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PROJECT TraRetro

(Coordinator: CUEBC; Participants: CERU + CEPRIS + ECPFE)

Revisiting Traditional Building Techniques for Appropriate Maintenance and Earthquake Retrofitting of Vernacular Constructions

Centro Europeu de Riscos Urbanos
Lisboa - Portugal

WP1 : Seismic Resistance of Portuguese Vernacular Architecture : A Critical Review

Activities developed by CERU (Portugal): Paula TEVES-COSTA (Coordinator)

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Foreword

The review of the seismic resistance of Portuguese vernacular architecture was performed by two researchers of Porto University (FEUP – *Faculdade de Engenharia da Universidade do Porto, Portugal)* and supported by CERU in the aim of the project TraRetro - Revisiting Traditional Building Techniques for Appropriate Maintenance and Earthquake Retrofitting of Vernacular Constructions (Leader: CUEBC; Partners: CERU, CEPRIS, ECPFE) sponsored by EUR-OPA Major Hazards Agreement, Council of Europe.

The following pages present the report delivered by the authors, describing the work performed in detail.

Note – In the report delivered by the authors the project is referred by LAReHBA because it was the first acronym given to this project.

Seismic Resistance of Portuguese Vernacular Architecture: A critical review

Nuno Pereira and Xavier Romão

A report developed at the request of the European Centre for Urban Risk (CERU), Portugal, within the context of the research project LAReHBA - Local Appropriate Retrofitting of Historical Built-up Areas - and of the EUR-OPA framework sponsored by the European Commission.

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Seismic Resistance of Portuguese Vernacular Architecture: A critical review

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1. Introduction

The present report was commissioned by the European Centre for Urban Risk (CERU), Portugal, within the context of the research project LAReHBA - Local Appropriate Retrofitting of Historical Built-up Areas coordinated by the Centro Universitario Europeo per I Beni Culturale.

The LAReHBA project has essentially two main objectives. The first objective is the development of a preliminary atlas including principles of local seismic cultures existing in Portugal, Italy, Greece and Morocco. It involves the survey of seismic resistant criteria and construction techniques that exist in these countries and the assessment of their usefulness to guarantee seismic safety. The second objective of the project consists in evaluating if and how these techniques can be used to dissipate the energy of earthquakes to determine what techniques can still be used or maintained today. The key research questions of the project are, therefore, how to identify these local seismic resisting techniques, how to validate the performance of these techniques and how to transfer the knowledge regarding the effectiveness of vernacular seismic safety techniques to decision makers.

To achieve the first objective of the project, a preliminary atlas serving as a basis for the calibration (at the country level) of a tutorial needs to be developed. This tutorial will provide a consistent and objective methodology to be used in the identification of local seismic culture elements in each country. Particularly, the tutorial will provide a consistent approach to identify "anomalies" in the construction (i.e. unusual or unexpected elements in a construction) and to classify them as elements of a local seismic culture or elements that are associated to other purposes (e.g. comfort improvement, prevention of effects from climate and environmental hazards or strengthening of the structural system for other loads). Some of these anomalies can be seen as measures that were adopted purely as anti-seismic measures, primarily as anti-seismic measures that, simultaneously, also improved other features (e.g. comfort or structural stability for other loads), or primarily as measures introduced to improve comfort or structural stability to other loads but also exhibit some anti-seismic properties.

The preliminary atlas can also be used as a tool for the calibration of the generic tutorial developed in previous studies (Ferrigni, 1989), in order to adapt it to the constructive and seismic historic background of each country. After this stage, the project aims to address the research questions by conducting field and/or numerical analyses studies illustrating the local seismic features of each country and by applying the calibrated tutorial to identify and validate the local seismic cultures of each country. The information collected at this stage will then be used to revise the preliminary atlas that was defined in the first stage of the project, thus increasing the resolution of the preliminary data with information collected in the field.

The present report provides data for the first objective of the LAReHBA project. Accordingly, it provides a preliminary analysis of seismic resistant elements found in Portuguese vernacular architecture. The referred analysis is based on a critical review of the literature and on available data, and involves a four stage evaluation process. The first stage involves a screening of the country at a macro-level to develop a generic typological map of Portuguese vernacular architecture. The second stage involves cross-referencing this macro screening map with data on short-term hazards, in order to understand the technical aspects that might have led to the adoption of each structural layout/system. The third stage correlates this map with data on seismological activity. From this analysis, the main properties that can only be associated to seismic hazards or other short term hazards will be singled out and regions with the highest probability of finding a local seismic culture will be identified. The fourth stage presents an historical and technical review of the data and literature available on different regions of the country towards the construction of the preliminary atlas.

2. Methodology

As mentioned before, the research included in the present report aims to address the research objectives for the first year of the LAReHBA project. To achieve such objectives, i.e. to develop a preliminary atlas on the local seismic culture in Portugal, a systematic review was performed. The critical systematic review that was carried out was divided into five tasks, developed sequentially during this research and that are presented in the following.

2.1. Task 1 – Preliminary definition of a typological map for Portuguese vernacular architecture

The first task involved making a systematic review of the data available on vernacular architecture in Portugal. Among the publications reviewed, the dataset developed by the survey carried out by the union of Portuguese architects (AAVV, 1980) was used as the foundation for the preliminary atlas to be defined. This survey was a field study conducted by teams of architects with the objective of making a reconnaissance of the characteristics of Portuguese vernacular architecture. The survey covered a total of six regions of the mainland country. More recently (OA, 2000; Mestre, 2002), extensions of the survey were carried out to cover also the insular parts of the country (i.e. the Azores and Madeira archipelagos) which resulted in the development of taxonomical maps for these regions. The eight regions covered by the three mentioned studies are shown in Fig. 1.

The aforementioned studies provided an extensive catalogue about the typologies found in the Portuguese vernacular architecture. A global map (designated hereon as the *reference map*) was constructed in this task which aggregates the information of the surveys from each region. Furthermore, a review of the documents was also made and additional studies were consulted to critically analyse the reference map and the characteristics of the buildings observed in each region. The analysis described in the present report was limited to address only the mainland part of the country.

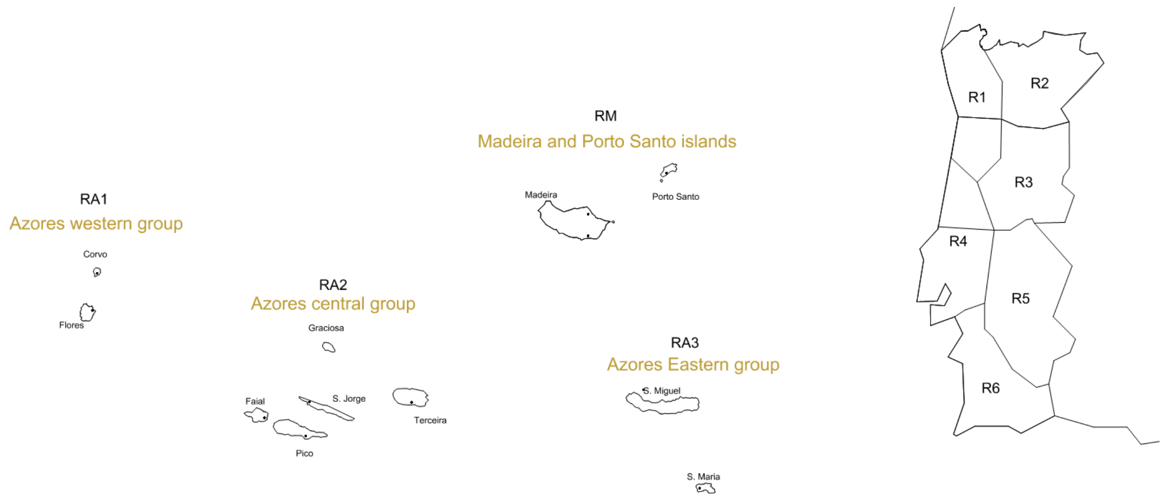


Figure 1. Regions considered in the surveys performed in Portugal

The reference map was then post-processed to derive the expected typological atlas summarizing a possible set of properties that characterising Portuguese vernacular architecture. The post-processing consisted in cross-referencing the map with available information regarding the geological background of the country (IGP, 2016; Pimentel, 1994) and several studies addressing the characteristics and properties of traditional construction in the different regions of the surveys. Among the reference studies that were reviewed, emphasis was given to the studies addressing the characteristics of timber and earth architecture in Portugal. Finally, after adding the collected information to the reference map, a generalized typological atlas was established based on which it was possible to define regional typologies. This new map was then used as the starting point for the subsequent correlation analysis between these typologies and several short and long return period hazards. Differences between similar typologies were analysed and the main anomalies that were identified were evaluated from the structural engineering point of view.

2.2. Task 2 – Correlation of the typological atlas with short return period hazards and climate conditions

The second task cross-referenced the developed typological atlas with data representing multiple environmental conditions and short term hazards. From the literature review that was performed, little to no information was found correlating traditional construction features with environmental effects or other short return period hazards. The few relevant studies that were found addressed the efficiency of traditional construction methods and materials regarding thermal isolation and sustainability (e.g. Fernandes *et al.* 2014; Ferreira *et al.* 2012; Ferreira *et al.* 2015). Hence, in order to identify structural measures that could be associated with the improvement of comfort levels, a spatial disaggregation of the available data was performed for four short term hazards/climate parameters including: temperature, precipitation levels, flood susceptibility and wildfires. Temperature and precipitation levels were considered by analysing climate data averaged over the period 1971-2000, thus representing the expectation of these conditions over a short average return period. The influence of precipitation levels on the construction details of the vernacular architecture of each region were also cross-referenced with the spatial disaggregation of the flood susceptibility index. Finally, wildfire susceptibility was analysed in order to correlate the characteristics of the typical buildings with the common slope of the terrain and with the amount of vegetation/ timber available in each region. By correlating these environmental and climate indicators with the typological atlas, a critical analysis was then carried out addressing the possible reasons for the use of particular construction elements in some regions. The structural elements that could potentially be associated with these climate and environmental hazards were identified by reviewing the reference map due to its higher resolution. The possible structural performance indicators were further integrated at a macro-scale in the next task to try to isolate locations with a higher probability of having traces of a local seismic culture.

2.3. Task 3 – Correlation of the typological atlas with long return period hazards: historical seismicity of the country and preliminary assessment of potential local seismic cultures

After attempting to isolate the possible effects of climate/short return period hazards in the structural conception and construction, a similar analysis was performed cross-referencing the typologies of buildings found with historical earthquake events that occurred in the country. The first stage involved a review of the historical seismicity, analysing particularly the differences in the seismic hazard across the country. The analysis that was performed involved a review of data available both from empirical and instrumental seismicity. From the instrumental data (IPMA 2004;2014), the period 1961-2000 was analysed. In addition, the datasets presented in other catalogues (Oliveira, 1986; Lopes *et al.*, 2008; Martins and Víctor, 1991) were used to identify the areas where damaging events occurred in the past.

The analysis that was performed evaluated what were the main seismic events that occurred in the past and to which some traces of a local seismic culture could be associated. The type of seismic culture that can potentially exist in each region according to the intensities and return periods of the ground motions was identified following the main ideas established by Ferrini (2015). A preliminary screening of the Portuguese territory was then performed, identifying the earthquake-prone areas and the historical evolution that may have led to the propagation of empirical knowledge regarding constructions practices and earthquake effects.

2.4. Task 4 – Historical review of construction measures adopted after the main Portuguese earthquake events

The characteristics of the historical seismicity in Portugal were analysed. The main earthquake events and the corresponding regions with higher levels of damage were isolated. The emphasis of the analysis was then on the measures that were implemented in the aftermath of these events and in the reconstruction practices. Due to the inexistence of available objective information regarding the 1531 earthquake, this event was not included in the study, despite the known destructive effects this earthquake had on the mainland territory. The analysis for the mainland country included the areas more affected and retrofitted after the 1755 earthquake. Furthermore, the review included the documented interventions that were observed after the major events that have occurred in Portugal, correlating the general typological map that was developed with the main areas where interventions occurred after earthquakes.

2.5. Task 5 – Definition of a preliminary atlas including the different locations where traces of a local seismic culture was identified

After analysing the interventions that were carried out after each event, a set of regions that could be defined as candidates for the existence of a potential local seismic culture were identified. These regions were compared with the typological map defined in Task 1. A set of macro regions and their expected type of building was then established. The field observations made by Correia *et al.* (2015a) were used to verify the observed anomalies and the consistency of the defined typological atlas. Based on this information, a preliminary atlas including the main seismic resistant features of Portuguese vernacular architecture was developed, identifying also the locations where preliminary local seismic cultures were found and illustrating their main elements. This atlas was cross-referenced with the initial typological atlas to validate its adequacy.

3. Critical overview of Portuguese vernacular architecture

3.1. Development of a reference typological map

Vernacular architecture can be defined as the type of construction that is primarily designed to fulfil the needs of the people. It is an aggregation and a reflection of the characteristics of a given region, namely its history, traditions and the technical skills of local builders. Therefore, it also mimics the resilience and the predisposition to change that is inherent to a given culture. This type of construction moves away from the typical formality or knowledge of religious architecture, which is typically associated with different forms, engineering elements, scales and materials. Local building conventions and available materials are the only formal elements of vernacular architecture and are the key to characterize its different types. Local building conventions reflect the common lack of stylistic and aesthetical elements where the construction typologies are driven by a more pragmatic perspective that involves a consistent level of repetition and a slow improvement of the constructive solutions based on empirical knowledge. Therefore, the vernacular construction is a reflex of the social, cultural and economic situations of a community, where the adopted constructive solutions, the developed empirical techniques and the main elements included in the constructions reflect its history and memory. In some cases, vernacular architecture also reflects the attempts made by builders to include formal or stylistic elements, forms and materials that are based on new technologies that were available at the time of construction. Changes due to lessons learned from the local environment or due to natural events lead to interventions that are made after an initial configuration. Vernacular architecture implies an imperative acceptance of the natural phenomena of the region where the constructions are located. The existence and prevalence of natural phenomena associated with extreme weather conditions, such as strong winds, storms, hurricanes, tornadoes, or other environmental events, such as earthquakes and volcanoes, outlines the characteristics of these constructions.

There is, therefore, a duality in vernacular architecture. On the one hand, it includes a replicability and constant slow improvement of the construction techniques while, on the other hand, it also features the quick changes that are introduced after a significant hazardous event and that may create a rupture with the traditional characteristics of the constructions that were being perpetuated. The inertia that characteristically leads to the maintenance and replication of known construction solutions and archetypes often ends due to a renovation spree that breaks with the past and leads to the destruction of the vernacular architectural culture that existed over the past years. The duality of these factors is usually seen in developed countries, where new constructive technologies break away from the ancient knowledge.

Vernacular architecture refers to all the forms of popular architecture (i.e. of the people) where there is a straight connection between the people and the environment they live in, the tradition and the heritage of a given region. It has, therefore, a regional character, depending on the environment where the constructions are in, the materials that are available and the topography of the terrain, the isolation of the region and the level of urban planning implemented after the construction. The cultural roots, the socio-economic statutes or the state of the development of a country, its exposure to natural or man-made hazards and its history have clear effects on its vernacular architecture. Figure 2 shows the reference map obtained from the aggregation of the information provided by the surveys considered in the present study. This reference map is based on the symbols, typologies and spatial distribution established by the reviewed surveys (AAVV, 1980). A general analysis of the reference map shows that, according to the survey data, no typological information was generated for region R5. The reason for this absence was mentioned by the survey team and was related to the variability of the observed constructions that did not allow the identification of typological trends or patterns of popular architecture, as was found for the other regions. Nonetheless, as in the other regions, examples and illustrations are provided which were cross-checked and cross-referenced herein with other publications analysing traditional buildings in Portugal (namely Oliveira and Galhano, 1992).

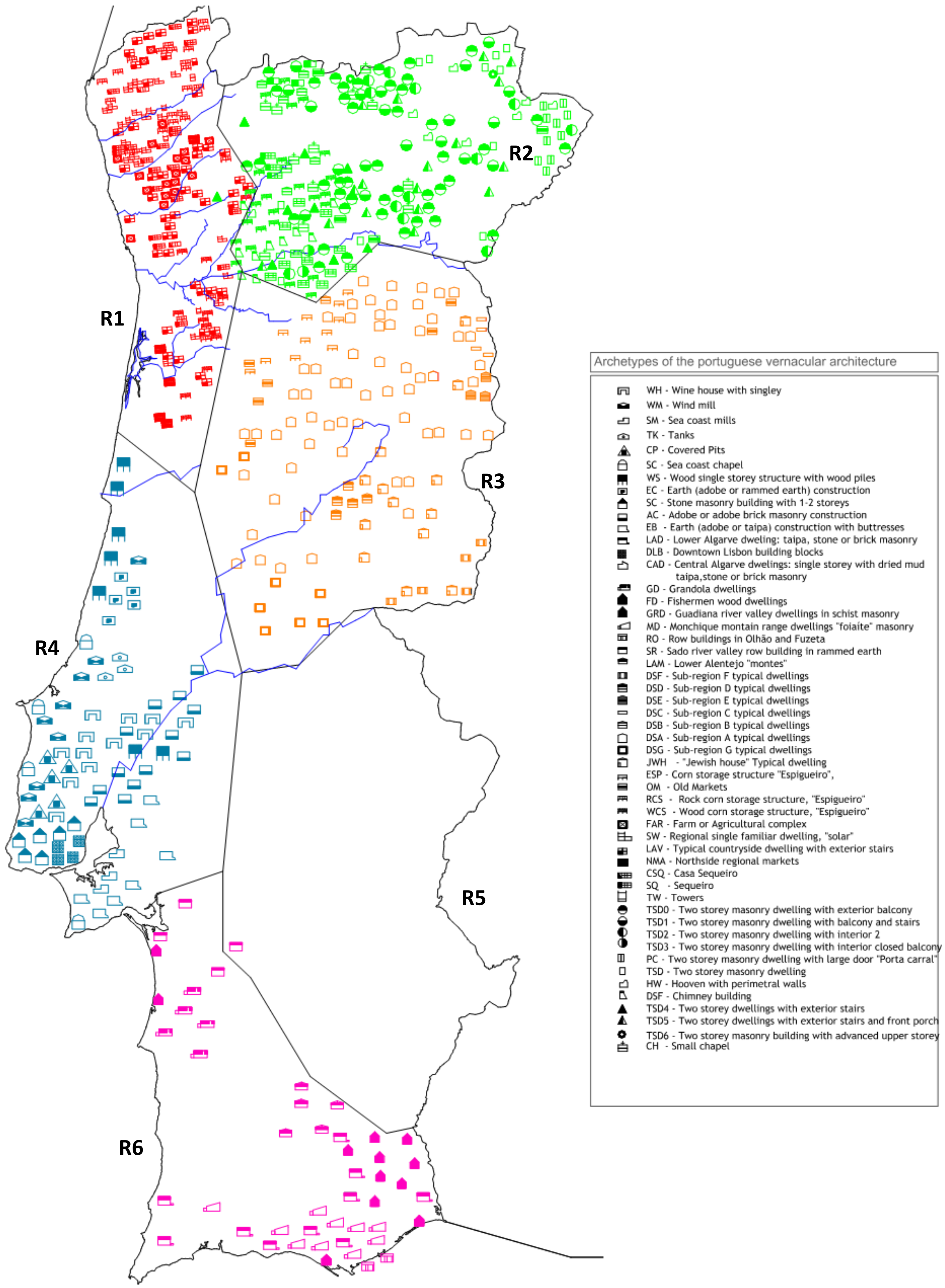


Figure 2. Reference typological map created based on the surveys conducted in the 1950's and 1960's in Mainland Portugal (data source: AAVV, 1980).

From the same general overview, it can be seen that patterns emerge regarding the type of materials used in each region. The northern part of the territory is clearly dominated by granite and schist masonry buildings, as opposed to the adobe houses found in the central coastal area and the rammed earth constructions identified to the south of the Tagus river valley. To have a better understating about the expected connection between local geology and the materials used in the buildings, a general geological map of the continental part of the country was constructed (see Fig. 3a) based on detailed geological data available in IGP (2016) and in the representation by Pimentel (1994). The shear wave velocities of the terrain (on the upper 30 metres of the subsoil, VS30) are also shown (see Fig. 3b) based on the representation proposed by Silva (2013).

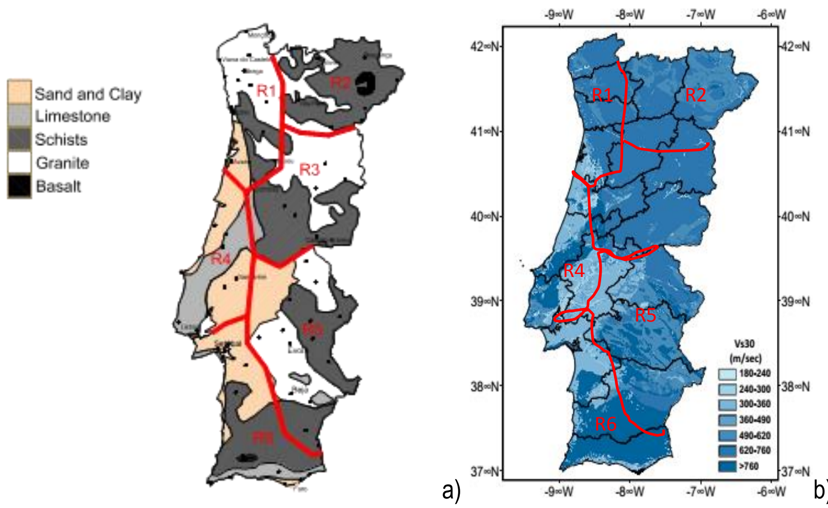


Figure 3. Adopted generalized geological map of Portugal illustrating the main areas where different types of materials can be found (based on IGP, 2016 and Pimentel, 1994) (a) and VS30 map proposed by Silva, 2013 (b)

As expected, there is a clear relation between the materials identified in the survey results and the basic geological features of the soil. Granite reserves exist in the north or region R1, R3 and in R5, particularly in the region around Évora. Soft soil deposits are found in the south of R1 (Aveiro), in R4 (together with limestone reserves) and in the Tagus river flood lands, extending to the coastal centre area of R6. Schists are available in a region covering almost the total area of R2 and part of R6. Despite the availability of schists in this latter area, the general construction typology identified uses a rammed earth system, while schist masonry is only adopted in the Guadiana river valley.

