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Earthen Architecture in Seismic Zones: Latin America and the Pacific Fire Belt

Cuitiño Guadalupe^{1*} Esteves Alfredo² Rotondaro, Rodolfo³

1. Faculty of Applied Sciences to Industry, National University of Cuyo, San Rafael, Argentine

2. Institute of Environment, Habitat and Energy, National Research Council Scientific and Technical, Mendoza, Argentine

3. Faculty of Architecture, Design and Urban planning, University of Buenos Aires, Buenos Aires, Argentine

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ABSTRACT

This paper analyzes the current state of earthen constructions in countries located in the Pacific Ring of Fire. In Latin America, countries such as Colombia, Ecuador, Peru, Bolivia, Chile and Argentina are located in the Pacific Ring of Fire and are subject to strong seismic exposure, making earthen constructions more vulnerable. From an analysis of the housing censuses of each country, it was observed that currently, earthen construction continues to be a construction option, that the percentage of earthen constructions varies from country to country, and that they make up a high percentage of dwellings; namely, in Colombia 5.3% (714.478 houses), Ecuador 8% (383.086), Peru 31% (2.390.625), Bolivia 37% (1.037.473), Chile 2% (121.756) and 1.9% in Argentina (230.185 houses). Peru, despite being one of the countries with the highest seismic risk, is the country with the highest number of earthen dwellings. It was concluded that in all the countries analyzed, earthen architecture prevails, employing different construction techniques whose characteristics are deeply rooted in each country's ancestral culture. This highlights the importance of having regulations in place and skilled workers in order to intervene correctly and repair the structures after a seismic event.

1. Introduction

For hundreds of years, countless civilizations have used earth as a construction material, building different types of housing and monuments that today constitute part of the world's earthen heritage. Thus, earthen architecture has been present from the very beginning in man's constructions and is present in almost all the world's warm and temperate climate regions, with a lower incidence in cold climates^[1].

Historic areas, monuments, urban centers, temples or

cultural landscapes in which earthen architecture is the protagonist can be found in 190 countries, where innovations that have combined technical knowledge, audacity, art and virtuosity are reflected. According to UNESCO, there are 150 architectural constructions built in whole or in part with earth that have been declared World Heritage sites. These constructions are found on continents as diverse as Africa, Europe, America or Asia, and in many cases, are located in areas of great seismic movement, as is the case with constructions situated in the Pacific Ring of Fire (PRF). In these regions, earthen constructions

**Corresponding Author:*

Cuitiño Guadalupe,

Faculty of Applied Sciences to Industry, Argentine;

Email: gcutino@mendoza-conicet.gob.ar

are often considered vulnerable and unsafe, negatively influencing their popular acceptance. This response is closely related to the lack of knowledge of the benefits that earthen constructions naturally provide, and to the erroneous concept that in seismic zones earthen houses will inevitably collapse. However, there are many regions that, in spite of their susceptibility to earthquakes, carry out research that contributes to preventing the earthen architectural heritage from being damaged or destroyed. Among the most important are those that have developed parameters allowing the adaptation of both new and pre-existing buildings, thereby contributing innovations in construction techniques and modern architectural designs to achieve safer, more economical, modern and sustainable constructions [2].

Earthen constructions in Latin America have been carried out both in seismic zones and in zones of low seismic risk. Figure 1 shows, on the left, the areas affected by seismic movements or volcanic activity and, on the right, the areas with earthen constructions.

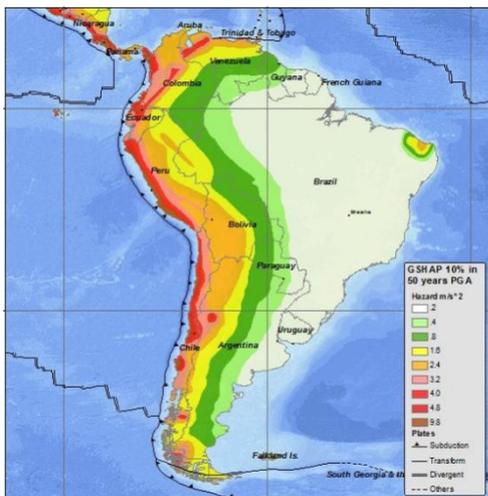


Figure 1. Top: Seismic zones of Latin America [3]
Down: Earthen construction zones in Latin America [4]

In Barichara, Colombia, located in the eastern mountain range of the Colombian Andes, most of its rammed earth buildings have been preserved intact after more than 500 years of use, in areas of high seismic risk. They are proof of its efficiency providing that, as with any other material, the buildings are well constructed and have been mindful of their limitations and scope; there are, for example, five-story rammed earth buildings like the ones in Yemen. Currently, in Barichara almost all new constructions are built with rammed earth, as can be seen in Figure 2, and all of them possess a building permit issued by the municipal Mayor's Office [5].



