2005. Revisión crítica de la analíticas sobre las fábricas de tapial en la muralla islámica de Sevilla. *Procedings of I Conference on Construction Research*. Madrid: Instituto de Ciencias de la Construcción Eduardo Torroja: 213–221.

Graciani, A. & Tabales, M.Á. 2008. El tapial en el área sevillana. Avance cronotipológico estructural. *Arqueología de la Arquitectura*. Vol. 5, January–December. Madrid/Vitoria: Consejo Superior de Investigaciones Científicas, CSIC: 135–158.

Iscarsah 2000. In press. Declaration of Assasi. *Assasi: Icomos International Scientific Committee on the Analysis and Restoration of Structures of Architectural Heritage*.

Martín García, M. 2005. La construcción del tapial en época nazarí: el caso de la muralla exterior del Albaicín de Granada. *Proceedings of the 4th National Congress on Construction History, Cádiz 27–29 of January 2005*. Madrid: Instituto Juan de Herrera. 741–749.

Monjo, J. 2007. Durabilidad vs vulnerabilidad. *Informes de la construcción*. Vol. 59, 507. Madrid: CSIC, Instituto Eduardo Torroja: 43–58.

Ontiveros, E. et al. 2006. Programa de normalización de estudios previos aplicado a bienes inmuebles. *Scientific coordination Esther Ontiveros Ortega*. Sevilla: Junta de Andalucia: 161–192.

Wilches-Chaux, G. 1993. La vulnerabilidad global. *Los desastres no son naturales* (Ed. Andrew Maskrey). Bogota: Red de estudios sociales en prevención de desastres en Latino América. Colombia: 11–41.