In areas where the soil is rich in clay and sand, earth construction is predominant in the vernacular architecture typologies that are observed. This conclusion is corroborated by the study of Fernandes (2013) who proposed an updated version of the map regarding the spatial distribution of earth construction techniques in mainland Portugal (see Fig. 4).

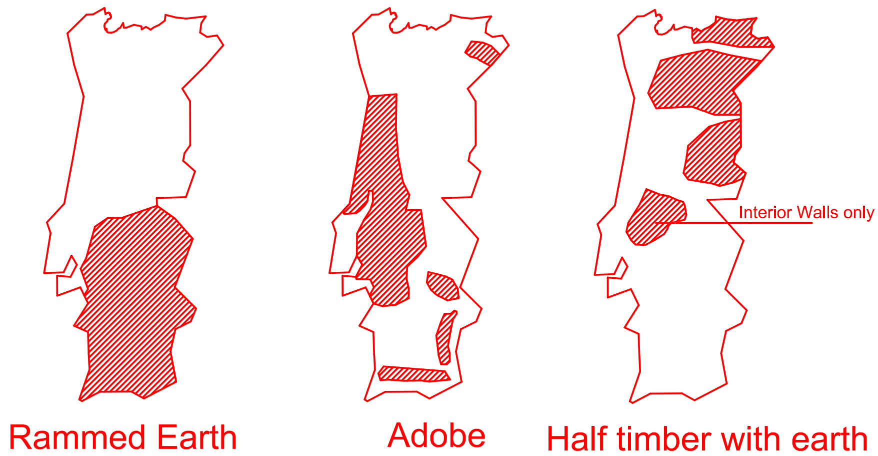


Figure 4. Distribution of the earth construction techniques in mainland Portugal according to Fernandes (2013).

A particular reference has to be made regarding the extensive use of rammed earth in constructions located to the south of the Tagus river. The existence of these techniques has been referred to date as far as to the 1st century in the Iberia Peninsula and benefited from modifications carried out by several civilizations, including, but not limited to, the Moorish occupations of the area (Pinto, 2004). Another reason for the use of this material, particularly when walls with large widths are adopted, may be connected to the climate of the referred region, as addressed later in this report. Half-timber with earth (hereon termed *tabique*) external structural walls are more typical in the northeast of the continental country, while adobe block constructions are more typically found in the Tagus river valley, limited at north by the Atlantic coast area of Aveiro (south region of R1). Regarding the tabique construction, a separation has to be made between constructions with interior tabique walls (which exist throughout the country) and constructions with exterior tabique walls, which are confined to the previously referred regions. Nevertheless, partition tabique walls also have an important contribution to the stability of buildings due to their location which make them act as a connection element between the principal structural elements, thus acting, in some cases, as bracing systems (Pinto *et al.* 2014).

3.2. Development of the general typological atlas

3.2.1 Analysis of traditional archetypes found in Region R1

Region R1 is characterized by a multiplicity of construction types which vary from the corn storage structures found in the agricultural areas, the great ministerial houses associated to rural living characteristics and the urban houses located in the Atlantic coast region. Located in the northern coast line of mainland Portugal, region R1 is dominated by three sub-regions: the coast line, the interior region in the mountains and the southern part of the region. The Douro and Minho river valleys are the most populated areas, with dispersed aggregates in the mountain areas. Regarding the geology of the soil, as observed in Fig. 3, the region is mostly composed of granite rock deposits in the north, schist deposits and metamorphic sedimentary rock, namely composed of clay and round stone near the Ria (submerged river valley) of Aveiro.

There are many remains of pre-historic constructions in this area, dating back to the Palaeolithic and Neolithic eras. The Roman occupation has also left an important legacy in the region, such as many bridges and infrastructures, several of them still existing nowadays. The invasions that followed left very small traces, while leading to the exodus of the population to higher ground, into the mountains, where isolated communities started to appear.

During the transition from the middle to the modern age, several cities were reorganized, in part as a result of the influence of the Catholic religious culture in the area and its connections to Rome. The city of Braga is a major example of this tradition which can be particularly seen in the organization and management of public spaces. The 17th and 18th centuries witnessed the addition of timber elements in the façades.

In a large part of the country, the enrichment of society, based on the riches coming from the colonies in Brazil, led to an extensive wave of construction using Italian-influenced techniques. These are clearly witnessed in the churches and monasteries constructed at that time using granite, lime and plaster in the adopted architectural style. These architectural traces have also influenced popular architecture. Houses typically with one or two storeys became a standard, either facing the newly built roads or the inside of a larger property, where the agricultural fields were located.

The city of Porto gained a particular importance in the national context near the end of the 18th century, which led to a flood of new habitants to the area and to the construction of new roads. The urban houses and streets created during this period are clearly influenced by the 1755 earthquake aftermath, with urban planning and some construction rules (e.g. associated to the height of buildings and the width of roads) being adopted in order to regulate the demand for buildings while preparing the city for the future. The urban houses constructed in Porto reflect many cultural and technical ideas. Arches in the bottom stories of houses, with balconies supported by short cantilever beams and advanced upper stories, and exterior walls made of half-timber with earth are examples of construction details that can be found.
As a contrast with these urban houses, the vernacular architecture of the region can be generically divided into three types of buildings (see Fig. 5). Nonetheless, all buildings, even those in the same location, are different. In the region near the Atlantic coastline (Fig. 5; A), specifically near the more urbanized centres, the houses are made of granite masonry with a white lime cover, in line with the higher social and economical status of the owners. In the interior regions (Fig. 5; B), the mountain regions, granite stone masonry is often found in the constructions, without any covering and, in some cases, without mortar connecting the large stone blocks extracted from local deposits. In these constructions, as shown in Figs. 2 and 5, it is common to find adjoining

structures located near the main house that are used as cereal storage units. These structures are also usually made of granite, but in some cases wood elements are also adopted due to the lower cost of the material.

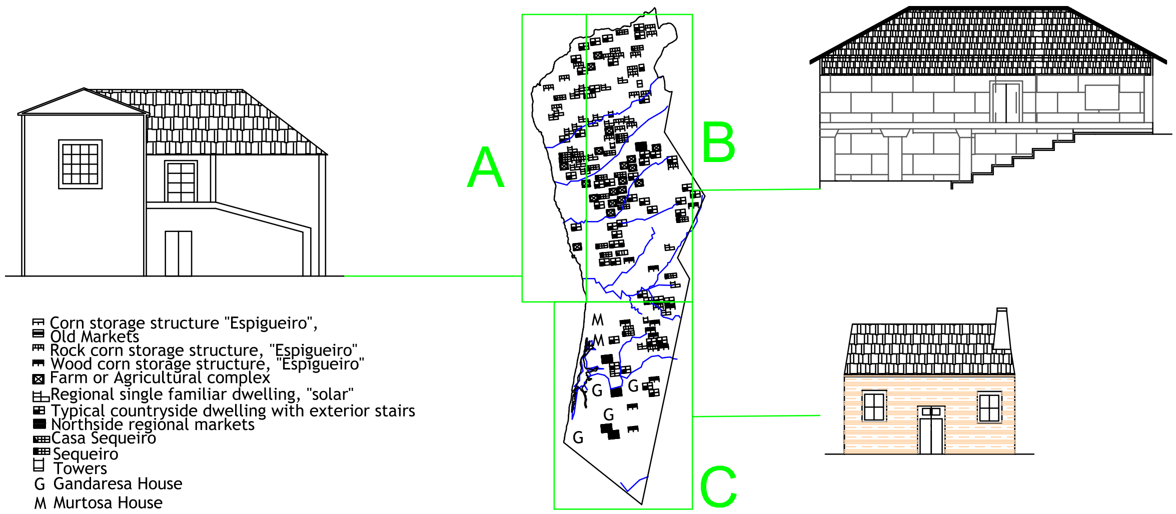


Figure 5. Proposed construction typologies for the generic atlas for Region 1.

Figure 6 shows an example of two storage structures located near each other: the left-hand side structure has a partial timber structure with ceramic tiles and the right-hand side structure is fully made with granite stone elements.

Figure 6. Example of storage structures constructed. Credits: http://www.aldeiasportugal.pt.

Finally, in the southern part of the region (Fig. 5; C), constructions exhibit a different structural typology when compared to those of the previous sub-regions. Due to the availability of materials, lime-stabilized adobe is vastly used in the coastal centre part of Portugal. Adobe bricks in the Aveiro district (where 40% of the constructions are made of adobe) are made of sandy soil with a reduced silt-clay fraction and between 25 to 40% of air-lime (see Silveira *et al.*, (2014) for a comprehensive material analysis). These adobe blocks are used in recent constructions, while older constructions are made of moulded sun dried clay adobe bricks connected with lime and sand mortar. The Murtosa and the Gandaresa houses are two cases of single storey buildings that are typical (Fernandes, 2013) of the southern part of region R1. Nonetheless, other structures can be found in the area comprising building with different configurations, such as the one shown in Fig. 7.

Figure 7. Adobe building in Aveiro. Credits: Aníbal Costa.

3.2.2 Analysis of traditional archetypes found in Region R2

Region R2 is located in the north east of the continental part of the country and is characterized by a mountainous terrain rich in schists with granite aggregates found in some locations also. It is a region characterized by large thermal variations throughout the year. The population lives in compact agglomerates in the mountains, with many side-by-side dwellings that share the same roof line and have few openings. The main typologies identified during the survey conducted in the 1950s are represented in Fig. 8.

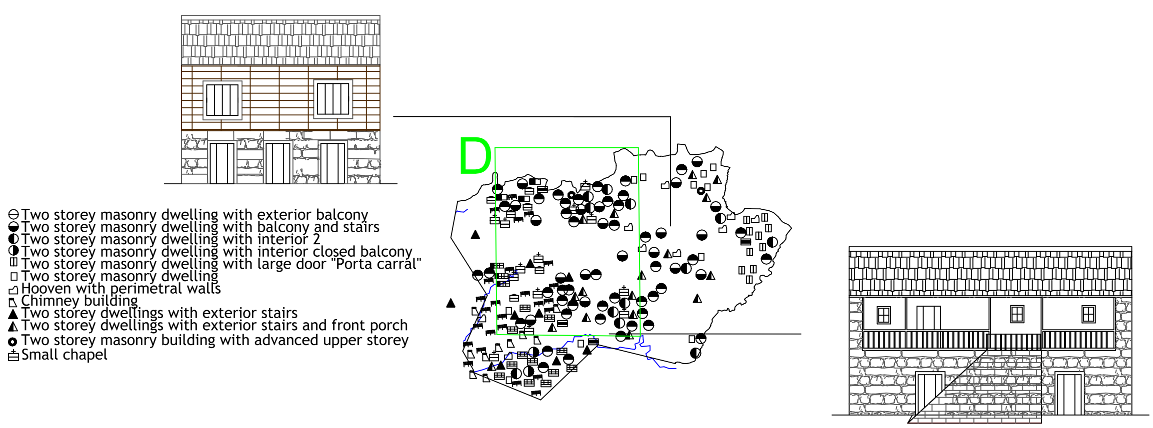


Figure 8. Proposed construction typologies for the generic atlas for Region 2.

As seen in Fig. 8, the main building typology identified is a two storey building made of schists with some wood or granite elements (when available) strengthening the corners, door and window openings or the connections between the roof and the walls. One specific element distinguishing the building configurations in R2 when compared with those of R1 is the existence of exterior stairs made of stone, leading to an exterior balcony or a porch where the entrance of the building is located. In some cases, the steps are made of schist pieces. Gable roofs predominantly are found, although in some cases hipped roofs can also be seen. These are either made of ceramic tiles or of schist slabs. In the areas where schist is more available, timber lintels and timber elements acting as ring beams connecting the roof and the walls are also often identified in the buildings of R2. In other cases, elongated blocks of schist are also used to connect the granite block masonry and the roof.

The existence of balconies and porches are the most distinctive feature in buildings that are otherwise similar in configuration to those that exist in R1. The balconies are usually constructed in timber (see Fig. 9), covered by part of the roof which is connected to the balconies by timber columns. The support of the balcony is also made of timber diagonal elements which are connected to the walls.

Figure 9. Schist masonry building with timber balcony and roof made of schist slabs. Credits: http://www.aldeiasportugal.pt.

The schist buildings are often strengthened with timber elements, particularly in the High Douro river valley and in the northeast region. Timber is also used in a different typology of buildings in R2 to construct the upper storey of the building. In some cases, the alignment of the upper storey is set forward with respect to that of the ground storey and is supported by stone walls or columns or by timber columns.

Martinho *et al.* (2011) performed a survey in the northern part of the region and identified several buildings with tabique walls in the upper storeys of two-storey buildings. A representation of the area they covered and the locations of the buildings assessed in their study is presented in Fig. 10. These constructions are made of timber elements filled with earth or more commonly lime-earth-based mortar (Pinto *et al.* 2014). The arrangement of the timber elements can exhibit different configurations, but structural walls commonly have an orthogonal grid of elements complemented by diagonal timber elements in specific places.

In the overall, it can be seen that two types of traditional building archetypes can be found in region R2. Buildings with masonry schist strengthened with timber elements or granite lintels and corners (due to the fragility of the schist masonry), and often with exterior stairs made of stone masonry and/or balconies made of timber (having nonetheless multiple configurations, as seen from the results of the survey in Figs. 2 and 8). The two-storey building with an advanced upper storey with tabique walls is also characteristic of the Trás-os-Montes region, as documented by Martinho *et al.* (2011) for the northern part of the country and as mentioned in Pinto *et al.* (2014) regarding the southern part of this area. These half-timbered walls (called *taipa de rodizio* if used in external walls) with diagonal bracing members used in the upper storeys of the buildings are more common in bourgeois houses. Noble houses were made of stone masonry with partitions in *taipa de fasquio* (lath and plaster walls) (Poletti and Vasconcelos, 2015). The use of half-timbered structures in the region has been associated with trade relations developed with people coming from Northern Europe (Stellacci *et al.* 2016).

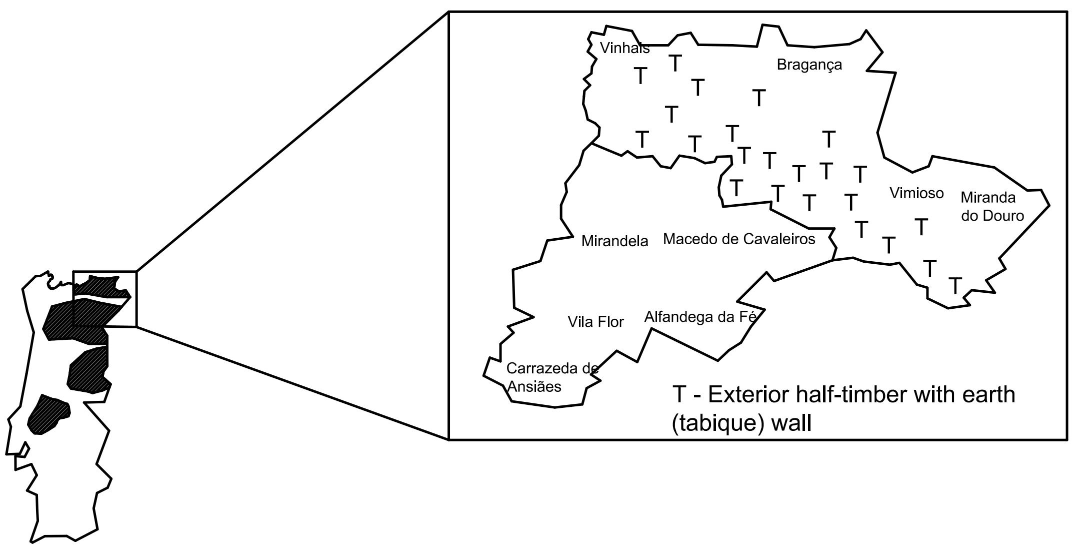


Figure 10. Locations where tabique structural walls have been identified in the study of Martinho *et al.* (2011)

3.2.3 Analysis of traditional archetypes found in Region R3

Region R3 includes the Central-Northern area of mainland Portugal where the local geology exhibits schists and granite. In the survey used in the present study, R3 was subdivided into seven sub-regions where different construction typologies have been identified, as shown in Fig. 11. This division aimed at separating the different types of stone masonry and building configurations found in the region. In sub-region A, two-storey buildings of granite or schist masonry were observed with porched balconies closed with glass windows and an approximately rectangular plan shape. The schist buildings have granite stones in the corners when this material is available. The roofs are also made of schist slabs and the chimney is small when compared with the building size. This type of buildings can be found in the village of Piodão (Fig. 12) which is known for its agglomerate of dwellings made of schist stone masonry.

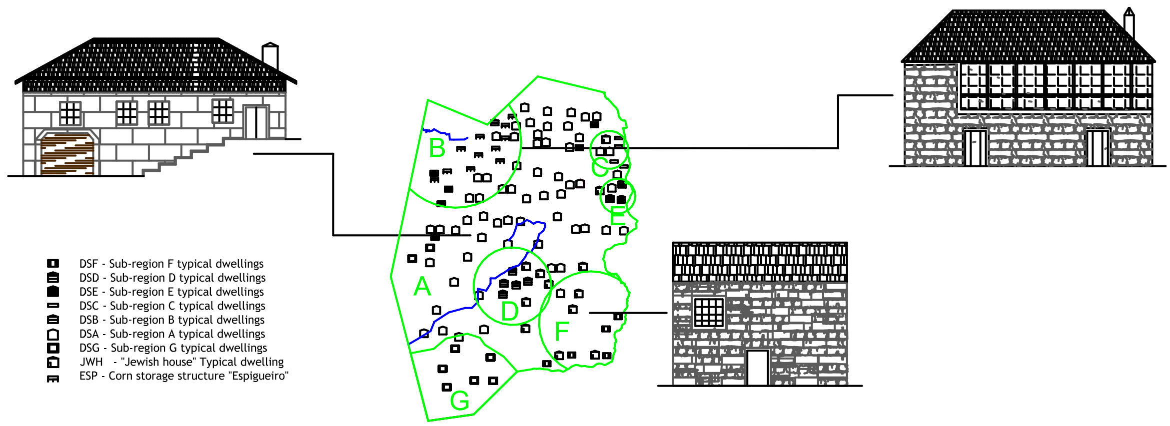


Figure 11. Proposed construction typologies for the generic atlas for Region 3.

Roofs are made of slabs of the same material and timber windows made with local resources are also found. The buildings have mostly two or three storeys. Lintels and doorposts are in timber. Double-leaf schist masonry walls is seen to be used where the exterior leaf involves stones with larger dimensions than those of the interior leaf, and the gap between leaves is filled with gravel and earth. The width of the walls decreases in height, leaving some extra space to support the beams of the floors.

Figure 12. A general view of the village of Piodão. Credits: http://www.visitcentrodeportugal.com.pt/pt/piodao/

In sub-region B, the buildings have a single storey and walls made of granite stone masonry. Roofs are thatched, tied with stones and straw lines to avoid destruction by the wind. There is a significant amount of storage structures similar to those found in R1. Sub-region C also has buildings with granite walls, but the masonry structure is mostly made of small granite stones thus differing from the regular dressed granite blocks used in R1. Lime covering is used to white wash the façades. The stone bench replaces the porched balcony characteristics of the schist construction in R2 and R3. Sub-region D is characterized by buildings having two or three storeys made of round stones collected in nearby rivers laced with layers of schist masonry. Clay-based mortar is also used. Setback balconies exist in the upper storeys and granite lintels and corner stones are adopted to confine the masonry walls. Upper storeys were made with tabique walls, in this case typically made with local clay and timber grids.

In sub-region E, one- and two-storey buildings with interior stairs and granite walls were found. Granite slabs are used to construct fences, walls, columns, roof tops and ground pavements. In houses with two storeys, granite blocks with large dimensions are used to form exterior stairs. Contrary to the majority of the region, buildings in sub-region F do not have balconies or exterior stairs. The vertical structure is made of schist masonry walls, with hydrated lime mortar applied in the corners and at the door spans. Finally, sub-region G is located in the transition between R3 and R4, marking also the transition from the North to the South of the country. Mortar is more often included in the masonry techniques, and chimneys are frequently observed.

3.2.4 Analysis of traditional archetypes found in Region R4

Region R4 is limited from the north by the city of Coimbra and from south by the region around Setúbal. The geology of the region includes two main areas: in the northern part of the region, sandy and clay soils are dominant, while in the southern part limestone is more commonly found. The main vernacular building typologies identified in AAVV (1980) are presented in Fig. 13.