Figure 2. City of Barichara in Colombia. Constructions with rammed earth walls [6].

Another notable example of the combination of the seismic factor and earthen architecture is Chile, a country where the earthen architectural heritage is a fundamental part of an ancestral building tradition whose beginnings date back to pre-Columbian times and where it is estimated that 40% of the architecture with heritage values is built of earth, mainly with the adobe technique. Among those considered part of the architectural heritage are the Andean churches, the colonial churches and the haciendas of the Central Valley as well as the residential heritage present in rural towns scattered throughout the country, from the extreme north of Chile to the Bío-Bío region [7]. The village of Chijo in the highlands of the Tarapacá region in Chile, which has been occupied since the 12th

century, is considered an example of the relationship between architecture and territory, due to its use of natural resources as construction materials, Figure 3.



Figure 3. Chijo Valley, Chile ^[8]

Some of the oldest buildings in Valparaiso, Chile, were built with adobe load-bearing systems, reinforced in openings, wall junctions and crowning with pieces of wood, preferably oak. Examples within this category are, La Matriz Church, Santa Ana Chapel, San Francisco de Barón Church and a number of anonymous houses where earthen blocks with wooden reinforcements can be seen ^[9].

One of the most notable countries with respect to earthen construction is Peru, where it is possible to find archaeological remains of earthen architecture, such as Chan Chan, Pachacamac, Huaca Puellana, among others, which, having defied the passage of time and seismic movements, constitute an important part of the cultural past of that country. The archaeological sanctuary of Pachacamac to the south of Lima, Figure 4, which has been continuously occupied for more than a thousand years, comprises a monumental complex built with earth and stone, including ceremonial and public buildings belonging to the various Lima, Wari, Ychma and Inca cultures, and displays a varied architectural richness both in its morphology and its spatial organization. The main raw material used in the construction of the different buildings in the archeological sanctuary was earth for making adobe bricks. It was declared a National Cultural Heritage Site and is on UNESCO's list of World Cultural Heritage Sites ^[10-12].



Figure 4. Sanctuary of Pachacamac, Pyramid with ramp ^[10]

2. Seismic Zonation of Latin America

It is common knowledge that the dangers associated

with geology have produced, throughout history, both loss of life and loss of constructions all over the world. The Latin American continent is located on the South American plate, off the west coast, specifically off the north and central coast of Chile, the coasts of Peru, Ecuador and Colombia, and is connected to the Nazca plate, an oceanic tectonic plate located in the eastern Pacific Ocean, Figure 5. The eastern edge of the Nazca plate slowly slides eastward into a subduction zone that intrudes beneath the South American plate, giving rise to the Andes mountains and the Peruvian-Chilean fossa ^[13]. Friction resulting from internal pressures and rising temperatures causes the subduction zone to begin to coalesce and expand, producing a further increase in pressure and consequently the ascent of magma. When the magma finally reaches the surface it erupts to form volcanoes, and the localized rocks on the crust break and shift in response to internal forces. As a result, the crust located above the subduction zone is characterised by volcanoes and active faults, which represent a mere fraction of the PRF along the Latin American continent, and it is the movement along these faults that causes earthquakes ^[14].

Latin America's exposure to this phenomenon of nature, has caused it to be the scene of some of the strongest earthquakes in history, such as that of El Salvador, which in 2001 suffered two earthquakes of 7.7 and 6.6 magnitude on the Richter scale, causing severe damage, the destruction of 200,000 adobe houses and the loss of 1,100 lives. In the same year, the areas of Arequipa, Moquegua and Tacna in Peru, suffered a magnitude 8.8 earthquake that caused the destruction of 25,000 adobe houses and the death of 81 people. In 2007, another earthquake occurred on the Peruvian coast, 169 km southeast of the capital, Lima, with a magnitude of 8.0, causing the partial or total destruction of 38,000 adobe houses and 500 deaths. In 2010, an earthquake occurred on the central coast of Chile, in the Maule region, with a magnitude of 8.8, seriously affecting the last remaining adobe houses and heritage buildings in Chile ^[15].