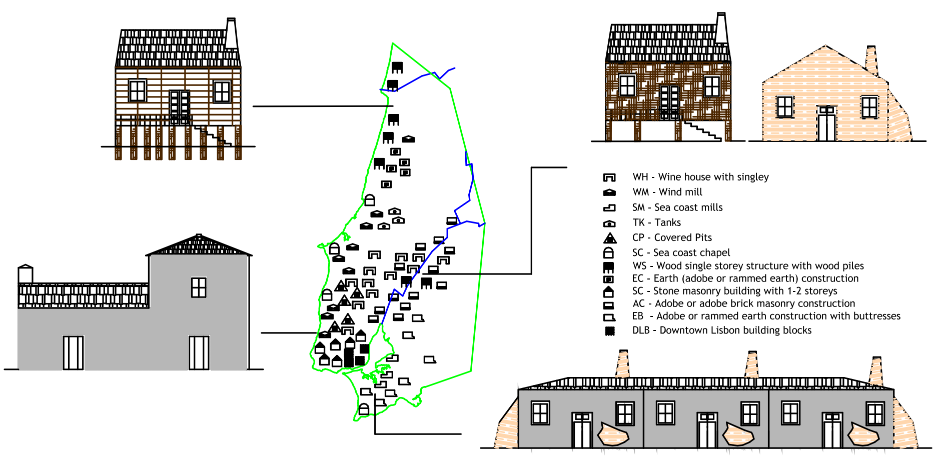


Figure 13. Proposed construction typologies for the generic atlas for region R5

Among the results of the survey, several types of constructions were identified. Timber buildings on top of piles are characteristic both in the Atlantic coast and in the Tagus river flood lands. In the areas where limestone is available, this material is used in the masonry construction. Limestone masonry structures can be found in Lisbon, along with a large number of masonry buildings strengthened with timber frames. Sintra uses granite from the surrounding hills in the constructions. In some regions near Lisbon, basalt masonry buildings are also observed. To have a better understanding about the type of materials that are used, a spatial disaggregation of the total survey of the area is shown in Fig. 14 based on the previously referred data.

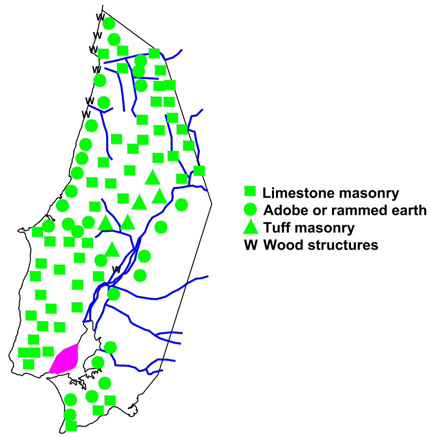


Figure 14. Spatial disaggregation of the buildings in region R5 by construction material

In the areas located near the Atlantic coast, particularly in the areas located near Leiria, the abundance of timber leads to its use in some constructions. Throughout most of the coastline, extending north until the region of Aveiro, timber houses with two storeys were common until some decades ago; currently, their presence in the area is scarce. These structures served initially as storage units and shelter for fishermen. Initially built on top of timber piles to avoid sand concentration from the nearby dunes, the so-called Palheiro structures were transformed into dwellings (tabique interior walls were inserted), during the 19th century, when bathing in the sea became a summer routine.

Figure 15. Some of the few preserved examples of the Palheiro timber construction that can still be found in Ílhavo. Credits: @ creative commons.

Timber structures with similar configurations (timber walls built on top of piles) are also found in both margins of the Tagus river, and are locally called Avieira houses. This typology has a deep connection with the river and was developed mostly by fishermen that settled in the region coming from the Atlantic coast (Virtudes and Almeida, 2012).

In the north shore of the Tagus river, a soft and compact limestone (tuff) was extracted in 50x30x20m^3 blocks. The masonry is complemented by mortar and small stones, and timber beams or larger blocks are used to make the spans. The walls are plastered and white washed with lime.

In the Tagus river flood lands and in some areas of the Atlantic coast line, solid bricks are used in the construction. The brick masonry replaced the rammed earth exterior and the tabique interior walls. Adobe block masonry is therefore typical of the area. The industrial production of adobe blocks is particularly common in the area of Rio Maior. In the Sorraia River area (Salvaterra de Magos, Benavente, Coruche, Mora, Ponte-de-Sôr), a combination of earth and adobe constructions can be found.

Figure 16. Adobe houses in Benavente. Credits: Aníbal Costa

Both the adobe masonry and the rammed earth constructions found along the Tagus river margins and in some cases in the Atlantic coast line, led to the adoption of buttresses and structures with a small storey height (single storey buildings). The lime white washing of the walls is very typical in R4 to protect the adobe, rammed earth and brick masonry. Buildings usually have few and small openings and secondary structures are often connected to the main house. In Ribatejo, tuff and adobe masonry is used in single storey buildings in many cases with large chimneys, stone benches and buttresses.

In Setúbal, a characteristic typology can be singled out which is characterized by single storey adobe and rammed earth buildings, elongated in plan and with few openings. Annex structures are connected to the main house, sometimes complemented by the use of massive buttresses made of limestone masonry.

Although it does not represent an example of vernacular architecture, as shown in Fig.17, downtown Lisbon presents an historic evolution that needs to be included in the present review due to the modifications that were implemented in the capital of the country. Downtown Lisbon can be divided into several areas which illustrate on the one hand the city expansion and on the other, the different types of buildings that were constructed prior and after the great Lisbon earthquake of 1755. Some of these buildings are structural solutions developed after the earthquake, i.e. the Pombalino buildings. Others, such as the Gaioleiro and the Placa buildings, are (vernacular) modifications resulting from the dissemination of reinforced concrete technology.

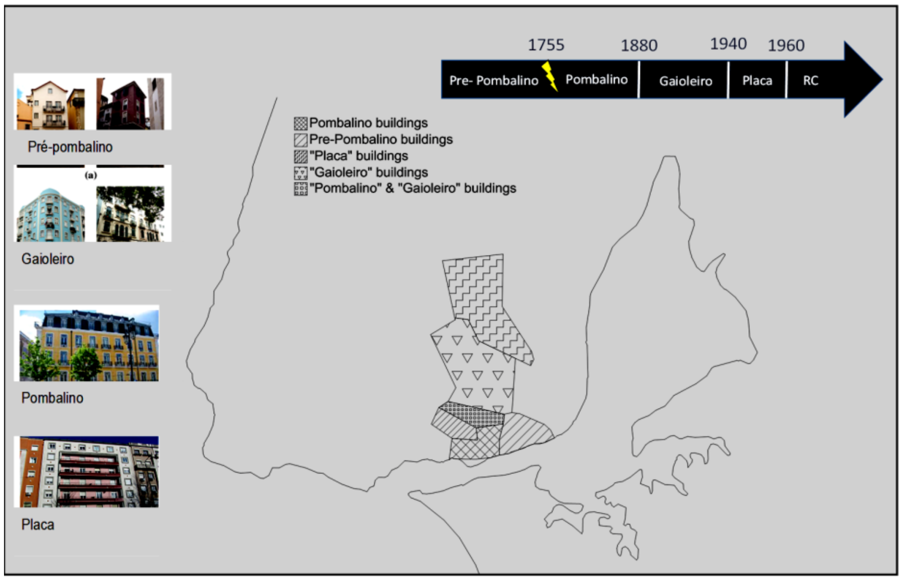


Figure 17. Illustration of the evolution of the architecture of Lisbon and main expansions of the city (based on Simões *et al*., 2015).

3.2.5 Analysis of traditional archetypes found in Region R5

As shown in Fig. 2, the survey performed in region R5 did not lead to the proposal of a typological map by the team assigned to catalogue the area. Although there was no formal map proposed, the analysis of the survey results indicated that 6 sub-regions could be defined, as shown in Fig. 18.

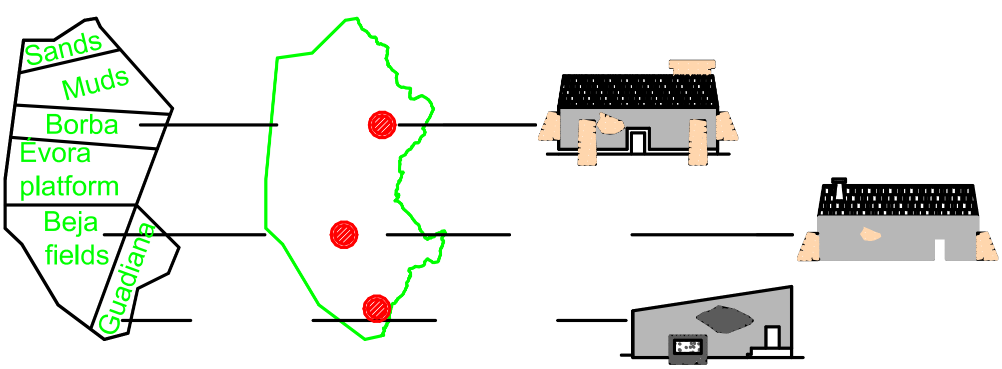


Figure 18. Main areas adopted in the survey when analysing region R5 and proposed construction typologies for the generic atlas.

The constructions present several anachronisms and contradictions due to the probable aggregation of several cultural influences from the past. Still, rammed earth is the most common construction technique found in the region. Rammed earth walls (typically made of sand with gravel bonded with clay) do not have the capacity to sustain lateral forces generated by the weight of the roof and, in some cases, due to the existence of arches and vaults. Hence, despite having considerable widths (0.45-0.70m), these elements are often strengthened with large and massive buttresses made of schist or granite masonry, which confine the walls and prevent damage associated with the lack of lateral stability. These buttresses are necessary in cases where the rammed earth is directly laid on the ground (i.e. without any stone foundations), when there are arches or vaults inside the dwellings, when the roof span is considerable or when there are no interior walls (Domingos, 2010). The triangular shape of these elements connected to the structural walls aimed at improving the structural stability of the structure (Pinho, 2008). Their constitution can include earth, adobe or massive bricks. Stone benches near the façades in rural buildings have a role similar to that of the buttresses, while also protecting the bottom part of the walls against rain (Domingos, 2010). White wash lime is used to protect the rammed earth walls from the effects of water. Furthermore, rammed earth walls are also strengthened with bricks in corners or door heads, which are also used in partition walls. Foundations are commonly made of schist, granite or dried clay generally complemented with mortar made with sand and lime. The roofs are made of timber or cane grids over which ceramic tiles are laid.

Two typologies that represent the general layout of the vernacular Alentejo buildings were defined. Both are based on a structure with rammed earth elements, timber roofs or vaults and often found in isolated areas (called *montes*). According to the survey results, these vaulted roofs have a very small height and cover spans in the range of 5-7m. Typically they can be found in houses located at the Évora plateau, Borba mountain range, Guadiana region, Serpa and Moura.

Figure 19. Typical Alentejo construction ("Monte Alentejano", painting by Salvação Barreto).

The sands sub-region (Fig. 18) encloses the villages of Castelo de Vide, Nisa, Portalegre and Crato. Lime is seldom adopted in the constructions of this area where the two storey building typology is frequent. Granite is adopted as lintels in the door spans and in the windows. Conversely, in the muds sub-region (Fig. 18), lime is the governing material. The chimney becomes a prominent element of the buildings in this region, which have only one storey. The floors were found to be made of schist slabs. The sub-region includes the villages of Ponte de Sôr, Monforte and Campo Maior. One noteworthy case consists on the city of Elvas, where arches sustaining balconies, openings and galleries are found in many constructions. Elvas is also known for the large erudite or ancient structures, such as the local aqueduct, which may be related with the incorporation of these elements in the constructions.

In the Borba mountain range, which includes the area between the villages of Borba, Vila Viçosa and a part of Alandroal, there is a generalized use of schist masonry with or without lime cover. Buttresses are used to sustain the buildings through the irregular terrain levels. Figure 20 shows an example of schist masonry used in the village of Reguengos de Monsaraz, whose buildings were constructed from 1830 based on the remainings of military structures left in the village, often using the materials from the defence walls of the village.

Figure 20. Schist masonry buildings in the fortified village of Reguengos de Monsaraz (Credits: @ creative commons)

Constructions of the Évora plateau sub-region exhibit several contrasting elements. Granite masonry contrasts with lime washing of some façades. The city of Évora has a visible Roman tradition in its architecture, but also exhibits the influence of the renaissance period. This influence is seen in the construction practice of arches and vaults, mixing granite masonry with limestone plastering. In the northeast part of the city of Elvas, arches are also used to support balconies and galleries mimicking large aqueducts. In the nearby city of Alandroal, buttresses can be found to sustain rammed earth buildings in slopped terrains.

In the Beja fields, among the villages of Alvito, Cuba, Beja and Ferreira of Alentejo, the typical building is made of massive rammed earth without stone strengthening. The chimney becomes a secondary element, more often a slender element as opposed to the frontal chimneys or large rectangular elements in other buildings.
Finally, in the North-Guadiana sub-region, which comprises the villages of Moura, Mourão, Serpa and Barrancos, the Arabic traces are more evident. Such traces are visible in the rammed earth columns, vaults with unnoticeable curvature and significant slenderness, and sometimes in decorated chimneys. Buttresses have been identified in isolated buildings in the area (Correia *et al.*, 2015a,b).

3.2.6 Analysis of traditional archetypes found in Region R6

Region R6 involves the Algarve region and the Atlantic coast line from the outfall of the Sado river. The geology of the region includes an area in the north where soft soils are found, an intermediate region with schist formations and in the south, in the Algarve, limestone is typically found in the region. The general types of constructions found in the region during the survey are presented in Fig. 21.

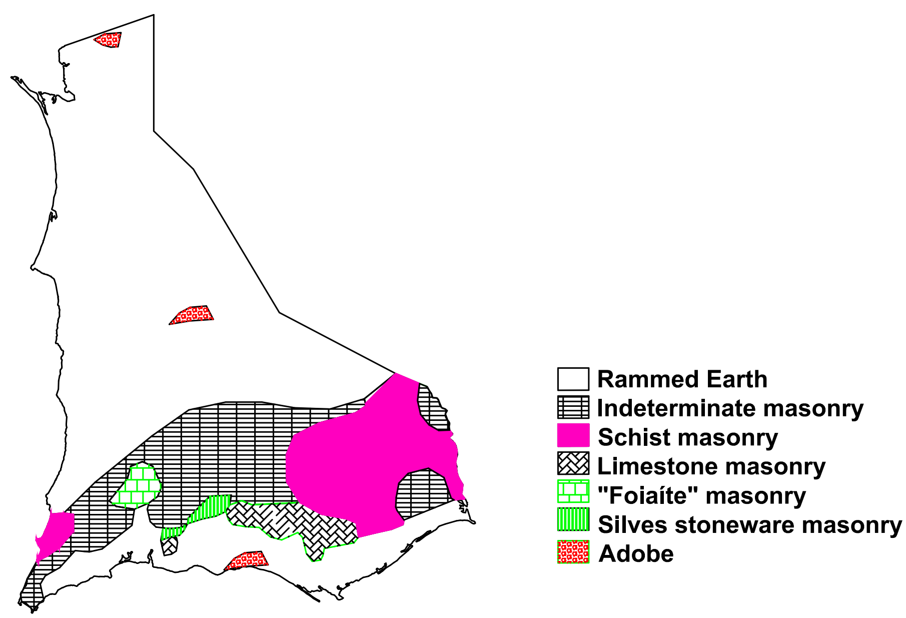


Figure 21. Types of materials and construction techniques adopted in region R6.

As can be seen in Fig. 21, rammed earth is the dominant construction technique used in the area. The Alentejo Atlantic coastline presents building typologies that are similar to those observed in the interior Alentejo dwellings, with the use of rammed earth and buttresses. In the outfall of the Sado river, groups of six houses in a row were observed spread over the elevation of the terrain. The rammed earth buildings have lime covering with buttresses that consolidate the walls (Fig. 22). The row buildings are common in this area, forming large one storey blocks. On the southeast side, schist masonry is more typical. It corresponds to the Guadiana river region. In this area, the buildings are masonry structures made of local schists which have also a considerable amount of clay and have shed roofs inclined towards the dominant wind direction to protect the buildings from rain infiltrations. Currently, fragile roofs have been replaced by ceramic tiles over timber structures.


Figure 22. Typical dwelling found in Melides.

Typical houses in the south of Algarve are made of limestone masonry or bricks. These buildings (Fig. 23) have balconies that are constructed on top of vaults that have a very small height. Chimneys are notable elements placed on roofs that have a very small slope (almost horizontal). Commonly these buildings are also made of rammed earth, and tiles are used in pavements and balconies.

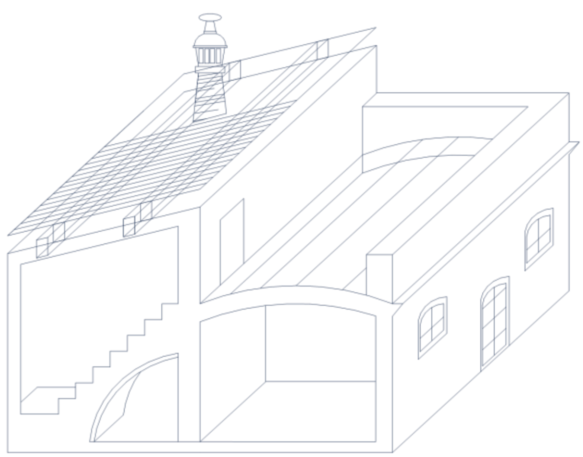


Figure 23. Typical dwelling found in the south of the Algarve region characterized by a balcony that has a low vault and a decorated chimney.

In Tavira, the so-called *telhados de tesouro* were adopted in buildings of the historical centre. These buildings have two or three storeys, they are made of limestone masonry and have openings aligned over the height. The hipped roofs have a considerable slope and usually have an interior lining made of timber planks. Fishing villages such as Olhão (whose construction dates back to 1790), Fuzeta or even the village of Vila Real de Santo António are cases where the vernacular construction is characterized by the repetition of the same construction system over row building aggregates.

After analysing the survey information, the main typologies that were identified are presented in Fig. 24 together with the typological map proposed by the survey of region R6 (OA, 2004). Essentially, the rammed earth buildings are the most characteristic dwellings of the Atlantic coast, throughout Algarve the limestone masonry building is typical and an area with schist masonry buildings is characteristic of the eastern part of R6, near the Guadiana river line.

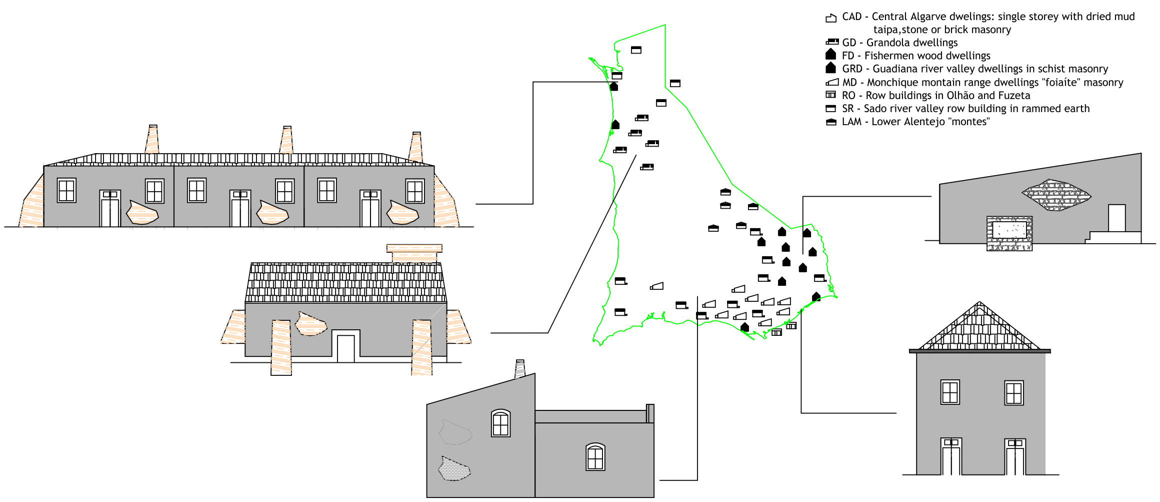


Figure 24. General typological atlas for region R6

3.2.7 Development of the general typological atlas using the results provided by the regional analysis

Based on the results analysed, on the data collected form the global survey conducted on mainland Portugal and after cross-referencing it with other studies addressing traditional buildings (Oliveira and Galhano, 1992) and traditional constructions (Fernandes, 2013; Correia *et al.*, 2015a; Correia *et al.*, 2015b), the final general typological atlas for the vernacular architecture of continental Portugal was established, as shown in Fig. 25. As stated before, this atlas contains the main characteristics and types of buildings existing in different areas, but it does not represent all the features and characteristics of all the buildings that exist in the country. The uniqueness of each building must not be forgotten when adopting the proposed typological atlas. In a general overview, it can be seen that the atlas is deeply associated with the type of material available in each region. Also, smaller (single storey) and simpler building layouts are more common in the south, with a lower amount of openings and higher importance given to chimneys.

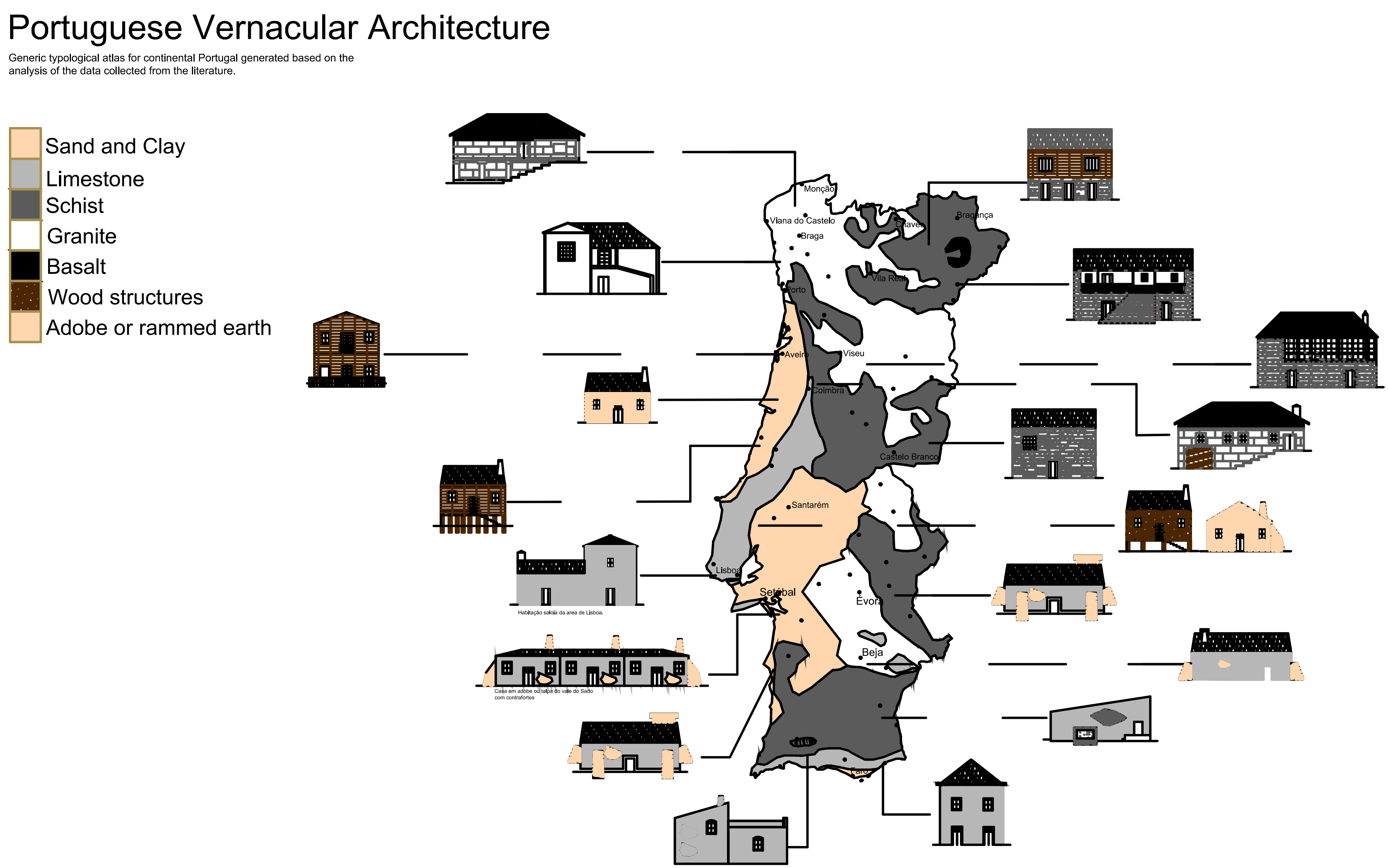


Figure 25. General typological atlas of Portuguese vernacular architecture.

3.3 Anomalies and particular features of traditional buildings.

Vernacular architecture reflects the historical, social, economic and technical conditions of a given population. As such, one can assume that there is a connection between the site and the building techniques, the social status and the archetypical constructions. In light of this, a set of anomalies (in the sense that they are characteristics that were not expected) can be highlighted in the archetypical atlas presented in Fig. 25:

- By analysing the global map, it can be seen that, in the north of the country, the available materials are the base for the archetypes found in the survey. However, a similar trend is not observed in **region R5 and in part of region R6**, where **rammed earth** is used in traditional buildings, **despite the existence of granites and schists.**
- The **number of storeys is also different when comparing buildings located in the north and in the south** of the country. While buildings in the northern part of the country (**R1, R2, R3**) have typically **two to three storeys**, most of the earth constructions south of the Tagus River line (**R4**, **R5, R6**) have only **one storey.** The main reason for this **limitation of the elevation** in these constructions may be associated to the **characteristics of earth-based construction**, which usually exhibit massive structural layouts that are vulnerable to out-of-plane loading and sensitive to lateral instability phenomena resulting from a lack of vertical alignment of the walls.
- **In all cases**, the **layout** of the buildings is usually **regular**, a fact that might be related to the use of stone **block masonry and rammed earth** as the main **construction techniques**.
- The **number of openings is higher in stone masonry** structures than in earth-based structures (for all regions), with the door heads and windows of the latter being, in many cases, strengthened with lintels made of local stone or timber, thus acknowledging **the added fragility of rammed earth** due **to the introduction of openings in the walls**.
- **Earth** isolated constructions (single or multi-dwelling blocks) of regions **R4, R5 and R6** are **strengthened with buttresses made of stone masonry**, but these elements are not found in the other regions.
- The larger urban cities such as Porto and Lisbon have a specific architecture which includes much less vernacular elements and more formal architectural buildings. The **chronological evolution of downtown Lisbon** highlights the **different types of constructions** adopted in different periods of time. A consistent modification can be identified by analysing the city's expansion.
- With respect to the use of timber in the constructions, half-timbered walls can be found throughout the entire country, not only in the *Pombalino* buildings in Lisbon but also in some regions of Alentejo and of the north, in medieval centres as Porto, Braga and particularly in Vila Real and Chaves.

4. Correlation of the typological atlas with short return period hazards

4.1. Short return period hazards considered

The reference atlas developed in Section 3 shows the main construction typologies that were developed in the past in the different communities of the country. Although in some regions there is a strong correlation between the identified building typologies and the materials available for construction in the area, other factors may have also influenced the structure and the construction systems adopted. Climate and other short period hazards are some factors that can be associated to the transformations of buildings that led to the existing typologies. Among the short period hazards, wildfires and flood susceptibility were analysed since wind (cyclonic winds, tornados, hurricanes) and snowfall are less relevant hazards for Portugal. Temperature (indirectly analysing drought-related issues) and raining levels were selected as the most important climate factors. These variables were analysed in order to assess their possible influence on the construction systems identified in the different regions of the typological atlas.

4.2. Correlation between the typological atlas and climate variables: temperature

Figure 26 shows the average of the minimum (a) and maximum (b) temperatures observed in the continental part of Portugal during the period 1971-2000.

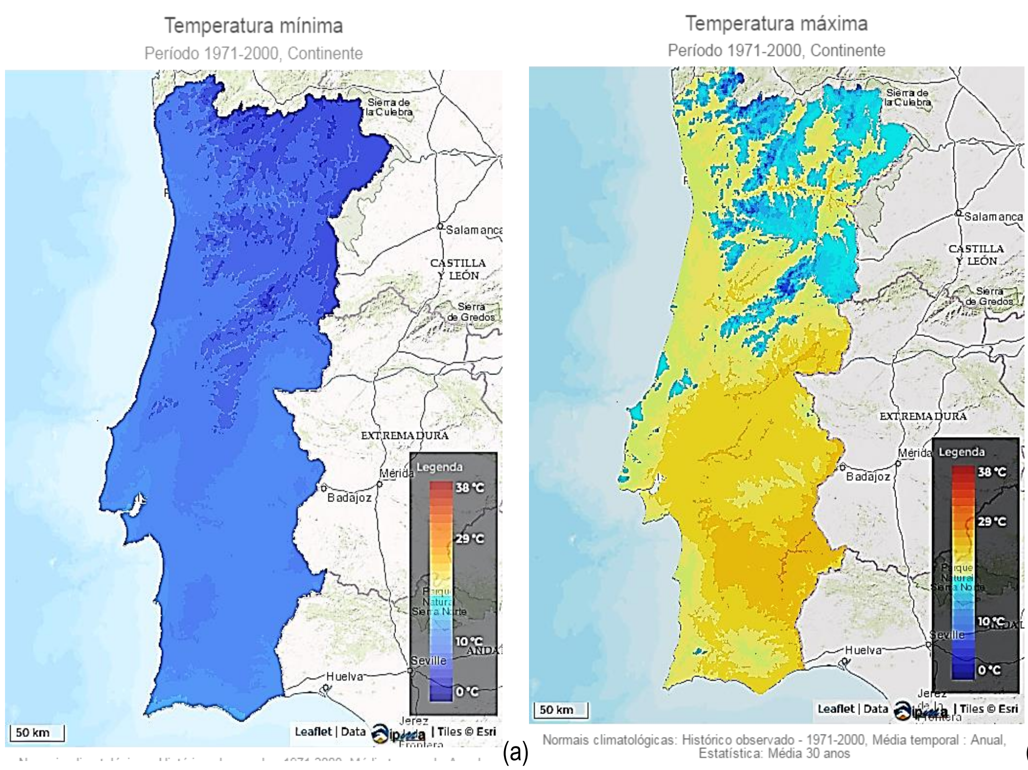


Figure 26. Average of the minimum (a) and maximum (b) temperatures measured in the continental part of Portugal during the period 1971-2000 (data from IPMA, 2016a,b)

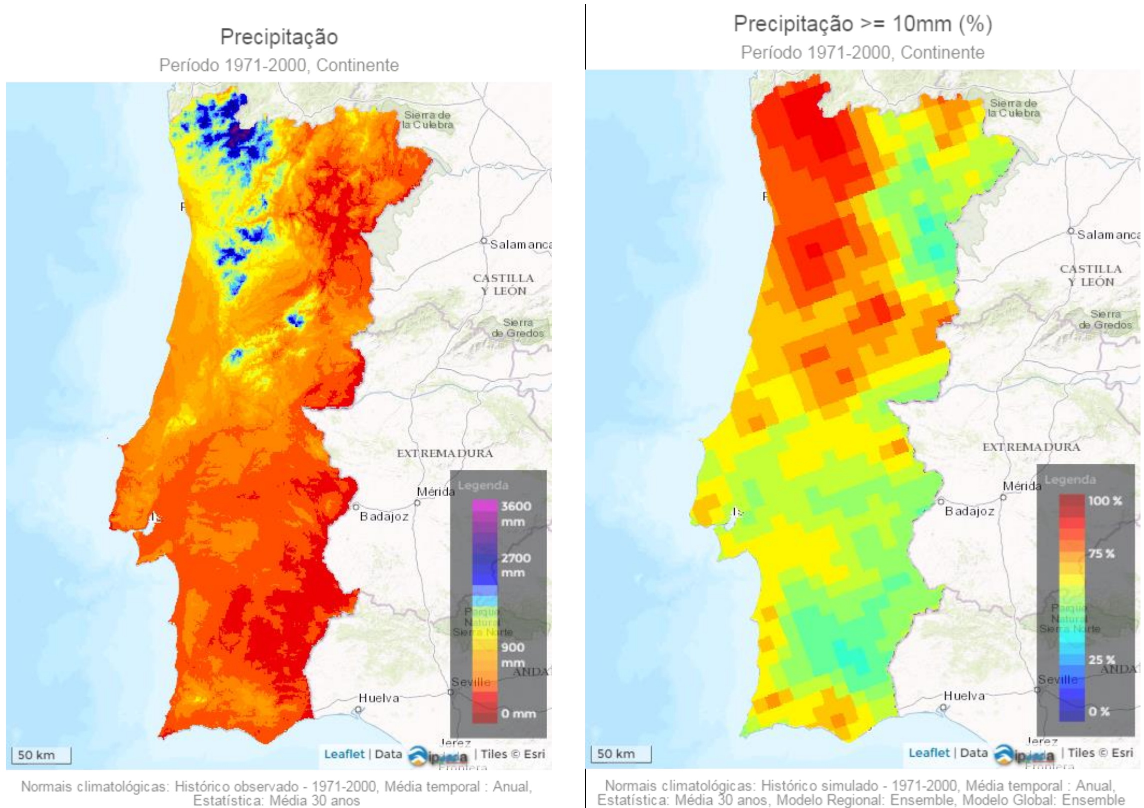
The thirty year return period considered for the averaging was assumed to be a Poisson process, i.e., it was assumed that similar conditions are observed on average every 30 years. As seen in Fig. 26a, the colder areas are located in the mountainous areas, in regions R2 and R3. In the winter, minimum temperatures as low as 2 ºC are felt in mountainous regions, with values 10 ºC higher felt in the southern region of Algarve. In the R2 and R3 areas, the traditional dwellings identified were characterized by a solid and robust granite or schist masonry, typically without any type of mortar or covering. Nonetheless, it was noticed that, as opposed to the R1 dwellings, the R2 and R3 traditional buildings exhibited balconies with or without glass windows. According to Fernandes *et al.* (2012), the vernacular architecture of these regions was conceived in order to improve solar exposure, particularly with the southwest oriented balconies, which also reduce the loss of heat to the exterior of the houses. Thus, these balconies (particularly glazed-balconies) typical of region R3 have a dual action as a heat increasing and heat loss reduction measure.

In Fig. 26b, it can be seen that the maximum summer temperatures occur in the Alentejo region, particularly in the lower part of region R5. As also denoted by Fernandes *et al.* (2014), several techniques were developed in this region to prevent heat from penetrating the houses. For example, adopting a reduced number of openings, usually with small dimensions, the use of materials with a high thermal inertia (rammed earth and adobe) and the use of lime to white wash the walls to reflect sunlight. The selection of rammed earth walls with a large width also explains the protection against high temperatures, with the lime white washing of the façade limiting the absorption of heat.

4.3. Correlation between the typological atlas and climate variables: precipitation levels

As seen for the case of temperature, the spatial distribution of the precipitation levels also shows two distinct patterns, one in the north and one in the south of the continental country. In the northern region (R1, R2), average annual accumulated precipitation levels are higher than 3000mm, while regions in R5 and R6 the accumulated rainfall level is lower than 500mm. Region R5 is known for its considerable levels of desertification.

Figure 27 shows the average precipitation in mm (a) and the percentage of days with a precipitation level above 10mm (b) for the continental part of Portugal during the period 1971-2000. A careful analysis of the map finds patterns that are coherent with those analysed previously in Fig. 26. The colder mountainous areas in the north of the country and the proximity of the Atlantic Ocean favour the development of higher levels of precipitation. Conversely, the lowest precipitation levels are observed in the areas where the highest average maximum temperatures were found, namely those located south of the Tagus river. The lowest raining levels are found in the lower Alentejo region, in region R5. It is interesting to notice the pattern observed in Fig. 4 and the typological atlas of Fig. 25. Accordingly, it can be seen that earth construction is often found in areas with lower levels of rain, in regions R4, R5 and R6. The high sensitivity of this construction material to water effects leads to its absence in the northern part of the country. In region R5, it can be noticed that despite the existence of granite and schists, the rammed earth technique is often found. Conversely, in the northwest region of the country, the structural typology adopted for the storage structures is an indication on how to cope with the higher rain levels, since they are raised on piloti-like elements, as shown in Fig. 6.



(a) (b)

Figure 27. Average precipitation in mm (a) and percentage of days with a precipitation level above 10mm (b) for the continental part of Portugal during the period 1971-2000 (data from IPMA, 2016c,d)

4.4. Correlation between the typological atlas and flood susceptibility

Flood hazard in continental Portugal has been studied by Jacinto *et al*. (2015) by analysing a flood susceptibility index. Figure 28 shows the spatial distribution of this index, where the value of 1.0 represents the higher susceptibility level of an area to short term flood hazard. It must be noticed that tsunami hazard is not included in the referred map since it represents a long return period hazard. In the map, it can be seen that the Tagus river flood lands constitute a major representative area, as are the outfall of the Douro and Mondego rivers and the Aveiro ria. The only correlation that appears evident when cross-correlating the typologies identified in Fig. 25 and the areas susceptible to flood refers to the timber buildings built over piles that existed in the Atlantic coast line and the Avieira wood house, typical from the Tagus river flood lands. In the Alentejo, the flood susceptibility index is high in many regions, despite the very low levels of precipitation, which may also be a factor that contributed to the location of the isolated typical dwellings of the region (usually single storey houses located on the top of small hills, spread across the region).

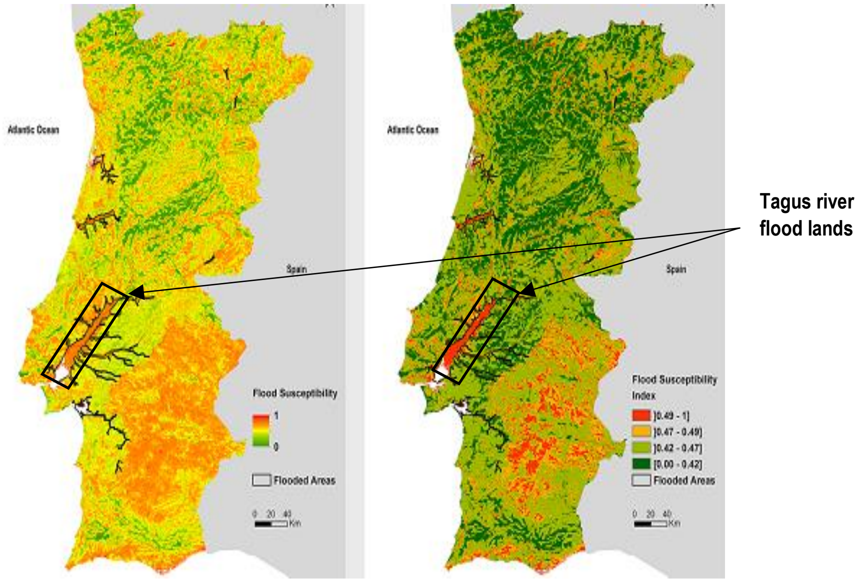


Figure 28. Continental Portuguese territory flood susceptibility index (adapted from Jacinto *et al.* 2015)

4.5. Correlation between the typological atlas and wildfire susceptibility

Wildfire susceptibility was analysed to have a mild indication about two factors that might have an important influence on the construction properties: the slope of the terrain where these buildings are located and the amount of forest, which indicates the availability of timber at each location. Figure 28 shows the slope map and the fire susceptibility map for mainland Portugal proposed by Parente and Pereira (2016).

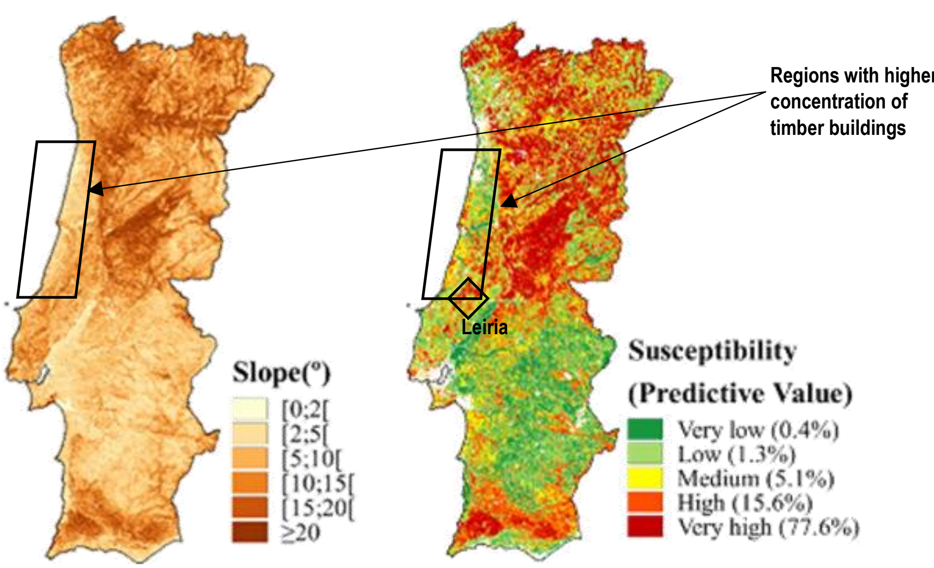


Figure 29. Slope map of mainland Portugal and fire susceptibility map for mainland Portugal with 5 classes defined by the quintiles of the susceptibility values (adapted from Parente and Pereira, 2015)

As seen in Fig. 29, timber availability is often associated with areas with higher slope values. In regions R1-R3, it can be seen that despite the available resources, the climate of the regions favoured the use of more robust houses, thus excluding the use of timber apart from door heads and lintels, balconies and in *tabique* structural systems. As seen in the typological atlas, most of the timber constructions that were identified are located in the Atlantic coast line between Aveiro and Peniche. As seen in Fig. 29, these areas correspond to regions where timber resources are available and that are mostly flatlands and plains, unlike the interior and northern regions. Also, the plains of region R5 are characterized by a very low wildfire susceptibility, which reflects the low levels of vegetation of the area.

4.6. Overview

A global analysis of the results aggregated from the literature regarding short return period hazards shows that there is an apparent correlation between the location of earth and timber constructions and the average climate variables. The main conclusions retrieved from the review are summarized in the following:

- The appearance of **timber balconies** in the colder mountainous regions (**R2** and **R3,** see Fig. 1) and of southwest-oriented **openings** are a clear evidence of a vernacular approach to **improve heat gains**, especially when a comparison is made with the buildings in the coastal areas of R1 .

- On the other hand, the **earth construction, the absence of openings and the white washing of the façades** with lime based coatings in the southern areas (mainly in **Alentejo, R5** in Fig.1) are clear evidences of climate-related modifications of structural systems that were applied to improve **isolation from the exterior heat**.