2.1 Objectives

The Latin American countries located in the Pacific Ring of Fire, while constantly exposed to seismic movements, some of great intensity, also live with the fact that their buildings are vulnerable to the consequences of this phenomenon, especially their earthen architecture. However, and in spite of the destructive consequences of earthquakes, on several occasions it has been observed that many communities rebuild and/or restore their earthen houses, while still undoubtedly aware of both the advantages and disadvantages of this technology. This paper

examines the reasons behind this conviction to continue building with a technology that has proven to be susceptible to these natural phenomena.

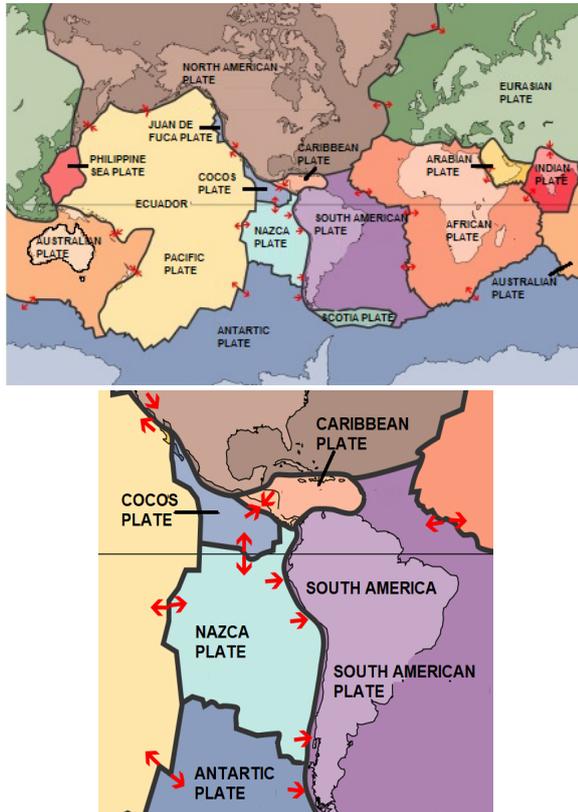


Figure 5. Map of tectonic plates ^[16]

Consequently, this paper will put into perspective the situation regarding the earthen habitat in Latin American countries located in the PRF, highlighting how earthen construction is not only a part of the culture and identity of so many communities, but also represents a connection with the past, present and future of the heritage and history of their origins.

2.2 Methodology

The databases of the latest housing censuses of the Latin American countries located in the PRF, namely Colombia, Ecuador, Peru, Bolivia, Chile and Argentina, were consulted. From the information obtained, comparative analyses were carried out to determine the incidence of earthen constructions with respect to the total number of existing dwellings. The current situation of earthen construction in these countries is presented below.

3. Case Studies

3.1 Colombia

Colombia is a country that is subject to high seismic

activity, see Figure 6, which varies from a low seismicity zone with an acceleration of 0.05 g to a high seismicity zone with an acceleration of 0.45 g. According to Duque-Escobar, approximately 35% of the Colombian population is located in high seismic hazard zones; the equivalent of 51% of the population lives in intermediate seismic hazard zones and 14% in low seismic hazard zones^[17]. In the last population census in Colombia conducted by the National Administrative Department of Statistics (DANE) in 2018, the population stood at 48.258.494 and a total of 13.480.726 existing dwellings were censused^[18], Figure 7.

Earthen construction in this country is a practice that has been adopted since antiquity, having developed several variants with local appropriations that are indispensable for the evolution of regional native earthen architecture and that keep Colombian architecture alive. Currently, the earthen construction techniques in Colombia are; adobe and rammed earth in the highlands, and in the indigenous areas and along the banks of the Magdalena and Cauca rivers, bahareque^[19]. As seen in Figure 7, 81.6% of the houses have walls of block, brick, stone, wood; 5.7% of rough wood, board, plank; 5.3% of rammed earth, bahareque, adobe; 4.6% of poured concrete; 0.8% of prefabricated material; 0.8% of waste materials (zinc, cans, plastics); 0.7% of cane, wicker, and other vegetable matter; 0.3% of guadua; and 0.1% have no walls. Of the houses built, 5.3% are made of adobe, tapia and bahareque, corresponding to 714,478 dwellings. In addition, the third National Agricultural Census (CNA) conducted by the DANE in 2015 which included a 2014 census of specifically rural populations^[20], revealed that in 49.1% of occupied dwellings in the sparse rural areas, the predominant material used in walls was block, brick, stone or polished wood; 25.5% was made of materials such as rammed earth, adobe or bahareque. It is apparent that, regardless of the seismic zone of the location, earthen construction in Colombia continues to be a valuable resource when it comes to building a house.