- **Flood effects** are clearly reflected in the timber constructions found in **coastal** and **Tagus river areas** (they were built over a **plinth** or over timber **or stone short pile** systems). However, only minor construction characteristics can be associated with heavy rain issues in the **Northern regions** (e.g. **the living quarters of houses located in the second floor** or **the raised construction of storage structures)**.

- **Water also affects the structural stability of adobe masonry or rammed earth** constructions. The use of **lime-based plasters** is a clear indicator of the awareness of this fact. Furthermore, **foundations are usually made of stone masonry to protect the integrity of the walls**. **Stone benches** have a similar **protective effect**, but it may be **difficult to correlate this structural feature with rainfall** in the Alentejo region where these elements are predominant.

- Finally, wildfires do not appear to have a significant correlation with the typological atlas that was developed.

5. Correlation of the typological atlas with long return period hazards

5.1. Considered long return period hazards

Earthquakes and tsunamis are the major long return period hazards to which continental Portugal is exposed to, since there are no active volcanoes. Continental Portugal is located in the southwest hemisphere of Europe, thus part of the Eurasian plate near its interface with the African tectonic plate. The discontinuities in crust have thus the potential to generate both ground motions and tsunami waves, and several events that affected Portugal originated from this area. Historically, inland faults have also been associated with severe ground motions, causing destruction and, consequently, affecting the way of building adopted by the population.

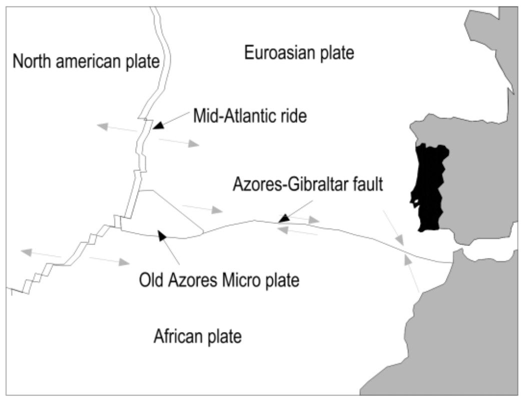


Figure 30. Macro-tectonic environment near continental Portugal

Although nearby submarine earth structures are capable of generating tsunamis, no evidence was found of transformations of vernacular constructions with the purpose of withstanding the power of tsunamis. Therefore, this hazard was excluded from the current analysis.

5.2. Historical seismicity in continental Portugal: Global Seismic Culture

5.2.1 Seismicity in continental Portugal over the past 40 years

In the context of analysing the influence of earthquake hazard in the characteristics of vernacular construction, both short term and historical seismicity are considered herein, the latter being analysed in the next section. In order to evaluate the short term awareness, the data available from IPMA (IPMA, 2004; IPMA, 2014) referring to earthquake magnitudes and epicentres measured between 1961 and 2000 was analysed, as shown in Fig. 31. From this data, the number of events with a magnitude higher than M4 is seen to be significantly less than the total number of events detected in the forty year period range that was considered. When considering magnitude M4+ earthquakes, the number of events with magnitude in the range M5-M6 (yellow circles) can be seen to be much lower than those falling within the range M4-M5 (green circles). Furthermore, only two events with magnitude M6+ were observed: the March 15th, 1964 earthquake, with epicentre in the Atlantic ocean approximately at 70km of Faro (M6.1 IPMA, 2014a) and the February 28th, 1969 earthquake, with an epicentre southeast of the Saint Vincent Cape, in the Atlantic ocean (M8.0; IPMA, 2014a).

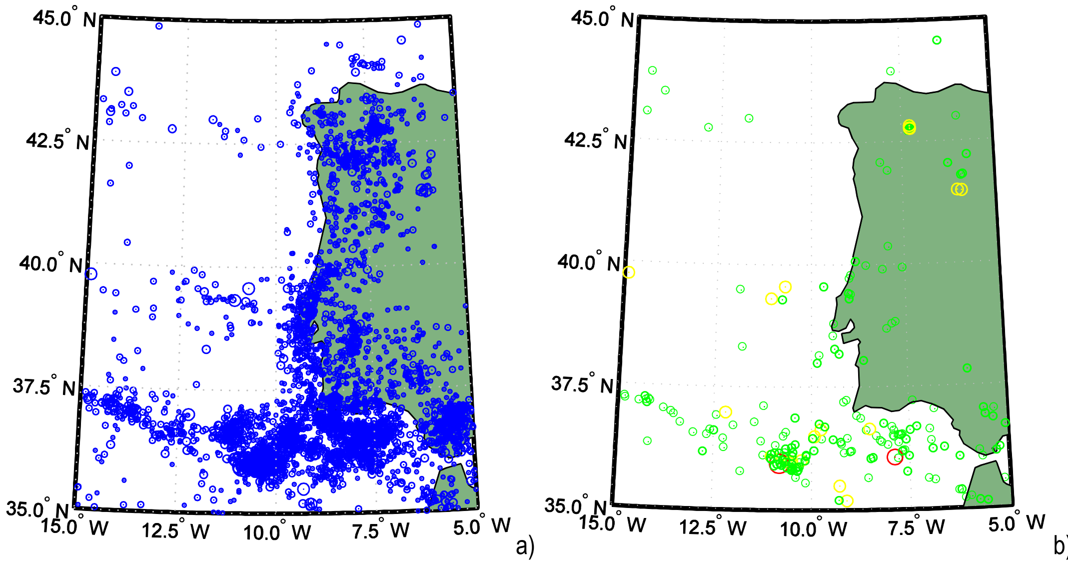


Figure 31. Location of all registered earthquakes between 1961 and 2000 (a) and disaggregation of events with M4+ by location and magnitude: M5- (green), M5-M6 (yellow) and M6+ (red) (b) (data from IPMA, 2014a; IPMA, 2014b).

In terms of damages, these two earthquakes presented some relevant consequences, particularly in the southern areas (Region R6 in Fig. 1). The isoseismal lines corresponding to the damages induced by these two earthquakes are shown in Fig. 32 following the reports presented in (IPMA, 2014a). The Wood and Neumann (1931) scale (WN) was adopted in the referred classification (IPMA, 2014a) although it is mentioned that the majority of the results would be similar to those given by the Modified Mercalli Intensity (MMI) scale (Richter, 1956). Fig. 32b presents the combined results of the IPMA (2014) and Moreira (1991) reports.

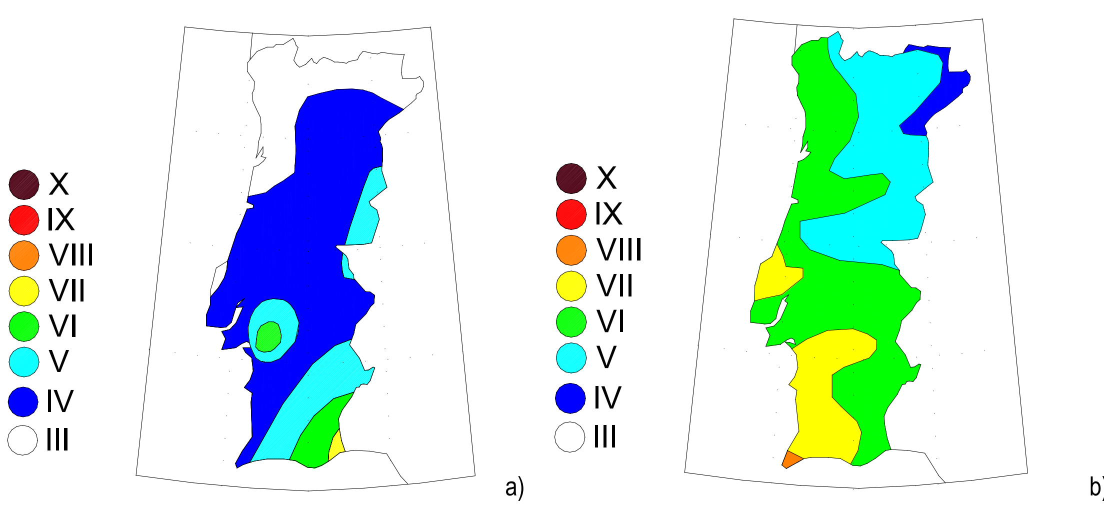


Figure 32. Isoseismic lines corresponding to the Wood and Neumann (1931) intensity on the mainland country due to the effects of the a) March 15th, 1964 earthquake and b) the February 28th, 1969 earthquake (adapted from IPMA, 2014a).

As seen in Fig. 32b, the 1969 Earthquake led to a significant level of damage in many cities and constructions, not only in Portugal but also in some locations in Morocco. One particular feature of this earthquake consisted on the high number of moderate magnitude aftershocks (47 in total). The duration of the mainshock has been referred to be about 1 min, although the only record available (from Lisbon) only contains 26 sec of ground motions. Several chimneys and walls collapsed in Lisbon and a power outage followed the main event. The major damages were nevertheless concentrated in the Algarve region where about 400 buildings needed to be demolished or suffered collapse (Miranda and Carrilho, 2014). The reconnaissance made by Trêpa (1969) covered most of the areas in regions R5 and R6 (see Fig. 1). In the village of Odemira, an area was reported to be completely destroyed due to the collapse of buildings mostly made of clay with rounded stones masonry. The buildings made of stone and clay in Bensafrim collapsed (20 buildings collapsed as mentioned by Miranda and Carrilho, 2014). In the vicinity of Lagos and in Vila do Bispo, several buildings built with materials similar to those of buildings of Bensafrim and Odemira also collapsed (Trêpa, 1969). Figure 33 shows some of the pictures taken by Trêpa (1969) in the referred areas after the earthquake. The cities of Loulé, Faro and Olhão only exhibited small damages, mostly in older buildings. The report also mentions that when heading west from the village of Fuzeta, the earthquake effects started to be worst, which was considered to be influence of the soil conditions (the different value of the expected VS30 velocity in this area was shown in Fig. 3). Buildings said to have bad construction characteristics suffered extensive damage in villages such as Vila Real de Santo António and Tavira. Regarding region R5, Beja was not heavily hit by the earthquake, with minor damages being reported in older buildings. The damages levels were even lower in the city of Évora, a fact which was assigned to the higher robustness (despite the heavier mass) of the constructions in that area.

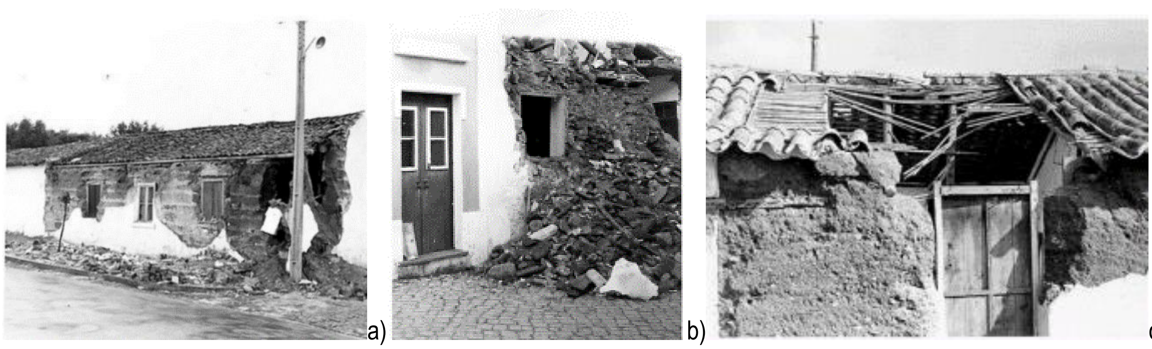


Figure 33. a) Partial collapse of the corner of an apparent rammed earth building in Grândola b) stone and clay masonry collapsed walls in Vila do Bispo and c) partial collapse of door head and roof in the village of Longueiras (Trêpa, 1969).

As mentioned in Trêpa (1969), there was a clear distinction between the state of conservation of the so-called older buildings and the newly built reinforced concrete (RC) multi-storey structures. While the former suffered considerable damages, only a few RC buildings have shown signs of bad behaviour, which may have led to the impression of a better performance of this kind of structures during ground motions. Also, the fact that these buildings were designed following existing seismic provisions was noted as a positive feature in the report. Probably due to this fact, the state of conservation of vernacular buildings, which was pointed out as one of the main factors that led to the observed collapses, started to decline in the following years. Today, it is common to find some of these constructions totally abandoned, especially in remote locations.

5.2.2 Main historical seismological events with effects in continental Portugal

As referred before, the 1960's earthquakes and their damages are the most recent reminder of earthquake risks and consequences in Portuguese history. However, such awareness about earthquakes has faded and the only event that is still embodied in the people's shared memory is the great Lisbon earthquake of 1755.

One of the main factors that may have led to this lack of awareness is related to the properties of the seismological activity that affects the continental part of Portugal. To illustrate these characteristics, Fig. 34 shows the location of the epicentres and the corresponding unified magnitude (as defined by Martins and Víctor, 2001) of the historical earthquakes included in the catalogue of Martins and Víctor (2001) ranging from 1356 and 1961.

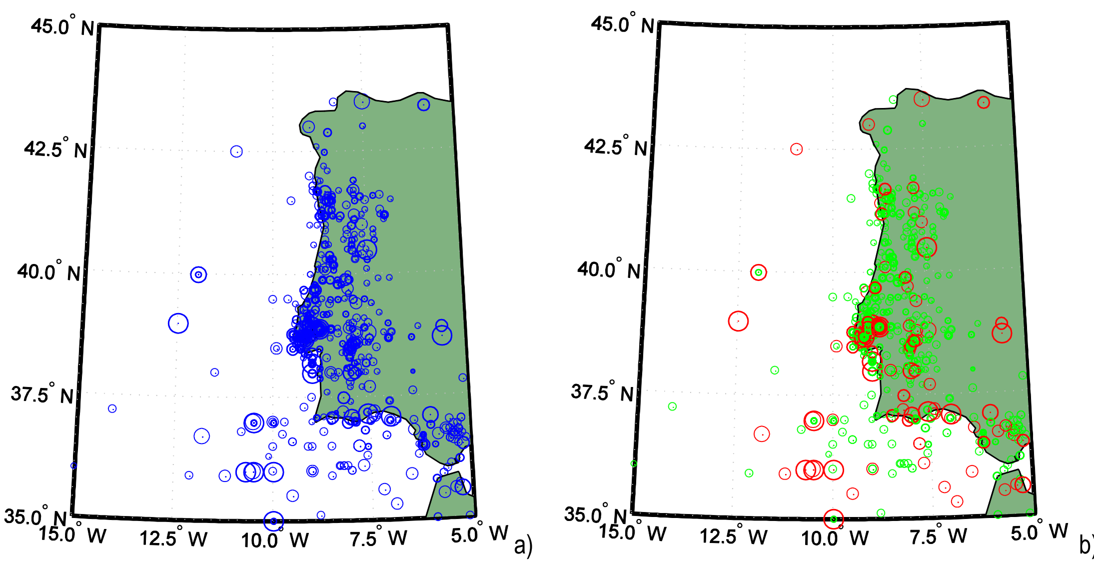


Figure 34. Location of all registered earthquakes prior to 1961 and disaggregation of the events with unified magnitude M_g (as define by Martins and Víctor, 2001) M_g4+ by location and magnitude: M_g5- (green), M_g5-M_g6 (yellow) and M_g6+ (red) (data from Martins and Víctor, 2001).

As can be seen from Fig. 34, very large earthquakes have hit mainland Portugal in the past, with magnitudes capable of generating MMI values as high as level XII. As mentioned before, the evolution of the construction trends must be correlated with the damages induced by ground motions rather than with the source mechanisms and the characteristics of the earthquake. Bering this in mind, Fig. 35 illustrates the historical evolution of the damages induced by earthquake events in the period range between the 1344 and 1960.

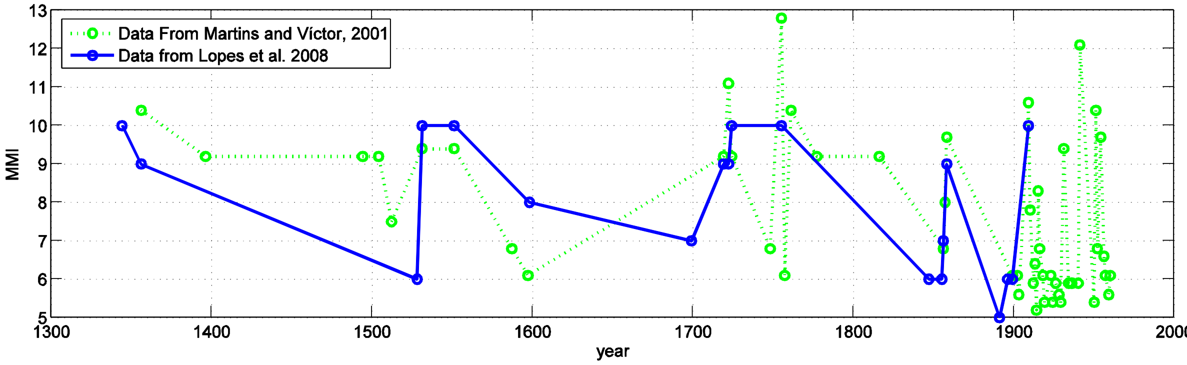


Figure 35. MMI observed in mainland Portugal after the historical earthquake events from 1344 to 1960 using the transformations of the unified magnitude into MMI as indicated in Martins and Víctor (2001) and the catalogue of main historical events presented by Lopes *et al.* (2008).

As can be seen in Fig. 35, the seismological activity in mainland Portugal is composed by sets of very destructive events that occur separated by intervals of about 100-150 years. This particular characteristic of the historical seismicity of the mainland country can be related to the referred seismic risk awareness. Since the larger events triggered the destruction of several communities, rebuilding measures may have included some reactive measures. Furthermore, Fig. 35 also shows the existence of sets of multiple events occurring in a time window of 20-50 years (1531, 1755, 1909). These sequential events contributed to an effective short-term awareness, which might have led also to the (reactive) strengthening of structures that survived to major events.

The analysis of this historical data indicates that a set of earthquakes may have had a key role on the definition of seismic resistant features of vernacular architecture. Accordingly, the analysis of Fig. 35 enable five major periods to be isolated: 1) the period triggered by 1356 earthquake, 2) the period triggered by the 1531 earthquake, 3) the period triggered by the 1755 earthquake, 4) the period triggered by the 1858 earthquake and 5) the period triggered by the 1909 earthquake. Among these events, the 1356, 1755 and 1969 earthquakes have an epicentre offshore, while the for 1531, the 1858 and the 1909 earthquakes the epicentre was onshore.

The 26 of January 1531 earthquake

The January 26th 1531 earthquake occurred between 4h00 and 5h00. It was mostly felt in Lisbon and in the villages located along the Tagus estuary. The ground motion caused severe damage in the downtown part of the city and in areas located along the lower Tagus basin, leading to approximately 1000 fatalities (Justo and Salwa, 1998). There were floods registered in the Tagus flood lands due to the water rising. According to Miranda *et al.* (2012), the ground motion lead to the destruction of one third of the buildings existing in Lisbon at the time. Many locations around Lisbon suffered numerous collapses and destruction according to past reports. As summarized by Justo and Salwa (1998; Appendix 2; see references therein), the following nearby locations and damages were mentioned (see Fig. 36): in Castanheira, all the houses and the church were shaken down; in Lavradio, many houses were knocked down, and cracks appeared in the country-house of the *Infante*; in

Santarém, the buildings along the riverbanks fell down, the Agostinos Monastery sustained several local collapses, most buildings were shaken down; Torres Vedras was described as being unsettled; in Setubal, no house was damaged with less than twenty cracks; in Benavente, most buildings fell down; in Alenquer, some of the houses of the *Infante* Don Fernando, the whole Saint Francis Monastery and the Saint Geronimo Monastery fell down, with many collapsed villas also. Henriques *et al.* (1988) mentioned that, in that period, stone was reserved for the so-called "public buildings" (palaces, churches, etc.) and common houses were constructed with rammed earth or adobe and timber elements in floors and ceilings.

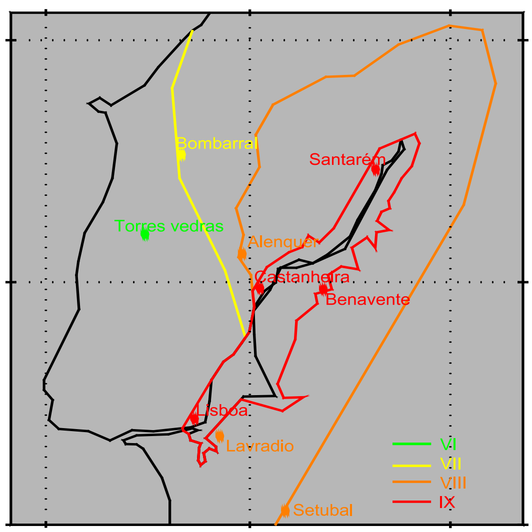


Figure 36. Cities most affected by the 26th of January 1531 earthquake (data from Justo and Sawal, 1998).

The 01 November 1755 earthquake

The November 1st 1755 earthquake destroyed a large part of the city of Lisbon, particularly the downtown area. Atlantic coast line cities such as Setúbal and most of the Algarve coast line were also greatly affected by the estimated M9(?) earthquake. A tsunami and urban fires occurred after the earthquake, leading not only to further destruction in cities already vulnerable due to the ground motion but having also a considerable social impact in the populations. The downtown of Lisbon was flooded by waves that reached a height of 6 m. The water flooded an area with an extension of around 250 m from the coast. Death estimates vary between 10 000 and 90 000. Before the earthquake, the number of dwellings is estimated to be around 35000, as it can be inferred by comparing the observations made by different historians (see table 1).

Table 1. Estimates about the number of dwellings in Lisbon prior to the 1755 earthquake according to different historians (Santos, 2008 and references therein).

Historian	Francisco Santana	Bautista de Castro	Ana Barata	Father Luis Cardoso	Pinho Leal
# dwellings	36643	32735	33454	32878	39615

Santos (2008) estimated that 17 017 buildings were destroyed, which represents around 50% of the total number of dwellings existing at the time of the multi-hazard event triggered by the earthquake.

The damage that was observed in different types of constructions was also analysed by Oliveira (2008), showing the intense damage that was induced not only to regular dwellings but also to monuments and other structures such as hospitals and small churches. Figure 37 shows the type of damage and the respective percentage of buildings affected by the multi-hazard event according to (Oliveira, 2008). Santos (2008) also mentions that 17 monasteries were destroyed by the fire, and another 34 collapsed, 17/34 churches were destroyed by the fire/fire and earthquake, only 11 of the 65 convents remained partially intact, all the 6 hospitals were consumed by the fire, the jails were destroyed and many palaces were also destroyed both by the effect of fire and of the ground motions.

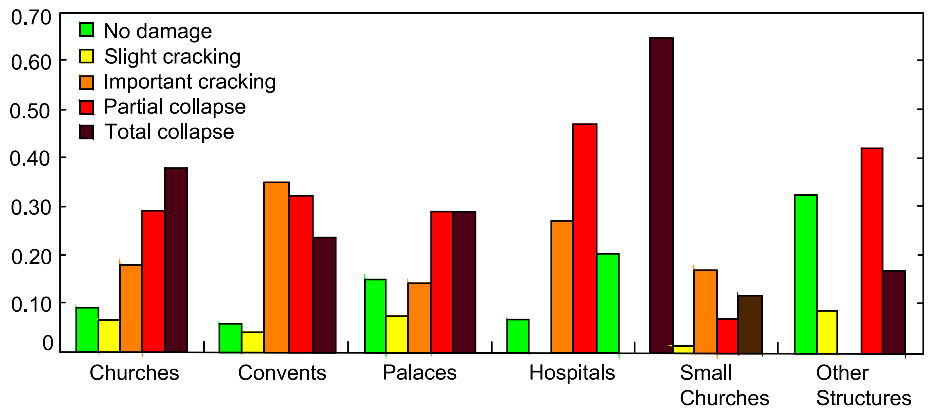


Figure 37. Damage statistics for the city of Lisbon (Data from Oliveira, 2008).

Although the case of Lisbon is often remembered by the catastrophic consequences, partially due to the importance that the city had in the European context of the 18th century, many other villages and regions were considerably affected by the earthquake and the tsunami. Chester (2008) analysed the damage in the Algarve using the classification made by Martínez-Solares and López-Arroyo (2004), dividing the damages between traditional one and two storey masonry buildings constructed in stone, brick and rubble (Type 1) and structurally more complex and taller churches, castles and monasteries (Type 2). According to the analysis made by Chester (2008), both the vernacular Type 1 buildings and the formal archetypes (Type 2) were destroyed in Sagres, Vila do Bispo and Lagos. Nonetheless, in the eastern cities of Olhão and Tavira, many public and ecclesiastical buildings collapsed, while the vernacular constructions performed better than those located in the cities near the west coast. Chester (2008) also denoted that, in Tavira, local soil effects may have led to different consequence levels in different areas (and cities), since the areas closer to the coast line or in river margins (e.g. cities like Faro sitting entirely on soil deposits) were more seriously damaged than those sitting on outcrops of 'hard' limestone. Figure 38 shows the isoseismal map for the 1755 earthquake in Algarve according to Pereira de Sousa (1914).

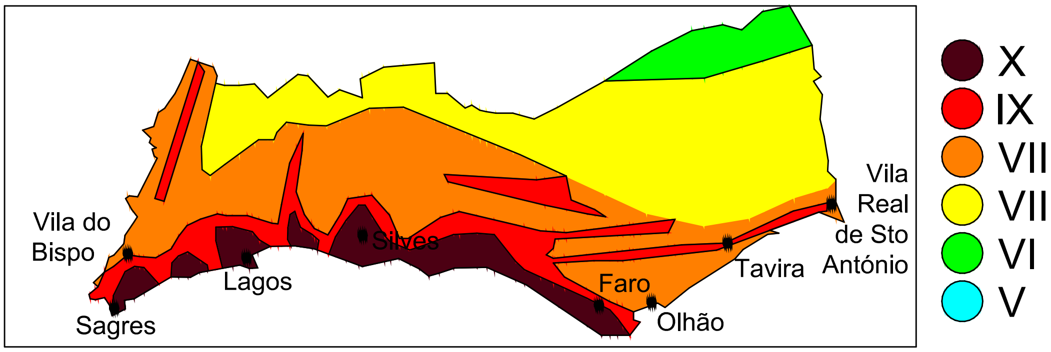


Figure 38. Isoseismal map for the 1755 earthquake in Algarve according to Pereira de Sousa (1914)

The damages in Sagres included the collapse of all houses. With the exception of the walls of the fortress, all other substantial state, religious and private buildings were severely damaged. In Vila do Bispo, only one building remained standing after the earthquake. With respect to Lagos, many state, religious and private buildings were totally destroyed. These included: over twelve major religious buildings; the town hall; the jail and most of the houses. Nearly all other religious buildings and all the remaining houses were severely damaged.

In Silves, the castle walls, cathedral, town hall, other public buildings and most of the houses were totally destroyed. The remaining houses were damaged. In the village of Faro, the cathedral, the bishop's palace and eight major religious buildings (mostly within the historic city centre) were destroyed, together with more than 600 houses. The fortress walls and another church were severely damaged. The damages in Tavira included the collapse of the hospital, some religious buildings and houses near the river. Finally, the city of Vila Real de Santo António had to be completely rebuilt following the earthquake.

The 11 November 1858 earthquake

The earthquake of 11 November 1858 was a destructive event with an epicentre inland that caused significant damages around the region of Setúbal (Moreira, 1982; Moreira, 1991) but was felt throughout the entire country. The epicentre was probably located in a submerged zone near Setúbal, in Santo André. This earthquake was classified by Jonhston & Kanter (1990) as one of the major events that occurred in a stable continental plate. Only a few (less than 50) casualties are referred and limited information is available about the event. It is estimated that about 600 houses were destroyed in the region. The affected buildings consisted mainly in dwellings located in Santo André, Melides and Setúbal.

The 23 April 1909 earthquake

Identified as the largest crustal earthquake that occurred in the 20th century in Portugal, the 23rd April 1909 earthquake had an epicentre in Benavente and affected most of the areas on the Tagus river line near the epicentre. According to the survey report by Choffat and Bensaúde (1912), the oriental part of Lisbon was the part of the city that suffered more damage, where the oldest structures that were not heavily affected by the 1755 earthquake sustained more damages. Falling chimneys and cracks in structural walls were the more important damages observed in the area. Minor cracking occurred in buildings located in other parts of the city. The authors also reported that 40% of the dwellings of Benavente collapsed or were in a state that would require their demolition (Fig. 39).

Figure 39. Collapses observed after the 1909 earthquake in Benavente (source: http://www.cm-benavente.pt/conhecer-benavente/historia/terramoto-de-1909).

Regarding the remaining dwellings, it was estimated that 40% of the buildings were considerably damaged and 20% would still require repairing. The 1909 earthquake destroyed most of the buildings in Benavente and also caused significant destruction in the villages of Samora-Correia and Santo Estevão. Villages near the Sorraia valley, such as Salvaterra de Magos, Coruche, Mora, Ponte-de-Sôr or Melides, were also affected. "Colossal dust clouds" and "very loud noise coming from the collapse of buildings" were described at the time (Vieira, 2009). Partial collapse at the corners of buildings (mostly in adobe or rammed earth) and vertical cracking in walls were among the main damages observed. Figure 40 shows the isoseismal map for the 1909 earthquake in the Tagus river flood lands according to Teves-Costa and Batló (2011).

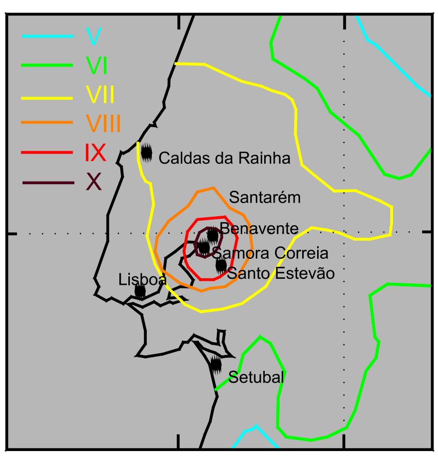
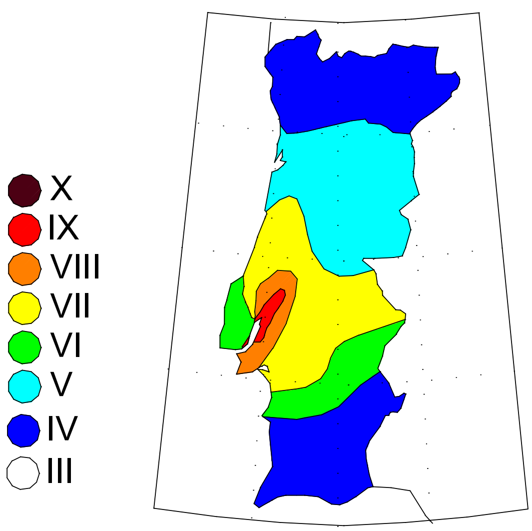


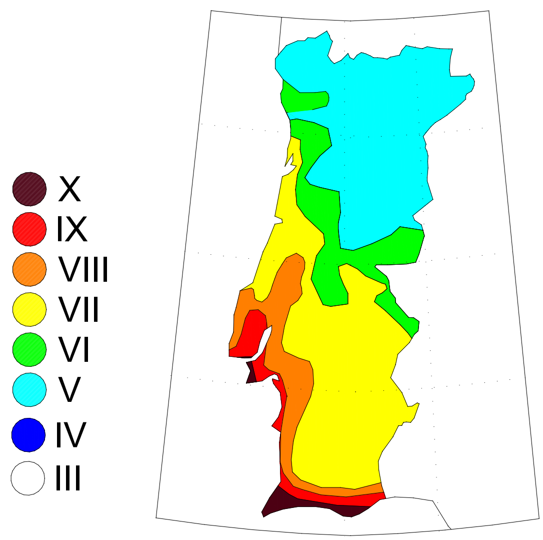
Figure 40. Isoseismal map for the 1909 earthquake in the Tagus river flood lands according to Teves-Costa and Batló (2011)

5.3. Correlation of the typological atlas with the global historical seismicity of the country

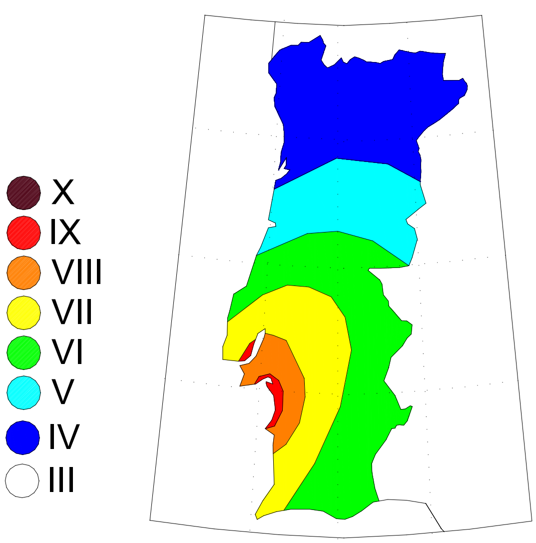
Due to the different origins and the importance that these events had in the construction practice of vernacular architecture in mainland Portugal, a spatial analysis of the damages associated to the 1531, 1755, 1858 and 1909 earthquakes was performed. This analysis was based on the isoseimal maps (MMI) of these four events, which are shown in Fig. 41. The isoseimal maps of the 1755 and the 1858 earthquake were constructed based on the proposals of Moreira (1982), while those of the 1531 and 1909 events were developed based on Justo and Salwa, (1998) and Teves-Costa and Batló (2011), respectively.



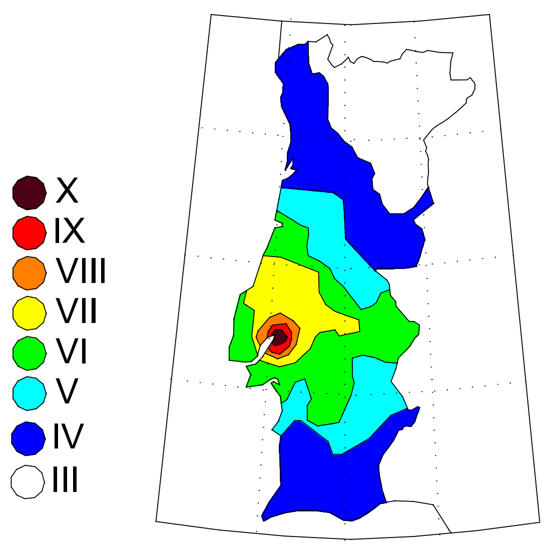
Isoseismal map for the 1531 earthquake (data from Justo and Salwa, 1998)



Isoseismal map for the 1755 earthquake (data from Moreira,1982*)*



Isoseismal map for the 1858 earthquake (data from Moreira,1982; Roque, 2009)



Isoseismal map for the 1909 earthquake (data from Teves-Costa and Batló, 2011)

Figure 41. MMI observed in the mainland Portugal after the historical earthquake events of 1531, 1755, 1858 and 1909.

As shown in Fig. 41, the effects of these key events can be clearly limited to a set of regions whose historical seismicity is more likely to have raised a short term awareness and to have a higher potential for the existence of a local seismic culture. If one assumes that the MMI level of VII can be defined as a threshold for the effective damage of a considerable number of buildings, four main areas of the mainland country can be singled out. The first of these areas is the Lisbon downtown area which, due to soil conditions and the seismic hazard of the site, has been strongly affected both by far (1755) and near source events (1531; 1858). The second area is the region that can be denoted as the Tagus river valley, strongly affected by the 1909 earthquake, but also with important damages due to the 1531 earthquake. The third region is the region near the outfall of the Sado river, including the northern Alentejo coast line, which was mainly affected by the 1755 and the 1858 earthquakes. Finally, the fourth region refers to the Algarve coast line, which was affected both by the historical 1755 earthquake (and the events that occurred prior and after the major event) and, as mentioned before, by the 1969 earthquake.

The map presented in Fig. 42 summarizes the historical seismicity areas of mainland Portugal as presented by the Portuguese institute of the atmosphere and meteorology (as *per* LNEC, 2016). Also, the typological atlas previously presented is replicated to allow for an identification of the vernacular archetypes identified in the first stage of the study. This new map summarizes the damages observed in the different areas due to the different events, as shown in Fig. 41, and correlates this data with the typological buildings that were assigned to each region.

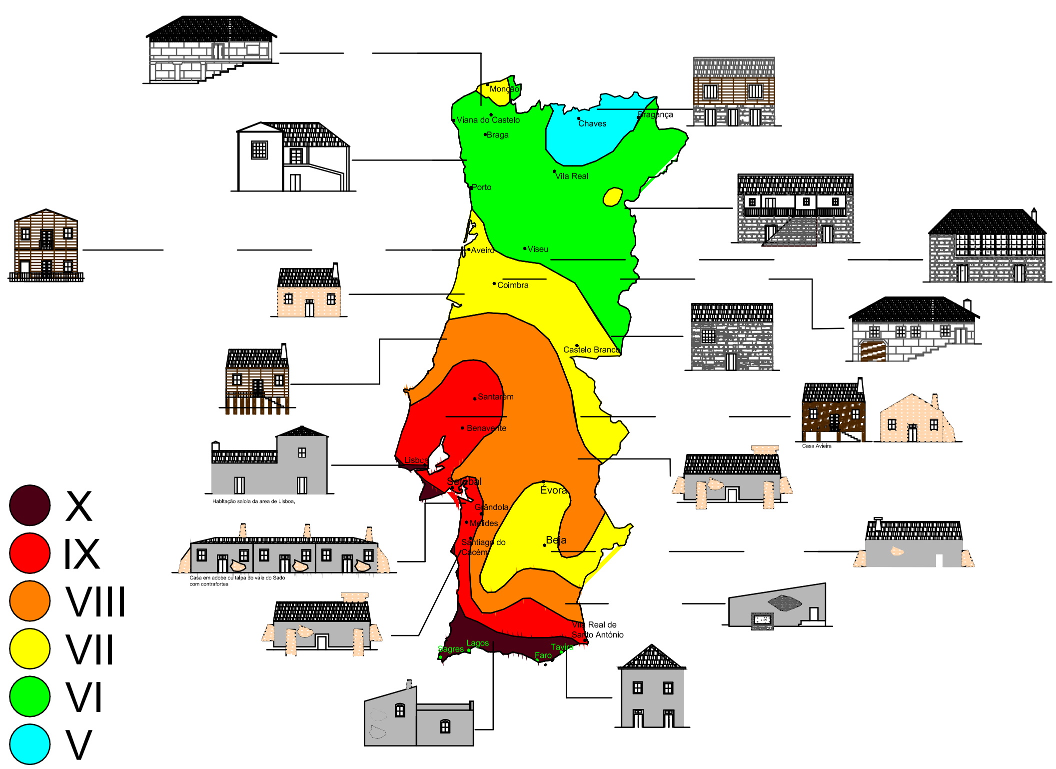


Figure 42. Historical seismicity of the Portuguese mainland territory (from LNEC; 2016) and its correlation with the typological atlas that was developed.

As seen in Fig. 42, the four areas previously referred include some distinctive features when compared with the remaining country. Among the anomalies described in section 3.3, it is clear that the building aggregates in the area around Setúbal and Grândola or the buttresses found throughout the areas with historical MMI VIII+ are measures that may be seen as seismic resistant features. Furthermore, the use of timber elements in the interior of rammed earth buildings, as documented in the survey, can also indicate a possible a strengthening technique that can be associated with seismic protection or structural consolidation due to the fragility of rammed earth constructions to lateral forces. As a result, there is a possible connection between some properties of vernacular constructions in these four areas and their seismicity. Nevertheless, as opposed to the short term hazard conditions whose cause-effect duality was clearly evident by comparing the climate variables and the archetypical construction, it is more difficult to distinguish the measures that are originally thought and adopted to resist earthquakes from those that were adopted to improve structural stability to other loads or comfort. Among the questions arising from the anomalies identified in section 3.3 and in comparison with Fig. 42, it is necessary to analyse the chronological sequence of the constructions in each of the identified areas, namely analysing the possible influence that a key event may have had on the strengthening or reconstruction of buildings.

5.4. From Global to Local Seismic Culture

In order to have a chronological sequence of the earthquake damages in the four areas previously identified and to isolate within these regions a set of centres to be studied in detail, the catalogue of isoseismal maps developed by Oliveira (1986) was considered.

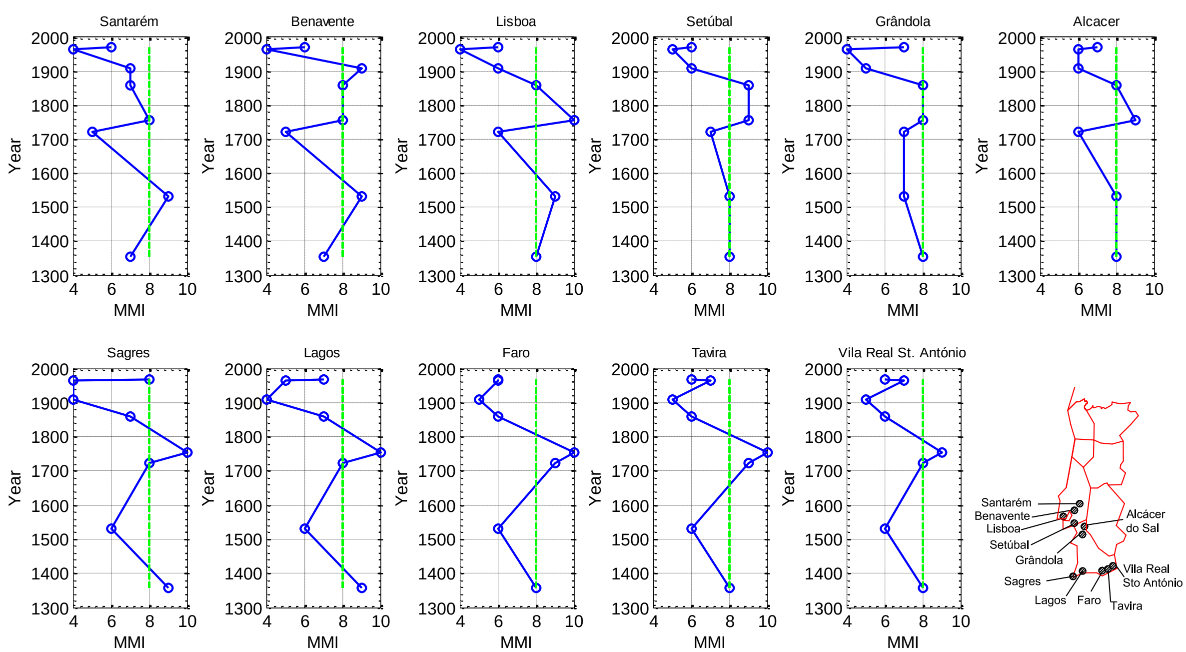


Figure 43. MMI observed in the centres selected from the four areas based on the analysis of the key events (data from Oliveira (1986), PROT (2004) and Moreira *et al.* (1993)).