3.2 Ecuador

Ecuador is a country based on traditions, where ancestral knowledge has a strong presence in the culture of construction. In this country, the use of earth is present in its various versions, such as adobe, tapia and bahareque, the last one being one of the most popular. The cultural transmission of bahareque relies on the continuity of its techniques through generational transfer which can either reinforce the identity of the people or, if not correctly valued, can affect the construction culture and therefore the loss of the construction technique^[22]. In the last housing

census in Ecuador, conducted by the National Institute of Statistics and Census (INEC) in 2010 [23], the census population was 14,483,499 with a total of 4.654.054 houses, Figure 9. Of these, 5% (249.913 dwellings) were built with adobe or tapia, 3% (133.173) with coated cane or bahareque, and 4% (198,405) with uncoated cane, giving a total of 581,491 dwellings built with earthen construction technology. Despite the fact that concrete and brick construction is the most prevalent in the country, the earthen imprint is present in each of the country's regions, with the exception of those located in the areas of greatest seismicity, Figure 8, as in the case of Manabí, where, out of a total of 337.970 houses, 8.85% (29.895) were built using earthen construction techniques.

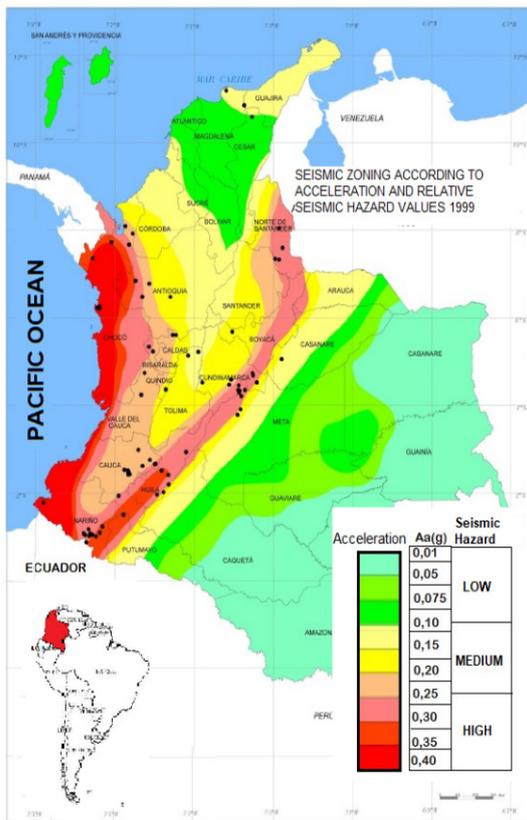


Figure 6. Seismic Map of Colombia and Seismic Hazard. (Source: adapted [21]).

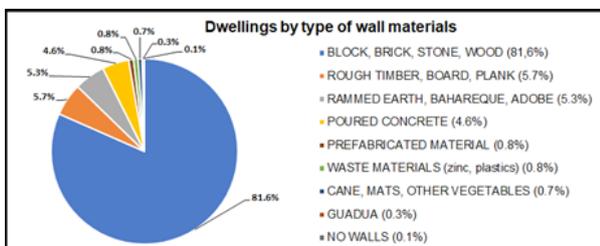


Figure 7: Housing Census of Colombia 2018 (Source: Own elaboration, 2021).

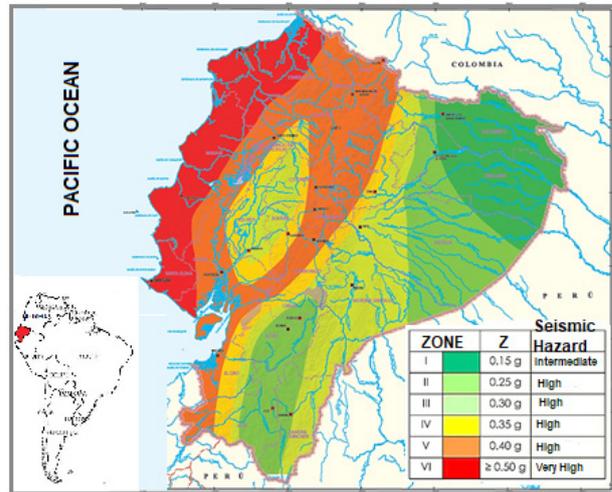


Figure 8. Seismic Map and Seismic Hazard of Ecuador (Source: adapted [24]).