The isoseismal maps by Justo *et al.* (1992) and Moreira *et al.* (1993) were also adopted for the 1356 and 1722 earthquakes, respectively. The intensities in MMI for a set of centres located within the referred four areas for the mentioned earthquake events are shown in Fig. 43. As seen in Fig. 43, Benavente, Lisbon, Setúbal, Alcácer do Sal and Sagres are the sub-regions where a local seismic culture has a higher probability of being found. Particularly, in Lisbon and in the Algarve locations (Sagres, Lagos, Faro, Tavira and Vila real de Santo António), the 1755 earthquake is a reference case, since it led to considerable damage levels in all the isolated centres. In case of locations in the lower Tagus Valley (Benavente), the 1909 earthquake led to the highest damage levels.

The information from a recent study (Correia *et al.* 2015a) combined with the AAVV (1980) survey results and other references analysed before in the present study can be used to establish an alternative component-based atlas which aggregates the features of the vernacular constructions in continental Portugal that can be seen as seismic resistant elements. The selected features from the catalogue defined by Correia *et al.* (2015a) were respectively: 1) timber frames (frontal walls, other timber strengthening elements used in rammed earth buildings), 2) buttresses, 3) tie-rods and 4) stone benches or plinths. The spatial disaggregation of the locations were each strengthening technique was found is represented in Fig. 44.

In the overall, a set of regions and isolated centres (i.e. cities or towns) can be seen to exhibit seismic-related strengthening measures in vernacular buildings, mainly related with the construction of rammed earth buildings and their inherent lack of seismic capacity.

In order to convert the general typological atlas developed before into an atlas of the Portuguese local seismic culture, it is necessary to evaluate, within the identified centres and possible anomalies (or strengthening measures), which can be associated to a local seismic culture.

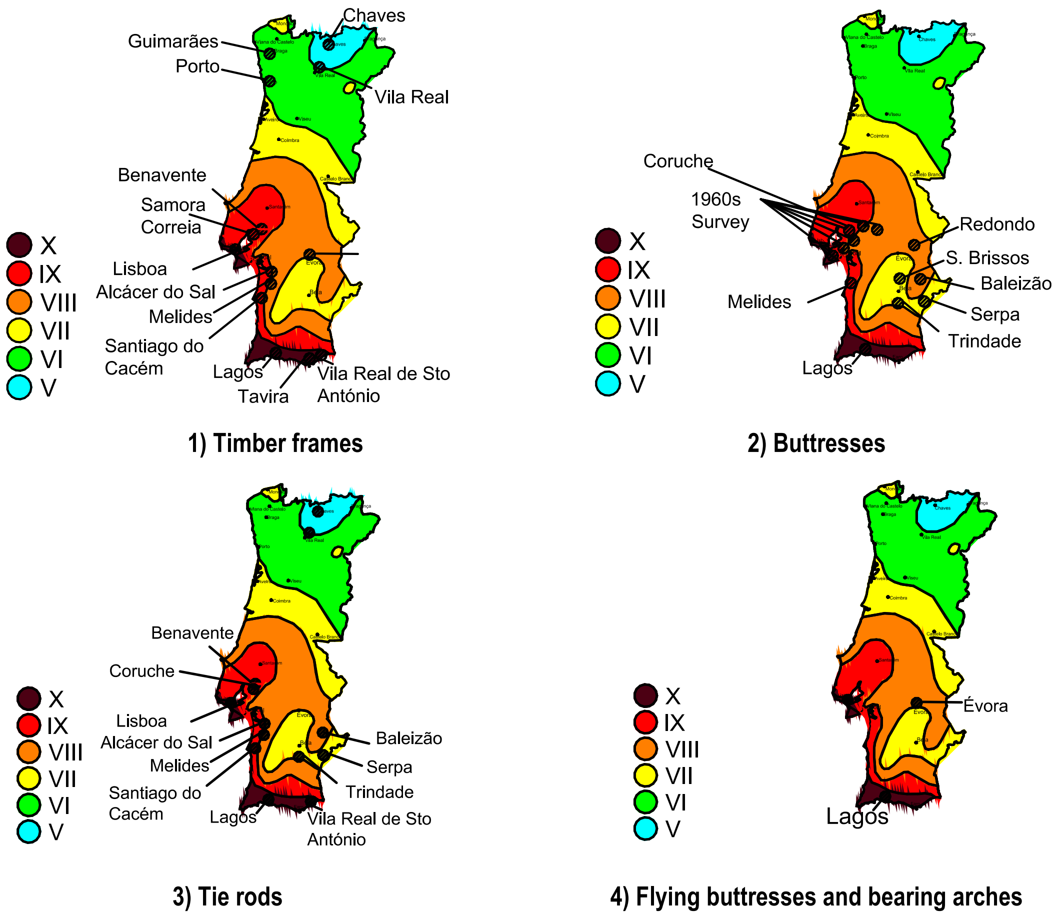


Figure 44. Representation of the main location where information was found about the existence of different seismic resisting elements

This assessment of the effective character of the potential seismic resisting features involves following a consistent procedure, as proposed by Ferrigni (2015), which includes analysing the following research questions:

Building Types/Techniques

Q1) What earthquake-proof regulations, political, economic or social factors changed during the historical seismicity of the centre?

Q2) Are there any construction techniques/building types found only in some of the towns of the area? Or only in some parts of the town under analysis? Or only in some parts of other towns?

Q3) If so, do these construction techniques/building types provide effective protection in the event of an earthquake? Do they present any analogies with traditional techniques found in other areas, or other countries, which have been defined as anti-seismic by the scientific community?

Q4) Do the construction techniques/building types in the town differ from those in other towns with access to similar resources, but which have not been struck by earthquakes of similar intensity or frequency?

Are they similar to those of towns with an analogous seismic history? Were there any significant variations following major earthquakes? Are they present in systems with access to the same resources, and which have had a similar political and social history, but a different seismic history?

Q5) Could the choice of construction techniques/building types have been determined by different needs, objectives or circumstances? In particular, could they have been conditioned by the lack of other materials? By the decision to imitate techniques adopted in traditionally more important towns? By requirements dictated by health, military or religious considerations?

Q6) To confirm the anti-seismic worth of the construction techniques/building types in question, are they ever (or only rarely) found in towns/areas with similar resources, but a different seismic history?

Seismic Resistant features

Q7) What construction 'anomalies' can be detected in the town's built-up areas? Are they the same as those referred to as anti-seismic strengthening works in other areas or in towns built with similar construction techniques?

Q8) What is the main role of the anomalies identified? Do they make the dwelling more comfortable, or increase the strength of the building; or both? Has any increased structural strength been obtained at the expense of the dwelling's comfort? Or to the detriment of public areas?

5.5. Overview

After analysing globally the results aggregated from the literature in terms of the historical seismicity of mainland Portugal and correlating the identified characteristics of possible global and local seismic cultures with the archetypes identified in each region, the following may be highlighted:

- Regions **R1, R2 and R3** have very **small hazard levels**, with the **only exception** being the **Vilariça fault (stretching along R2 and R3)** whose rupture in 1751 and 1858 led to earthquakes with M5+. As a result, the masonry buildings, which in some cases do not have mortar, have a **considerable vulnerability.** Still, the low level of hazard (and therefore **low level of risk**) led to the **general exclusion of any seismic provision.** The existence of **rammed earth walls** with diagonal bracings in exterior walls of buildings located mainly in the urban centre of **Porto and in R2** are associated with the **improvement of the static response** of the building **or** adopted due to **economic reasons**. Therefore, there is **no apparent direct consequence of ground motions**.

- **Region R4** is characterized by an **intense seismicity**, with multiple earthquakes occurring in the area with epicentres in the sea or inland. In the **Lisbon downtown**, the **1755** earthquake has shaped the **constructions**. The vernacular buildings in **Benavente and nearby areas (Samora-Correia, Santo**

Estevão, Salvaterra de Magos, Coruche, Mora and Melides) in both margins of the Tagus river have **buttresses strengthening the rammed earth buildings**, as identified before in the typological atlas.

- **Region R5** is characterized by a moderate seismicity with low levels of damage being historically associated to earthquakes. Notwithstanding this fact, **buttresses strengthening the rammed earth buildings are also found** in this area according to the survey results analysed before**. As in R4, some of these buildings also have tie rods** consolidating the structure and **improving** the **box-behaviour** effect**.** This fact raises **the doubt about the real reason for the use of these consolidating elements**, namely regarding its association with earthquake awareness or, as mentioned before, with a lack of strength of rammed earth construction to sustain out-of-the-plane forces. **Their use in very different seismicity contexts requires an in-depth analysis of local centres** to determine if a given measure is associated with **comfort, static stability, seismic strengthening** or a combination of the these factors.

- In **Region R6,** two areas can be isolated which are the **Sado river outfall** and the **Algarve** south coast line. In both cases, a regular and intense seismicity was observed.

- **In the Northern most part of Region R6**, several events have affected the city of **Setúbal** and many villages nearby (**Santo André, Santiago do Cacém, Alcácer do Sal, Grândola**). The main building typology that was found consisted **of row agglomerates with single storey rammed earth buildings** with **buttresses.** The identified archetypes have a **clear influence of seismic awareness**, since the linearity and the strengthening found indicates a concern for **seismic strengthening**. In the interior villages, buttresses and tie-rods are typically found, thus strengthening the connection between the seismicity and the vernacular constructions.

- The **Algarve region** presents a variety of typologies, although the typical **timber work used in the Tavira** archetype also indicates a **possible correlation of the areas' construction with seismic hazard awareness**.

6. Preliminary analysis of seismic resistant features in selected centres

6.1 Centres analysed

The preliminary analysis presented in the present document refers to the analysis of a set of centres that were identified in the previous sections has potential locations for the existence of a local seismic culture based on the historical seismicity. The centres selected herein for a critical review of the existing literature regarding the seismic resistant features of their constructions are the city of Lisbon and Benavente in region R4. The analysis that was carried out adopted the strategy defined by Ferrigni (2015) (see section 5.4) in order to complement and identify, based on the generic typological atlas developed in section 3, anomalies (excluding those that were related with short return period hazards) that could in fact be associated with a local seismic culture.

6.2 Lisbon

6.2.1 Building types/techniques

The historical seismicity of Lisbon (see Fig. 42.) is marked by the consequences and the post-earthquake measures adopted after the MMI X November 1st, 1755 earthquake. After the earthquake, most of the constructions in Lisbon that survived the ground motions were demolished. Being Lisbon one of the most important cities in the world at the time of the earthquake, a new plan was established, involving the urban redesign of downtown Lisbon and the construction of new buildings. Despite this incentive by the government, buildings were constructed over decades without rigid rules. Some practices disappeared over time; the quality of the construction declined over time when compared with that of the first buildings that were constructed. In the 1880s, the growth of the city lead to a new construction spree which included the construction of multiple residential neighbourhoods in an area north of the existing building stock. In the mid-1930s, the general urban construction standard (RGCU, 1930) recommended the adoption of RC structures in the ground storey in order to work as a bracing system for the masonry elements when the *pombalino* cage was not adopted. Constructions in RC started to appear in the early 20th century but the national seismic design code was only introduced in 1958 (revised later in 1961, 1983 and 2004). As a result, downtown Lisbon has currently four areas that can be seen as a result of the expansion of the city probably from the era of the 1531 earthquake, passing through the 1755 event until now. A representation of the different types of buildings existing in the city can be found in Fig. 45.

Figure 45. Illustration of the evolution of the architecture of Lisbon and the main earthquake events (map based on Simões *et al*., 2015).

As seen in Fig. 45, four types of masonry buildings can usually be found in Lisbon. These four types of buildings are respectively designated as ‘‘Pre-Pombalino’’ buildings, ‘‘Pombalino’’ buildings built after the 1755 earthquake, ‘‘Gaioleiro’’ buildings built between 1870 and 1930 and ‘‘Placa’’ buildings built between 1940 and 1960. After 1960, most of the modern buildings constructed have RC structural systems. Simões *et al.* (2015) estimated that from the 57724 buildings existing in Lisbon downtown, 1742 (3.0%) were built before 1755 (‘‘Pre-Pombalino’’), 15711 (27.2%) correspond to the ‘‘Pombalino’ structural system, 14067 (24.4%) to the ‘‘Gaioleiro’’ system, 12328 (21.4 %) were built between 1940 and 1960 and the remaining 13876 (24%) were built after 1960 with a RC structure. Furthermore, the transition between the different types of constructions is clearly associated with the seismic activity regarding the 1755 event, with a possible association of the 1880 transition due to the 1858 earthquake effects. None of the changes in the building typology after 1880 can be associated with a relevant seismic event.

6.2.2 Pre-pombalino building stock (-1755)

The *Pre-Pombalino* building stock involves a heterogeneous set of dwellings that have mostly two-three storeys and can be grouped into three categories: 1) made of high quality masonry; 2) made of low quality masonry and 3) with overhanging floors (Pinto, 2000). *Pre-Pombalino* buildings are associated with a lack of urban organization and planning measures due to centuries of unregulated city expansion (Simões *et al*. 2015). The overhanging buildings that are characteristic of this era have been studied by Stellacci *et al*. (2016) who have mentioned that this technology was imported from the northeast building tradition (Regions R2 in the current study, see section 3.2.2). The timber frame structure adopted in the upper floors (including the façade) was the subject of a regulation issued by king D. Manuel I (around 1500) which forbade the use of these structures due to urban planning issues and fire hazard (fires in 1369-73 and 1531 are mentioned in the review made by Stellacci *et al*. (2016), which may coincide with seismic events also registered around those dates). This law forbade the use of timber in the façades and limited the use of overhanging storeys, which lead to the subsequent replacement of the timber frame façades by lime mortared stone masonry (Carita, 1999; Stellacci *et al*. 2016). Figure 46 presents the main properties of an overhanging façade typical from a *Pre-Pombalino* building.

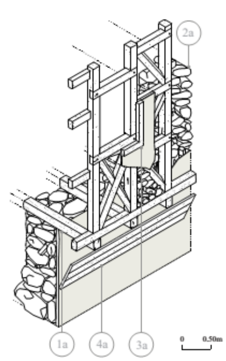
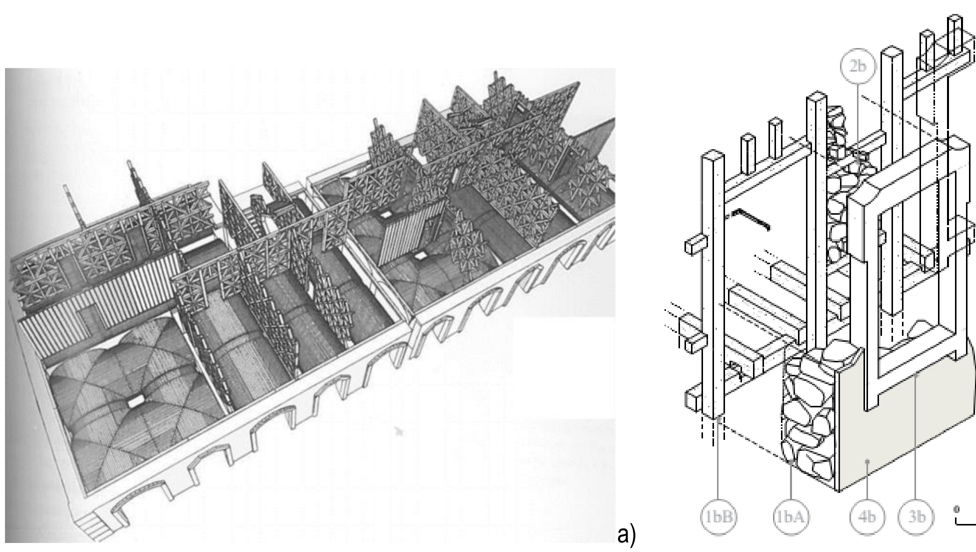


Figure 46. Overhanging façade schematics present in *Pre-Pombalino* buildings (from Stellacci *et al*. 2016).

6.2.3 Pombalino building stock (1755-1870)

A significant modification of the urban tissue of the city of Lisbon has been documented after the catastrophic consequences of the 1755 multi-hazard event. Among the reasons for the aforementioned modifications are the high number of *Pre-Pombalino* buildings that were destroyed. The new urban plan redefined the river front downtown area including the development of an orthogonal grid of buildings, with rectangular city blocks having similar dimensions and buildings with the same architectural configuration and structure. The new structural configuration, the so-called *Pombalino* building, is characterized by a mixed timber-masonry structure, known as the *Pombalino* cage. One of the main elements of this new construction is the frontal wall, a timber frame embedded in the masonry along an orthogonal grid. Originally these buildings were constructed with five storeys, including an attic and a ground floor. The total height of the building was approximately the width of the adjacent street. The exterior walls were constructed in a multi-leaf stone masonry with lime and ceramic pieces, with a 0.9-1.1m width at the ground floor. These walls are connected at the perimeter by orthogonal masonry walls with a 0.5-0.7m width. In the interior, frontal walls divide the space. The exterior walls are confined from the inside by timber frames and from the outside by the stone elements of the parapets, connected by metallic elements anchored in the stone. With this strategy, in case of an earthquake, the large exterior masonry walls are allowed to collapse while the interior timber frame will support the floors due to the lightness, ductility and redundancy of the cage system. The foundations are made of timber piles linked at the top by horizontal timber members placed on the base of the walls to stiffen the alluvium layers of the downtown area. The ground floor of the building is made of solid stone walls and piers linked by a system of masonry arches. Groined vaults spanned between the arches can also be found in the bottom storey in order to protect the upper floors from the spread of fire coming from the ground floor level. Figure 47a) represents a general view of the original structural configuration of a *Pombalino* cage building.



a) b)

Figure 47. Global schematic representation of a) an original Pombalino building (adapted from Cóias da Silva, 2005) and b) detail of the façade structure and its connections with the timber floors (adapted from Stellacci *et al*. 2016).

The solution developed by the military engineers in the reconstruction of downtown Lisbon has considerable similarities with the overhanging houses constructed during the medieval period (after the 1531 earthquake?). Among the three types of buildings existing at the time of the 1755 earthquake, overhanging buildings were the ones that shown a better response to the earthquake (Stellacci *et al*. 2016). A critical comparison can be established between these two structural systems, as shown in Table 2, based on the discussion made by Stellacci *et al*. (2016) and references therein.

As seen in the comparison made in Table 2, there is an apparent change in the building technology of the city after the 1755 earthquake which is also motivated by the good performance shown by the *Pre-Pombalino* buildings. Nonetheless, as highlighted by Stellacci *et al*. (2016), there is also a common line in terms of construction principles shared by the medieval *Pre-Pombalino* dwellings and the *Pombalino* buildings.

Table 2. Comparison between *Pre-Pombalino* and *Pombalino* systems

Property	**Overhanging building system**	***Pombalino* system**
Urban layout	Influenced by the irregular morphology of the terrain.	Regular and homogeneous urban grid, allowing for city block effects.
Timber frame	Irregular bracing elements in exterior walls and lack of vertical continuity.	Internal continuous system (cage) with systematic dimensions and configuration used in the braced timber frames.
Openings	Reduced to avoid the interruption of the exterior timber frame. The upper storeys hang on the ground floor façade.	Included within the multi-leaf masonry within the façade. No salient bodies or other irregularities exist in height.
Floors	Mono-directional and perpendicular to the main façade. Timber beams resting on continuous beam jutting out from the external wall. In some cases, stone cantilevers are used to support the overhanging façade.	Mono-directional and perpendicular to the main façade. Timber beams rest of continuous beam in the wall thickness. Selected quality, constant beam spacing, long plates of ironwork fixed on top surface of the beams or on the lateral side of the walls, connection between orthogonal walls using the vertical poles and between floors and walls.
Façades Ground floor	Walls made of mixed brick and stone masonry.	Dual leaf masonry walls with interior timber frames.
Façades Upper floors	Frontal walls with irregular timber frames and bracing configurations.	Dual leaf masonry walls with interior timber frames.
Foundations	Made of mixed brick and stone masonry.	Timber piles linked at the top by horizontal timber cross-members placed at the base of the walls
Connections	Traditional carpentry joints, namely half-lap and dovetail joints.	Traditional carpentry joints, namely half-lap and dovetail joints.

6.2.4 Anomalies introduced during the Ressano Garcia expansion (1880s): the Gaioleiro typology

In the end of the 19th century, the fast city growth to the north (planned by engineer Ressano Garcia in 1888) led to the construction of ''Gaioleiro'' buildings. These buildings, which were built during a period of real estate speculation, influenced the construction quality by giving more importance to a fast construction than to the details and material/detail quality that were part of the original *Pombalino* system. Hence, the new typology forgot most of the principles included in the post-1755 strategy and also didn't reflect the consequences introduced in nearby cities by the 1858 earthquake. The designation "*Gaioleiro*" refers to the alterations of the cage structure. As mentioned before, the quality of construction of the *Pombalino* buildings was not regular throughout the time, which is clearly reflected on the transition area observed in Fig. 17, with many connection elements between the floors and the walls. The main anomaly observed in the global structural system is the absence of a three-dimensional cohesion where the connections between orthogonal walls and the timber floors are rarely seen. The other anomaly is the decline of the quality of the masonry, including a reduction of the thickness of the walls in height and the introduction of irregularities such as open and closed-balconies and external stairs on the back façade wall with a composite structure made of 'I' or 'T' shaped steel sections connected by clay brick arches. The ''frontal'' walls were replaced by clay brick masonry walls, usually made of solid bricks at the bottom storeys and hollow brick at the top ones. The thickness of the walls decreases by changing the orientation of the bricks and, on the top floors, these were often replaced by light timber partition walls. The interior partitions were randomly placed inside the aggregates of ''Gaioleiro'' buildings. Square shapes are used in corner buildings, while the interior buildings have long rectangular shapes. A critical comparison can be established between these two structural systems, as shown in Table 3.

By analysing the main anomalies that were introduced, it can be seen that they are mostly associated with economical and logistic reasons, namely due to the need to quickly expand the urban tissue of the city. The seismic culture that was developed from the pre- to the post 1755 earthquake was almost eliminated, since the adopted anomalies or alterations disregarded the improvements made between the previous building types.

Table 3. Comparison between *Pombalino* and *Gaioleiro* systems

Property	*Pombalino* system	*Gaioleiro system*
Urban layout	Regular and homogeneous urban grid, allowing for city block effects.	Blocks of buildings, normally rectangular shaped.
Timber frame	Internal continuous system (cage) with systematic dimensions and configuration used in the braced timber frames.	-
Openings	Included within the multi-leaf masonry within the façade. No salient bodies or other irregularities exist in height.	Posterior façades have closed and open balconies.
Floors	Mono-directional and perpendicular to the main façade. Timber beams rest of continuous beam in the wall thickness. Selected quality, constant beam spacing, long plates of ironwork fixed on top surface of the beams or on the lateral side of the walls, connection between orthogonal walls using the vertical poles and between floors and walls.	Timber beams simply supported by indentations left in the masonry walls, on top which floor boards are placed.
Façades Ground floor	Dual leaf masonry walls with interior timber frames.	Interior walls made of stone or hollow brick masonry with structural functions
Façades Upper floors	Dual leaf masonry walls with interior timber frames.	Exterior walls made of stone masonry and interior walls are made of brick masonry. Interior
Foundations	Timber piles linked at the top by horizontal timber cross-members placed at the base of the walls	The walls have a continuity into the adopted superficial foundation systems. There are sometimes small footings.
Connections/box behaviour	Traditional carpentry joints, namely half-lap and dovetail joints. Cage made of a complete and strengthened connection between the timber floors and the *frontal* walls.	Connections using steel plates characterized by the lack of structural continuity and cage effect. Connections between the façade walls, orthogonal walls and the floors are rarely found.

6.2.5 Anomalies introduced during the Duarte Pacheco expansion (1940s): the Placa building typology

The expansion plan developed by Duarte Pacheco included the development of new multi-storey buildings in the northern part of the city, in part to respond to the increase in the population. Social housing was also constructed during this period. The expansion plan included the construction of the first building typologies including RC elements. Among the anomalies found in these building in comparison with the previous configurations, one can find embedded RC peripheral lintels used to strengthen the timber floors and RC frame structures at the ground floor, particularly if the building use includes stores which demanded open spaces in the ground floor. The main feature of these buildings is the replacement of timber floors by RC slabs (called *placas*). The *placa* buildings represents thus a typology that uses a mixed masonry–RC structure that marked the transition between the masonry and the RC building stock. These buildings, however, lack desirable design features as elements have very low ductility and shear capacity. The slabs are very slender (10-15cm) and, in some case, do not ensure a continuity between different spans. The low construction quality is also evident based on the lower concrete strength usually found in these buildings. The foundations of the masonry walls of the *placa* buildings are similar to those of the *Gailoeiro* buildings. Although the RC slabs could ensure a box behaviour due to the rigid diaphragm effect that is introduced, the connections to the walls cannot be considered to be effective. In fact, RC elements were not included in these buildings according to seismic provisions and can't be seen as an effective anti-seismic feature (Cattari and Lagomarsino, 2013). Interior walls are made of hollow brick masonry. The buildings have six to eight storeys, with the upper storey being constructed as a setback.

6.2.6 Anomalies introduced during the RC building period (after 1960)

The final phase of development of the city involved mostly the use of RC construction and adopted seismic safety regulations that were available at the time of construction. The typology of buildings varies significantly, including different typologies, number of storeys and configurations.

6.2.7 Evaluation of the Local Seismic Culture

Influenced by many of the regulations and novelties that were introduced in the construction process, the local seismic culture of Lisbon has clearly an evolutionary development (Fig. 48), ranging from a stage where there was a reactive approach triggered by the 1755 events (earthquake and fires) to the disruption of this principles in the following centuries, without a significant event causing a comeback to the awareness about earthquake risk or an evaluation about the effects of the modifications that were introduced. The referred awareness as only began to renewed, partly due to the numerous comprehensive studies that have been developed by academics illustrating the seismic response of the different building typologies that exist nowadays in Lisbon.

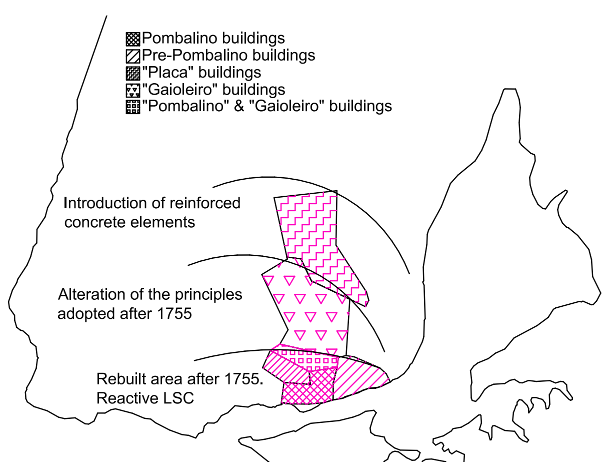


Figure 48. Global schematic representation of the different stages of the urban expansion of Lisbon.

6.3 Benavente

6.3.1 Building types/techniques

Benavente is in Region R4 (see section 3) and was identified in the performed macro analysis as one of the centres located within a relevant seismic area. According to CMB (2013), the Benavente municipality has suffered a five-stage expansion. The first stage refers to the medieval settlement representing the birth of the city, which occurred between the 12th and the 14th centuries. The second stage involved the consistent development of this settlement with an expansion up-north which occurred until the 17th century. The third stage involved an expansion of the still suburban city to the south until the beginning of the 20th century. The fourth stage was triggered by the consequences of the 1909 earthquake, thus responding to the need to build new homes for those that lost their houses in this event. An organized urban planning resulted in the expansion of the city to the south after the earthquake, creating building agglomerates that fulfilled the urban expansion needs until the mid-1940s. Finally, in the 1960s and 1970s, a new urban expansion took place that enlarged and modified the urban morphology into the configuration that can be currently found. The current urban grid can be divided in the three areas defined in Fig. 49: The grid built after the 1909 earthquake, the south expansion of the urban limits between 1909 and 1950 and the spread occupation of suburban fields after 1960s.

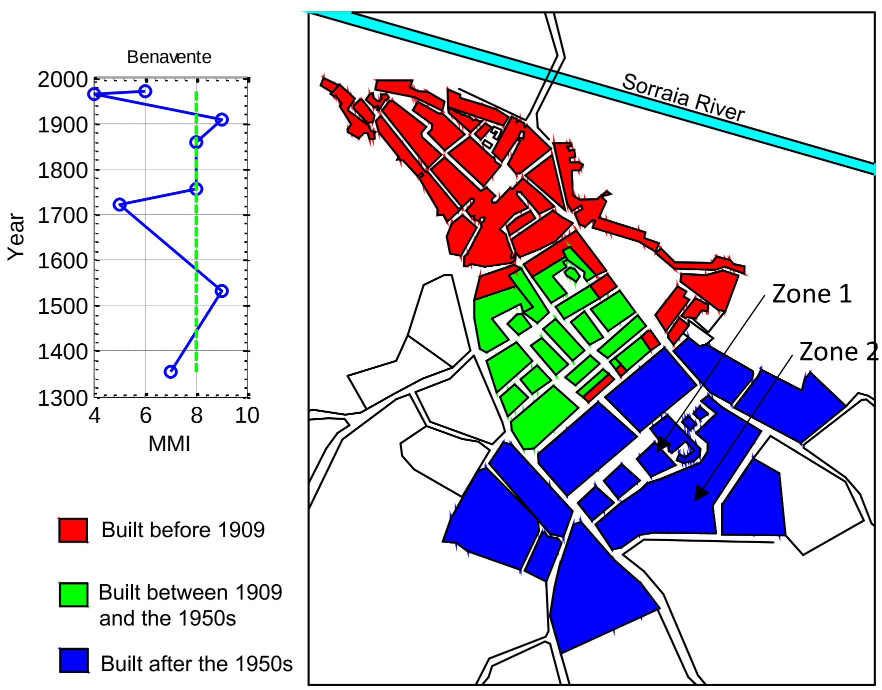


Figure 49. Urban expansion of the city of Benavente (map based on CMB, 2013) and the main earthquake events

The northern area (in red in Fig. 49) corresponds to the first urban settlement of the city, which was developed prior to 1909. The second area (in green in Fig. 49) is an orthogonal urban grid that, after the earthquake, redeveloped a sub-urban region that had been occupied since the 17th century. This area was the result of an organized plan that was designed prior to the 1909 earthquake (CMB, 2013). The construction of these agglomerates was rushed after the earthquake due to relocation needs. Furthermore, as also mentioned in CMB (2013), the decision to adopt a pre-fabricated solution that included the replication of a construction model in series was made in order to cope with economical constrains and the limited time available for the construction. Among the agglomerates constructed in this new urban area, the *Diário de Notícias, Cidade do Porto* and *Municipal* neighbourhoods represent a model that was occasionally replicated. The southernmost area (in blue in Fig. 49) can be divided into two zones. The first zone (Zone 1 in Fig. 49), is a heterogeneous area with single and multi family dwellings mixed with infrastructures such as the hospital and a school. The second zone (Zone 2 in Fig. 49) includes the replication of two archetypes: one following the directives of the post 1909 row aggregates at a smaller scale; another was implemented in a larger area as a part of social housing project after the 1960s and is mainly made of parallel four-five storey RC buildings. Other urban grids have been developed since the 1990s and include multiple building typologies which vary from three-four storey buildings to rows of twin villas with two storeys.

6.3.2 Consequences of the 1909 earthquake

The 1909 earthquake destroyed most of the buildings in Benavente, Samora-Correia and Santo Estevão. The nearby villages of the Sorraia valley, such as Salvaterra de Magos, Coruche, Mora, Ponte-de-Sôr or Melides (affected also by the 1858 earthquake) were also affected (e.g. Nisa). The occurrence of “colossal dust clouds” and “very loud noise coming from the collapse of buildings” was described at the time (Vieira, 2009).

Vieira (2009) and Fernandes (2013) analysed the typical Sorraia houses, namely the modifications made after the earthquake. Rammed earth constructions were replaced by a combination of adobe and rammed earth buildings. Even non-damaged buildings were strengthened with elements used in the reconstruction of housing areas. The modifications adopted included (Fernandes, 2013):

1) More regular use of adobe (baked) bricks.
2) Use of tie-rods connecting parallel walls.
3) Use of timber elements in rammed earth walls (*Taipa de rodízio*).
4) Strengthening of roof-walls connections with rows of brick or timber elements.
5) Construction of buttresses.

A recent study addressing the local seismic culture of the region (Gomes *et al.* 2015) reported also the existence of a large influence of the 1755 post-earthquake ideas (road plans, construction techniques) in the reconstruction of some villages. Longitudinal (linear) aggregates of residential single storey buildings were constructed with large streets separating the building rows.

The row buildings that were constructed in Benavente (see Fig. 50) have exterior masonry walls and interior structural elements made of frontal walls (similar to the façade walls of the *Pre-Pombalino* buildings and matching the interior walls used in the *Pombalino* structural system) where the internal filling part is made of adobe bricks or stone masonry. The backyard walls (in black in Fig. 50) were constructed in the alignment of the structural walls, thus serving as a bracing system for the building.

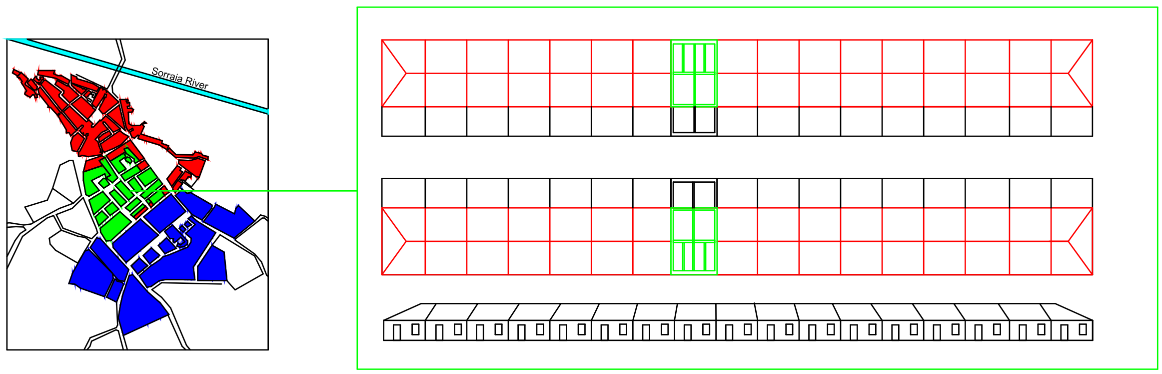


Figure 50. Linear building agglomerates constructed in Benavente after the 1909 earthquake.

6.3.3 Local Seismic Culture

An apparent reactive and preventive seismic culture was developed during the recovery of the 1909 earthquake that affected significantly the city of Benavente and villages nearby. This is clearly reflected by the fact that tie-rods started to be included in buildings that survived the earthquake, thus indicating that preventive actions started to be implemented to improve the seismic performance of buildings. In the case of the row buildings, the fact that the interior walls were built using the frontal wall system also recalls the post-1755 practice on how to improve the seismic resistance of buildings. Nevertheless, the fact that a rapid and economic solution was required after the earthquake may have had also a considerable role on the selected strategy. Further information is necessary to understand the rationale behind the solutions that were adopted. Even if the initial urban grid and typologies was already planned, as previously referred, the effect that it had on the buildings constructed in the near villages and also in the further expansions of the city indicate a possible propagation of the ideas formally adopted after the earthquake and, therefore, the temporary installation of a local seismic culture. To ensure the maintenance of this local seismic culture in further expansions, which can also be present in the symmetry and regularity of the RC building aggregates that were later constructed, it is necessary to understand in depth the characteristics and properties of these buildings in order to fully evaluate the possible seismic culture of the city. In conclusion, the area of Benavente has vernacular constructions where frontal walls, tie-rods and buttresses strengthening the masonry and especially the adobe and rammed earth buildings along the Sorraia river valley can be seen as properties that are associated with the seismicity of the area. Thus, the main typologies identified in the general typological atlas (see Fig. 42) can be seen as a vernacular response to the effects of the earthquakes, motivated in part by the seismicity and the response adopted after the 1909 earthquake.

6.4 Further centres to be analysed in detail

6.4.1 The Algarve region: Historical evolution and the main nucleus affected

Throughout the Algarve coastline, many people were homeless immediately following the 1755 earthquake. A long recovery period then followed which extended over the course of several months or even years. After the 1755 earthquake, the Marquis of Pombal sent the military to the Algarve in order to secure the locations against pirates taking advantage of the reconstruction operations in the region. A plan designated as the Restoration of the Kingdom of the Algarve involved putting in place industries and a complete reconstruction of the town of Vila Real de Santo António. This city was built to match the required response after the earthquake and it took only a few months to lay out a grid of buildings around the main square. Prefabricated units were shipped from Lisbon, including timber frames for the frontal walls. The urgency to rebuild possibly led to the adoption of a simplified version of the Pombalino cage structure. Four different types of buildings were constructed in Vila Real de Santo António: two-storey river-front buildings with an attic, two-storey main square buildings, single storey dwellings and single storey salting factories. The ground floor of the multi-storey buildings usually includes solid brick masonry and, in some cases, vaulted ceilings are also adopted. Timber roof trusses and rafters, floor beams and frontal walls are used in the upper storeys (Fig. 51).

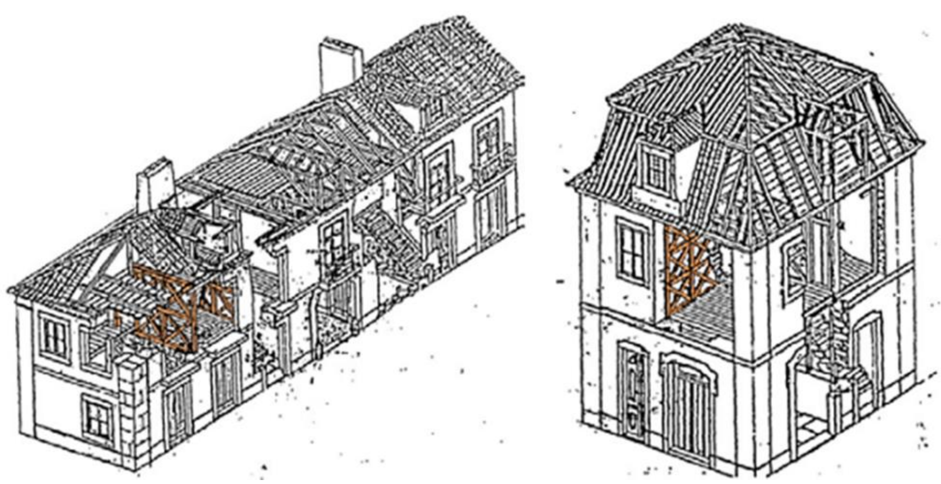


Figure 51. Two storey buildings built after the 1755 earthquake with detailing of the roof structure and of the frontal walls. (Adapted from Mascarenhas, 2004)

As analysed by Chester and Chester (2010), the recovered cities of Lagos, Portimão, Silves and Faro only regained their prosperity in the 19th century. Still, according to the authors, some suburban areas of Faro were still in ruins in the early 20th century. The larger destruction of Faro when compared to that of Tavira led to a migration of the central services of the Algarve region from one city to the other. The status of main city of the Algarve was only reclaimed back by Faro in the 19th century due to the economic growth resulting from the industries that settled there.
According to the modifications and evolutions that were observed, several cities can be seen as potential centres where a local seismic culture may have developed. Among the centres that should be analysed (bearing in mind the importance of the abovementioned historical developments) the following are suggested: Sagres, Lagos, Faro, Tavira and Vila Real de Santo António. The analysis of these cities must include a detailed examination of their urban planning evolution and the identification of the seismic-related strengthening elements, such as was performed in sections 6.2 and 6.3.

6.4.2 The coastal Alentejo region: main centres that were affected

Due to the effects of historical earthquakes, including the 1858 event, several villages may be seen as potential sources of a local seismic culture. Among these locations, Setubal, Alcácer do Sal, Melides and Santiago do Cacém can be seen as potential centres with a local seismic culture and should be analysed in a subsequent stage of the present study.

7. Conclusions

The present report performed a critical review of the seismic resistant features of Portuguese vernacular architecture. A generic map representing the Portuguese vernacular architecture was first developed and the analysis of this data established the main archetypical buildings constructed in different regions of Portugal. The comparison between several climate, morphological, short and long term hazards and the typological atlas led to the following conclusions:

1) Portuguese vernacular architecture can globally be divided into two main typologies: in the northern part of the country, granite and schist masonry structures are common, while buildings in the southern part of the country are mostly built with earth-based materials (rammed earth and adobe).
2) The number of openings, the typology of the windows and the plastering of the façades were seen to be related with the low and high temperatures that are generally felt in the northern and southern parts of the country.
3) The seismicity of the country is also different in the north and in the south. The northern part of the country has significantly lower hazard levels than the south. In terms of the construction characteristics,

the existence of structural elements aiming to sustain lateral forces and to improve the box behaviour of the rammed earth and adobe structures were seen as the main indicators of seismic provisions being adopted in vernacular constructions. The incidence of these elements is considerably higher in constructions located in the south of the country, particularly in regions with a higher seismic hazard.

4) A correlation was made between four components identified as seismic resistant features and the seismic hazard of the country. Also, given the properties of the historical seismicity, four areas with a higher probability of finding a local seismic culture were also defined. Within these four regions, the properties of the respective archetypical structures were analysed, and the main centres were isolated. The main centres identified were the city of Lisbon, Benavente and nearby villages, Setúbal, Alcácer do Sal, Melides and Santiago do Cacém and several cities in the Algarve, namely Sagres, Lagos, Faro, Tavira and Vila Real de Santo António. Alentejo cities such as Èvora and other villages such as Beja also show some elements that could be the result of a seismic risk awareness, although no evidence could be found in the seismicity to support this fact.
5) A detailed analysis of the city of Lisbon and of the city of Benavente was performed as a result of their position among the historical seismicity analysis of several centres and regions. The analysis confirmed the key influence of several high magnitude events and that rebuilding activities after these events resulted in a reactive and preventive seismic culture that could not be confirmed in the subsequent stages of development/expansion of the cities.
6) An in-depth local survey is recommended for the referred centres in order to clarify the existence of a local seismic culture according to the detailed protocol proposed within the LAReHBA project. Such study will allow for a complete separation among the comfort, static stability or seismic resistance improvements and features, including the historical definition of the sources of the elements found in the Alentejo and some cities in Algarve.

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