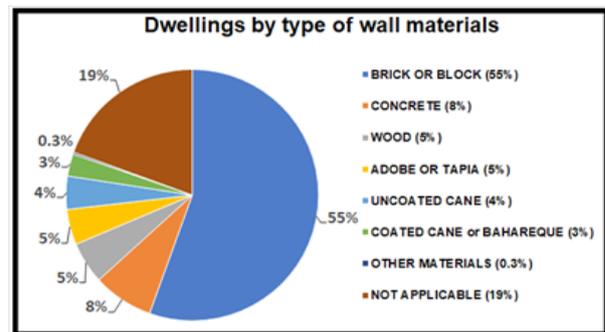


Figure 9. Housing Census of Ecuador 2010 (Source: Own elaboration, 2021).

3.3 Peru

Peru, located in the Pacific Ring of Fire, is very prone to seismic movements, Figure 10, however, it is a country that for decades has dedicated research efforts to improving earthen construction technologies in seismic zones, since the most commonly used technologies for housing construction are adobe, tapia and wattle and daub [25]. To illustrate this, in 1746 an earthquake occurred that was estimated between 8 and 8.6 on the Richter scale and X on the Mercalli scale, which severely shook the Peruvian coast and almost completely razed the city of Lima where close to three thousand houses were destroyed [26]. Almost 200 years later, in 1940, another earthquake with a magnitude of 8.2 on the Richter scale again shook Lima, causing similar damages to houses as in 1746; five thousand were destroyed in the port city of Callao, as well as 80% of the houses in Chorrillos. Old buildings in Lima suffered major damage, including damage to reinforced concrete buildings in Callao (National Beer Company), two build-

ings belonging to the Agrarian University of La Molina, and some land subsidence in the port area with damage to the docks and the railway line [26,27]. For the reconstruction of dwellings in Lima, the recovery of materials and the intensive use of the wattle and daub technique were proposed. This technique has established itself as a reliable construction system in the face of high earthquake risk and is currently one of the most widely used. In addition, it is the technique most recommended by several contemporary studies as a constructive alternative due to its mechanical qualities against earthquakes.

According to their 2017 census, Figure 11, Peru has 31.237.385 inhabitants [28] and 7.698.900 dwellings, of which 31% (2.390.625) correspond to earthen constructions due to the fact that in this country, most rural housing and those in some urban centers are constructed with earth, either because it is a simple and economical alternative or because, in some cases, it happens to be the only option for home ownership [29]. Peru has a Technical Building Standard for adobe [30] as well as a large number of research studies and manuals aimed at optimizing the structural behavior of earthen constructions in seismic risk zones [31-33].

3.4 Bolivia

In Bolivia, the seismic hazard is classified as medium, meaning that there is a 10% probability of a potentially damaging earthquake occurring within the next 50 years [35], with maximum accelerations reaching a value of 0.25 g, Figure 12. However, in 1998, a strong earthquake affected central Bolivia with an intensity of 6.8 on the Richter scale, causing the total collapse of almost 80% of the houses in the towns of Aiquile and Totorá, located 150 km from the epicenter [36], proving once again that even countries near the PRF are not exempt from earthquakes. In terms of habitational demand, Bolivia is one of the Latin American countries with the highest demand for housing needs and with fewer resources than other countries, and where large buildings can be found that use earth as the main construction material.

According to the housing census carried out in 2012, Figure 13, Bolivia has 2.803.982 occupied dwellings of which the highest percentage of material used in exterior walls is brick-cement block and concrete with a percentage of 52%, followed by adobe and tapia with 37% (1.037.473 dwellings). In the particular case of La Paz, which is more exposed to seismic movements, of its 852.573 houses, 43% corresponds to houses with brick-cement block and concrete enclosures and 51% to houses with exterior walls of adobe and rammed earth, showing that, despite the availability of industrialized construction

materials, the extensive use of earthen constructions in Bolivia exerts a strong influence associated with the traditions of the prevailing cultures.

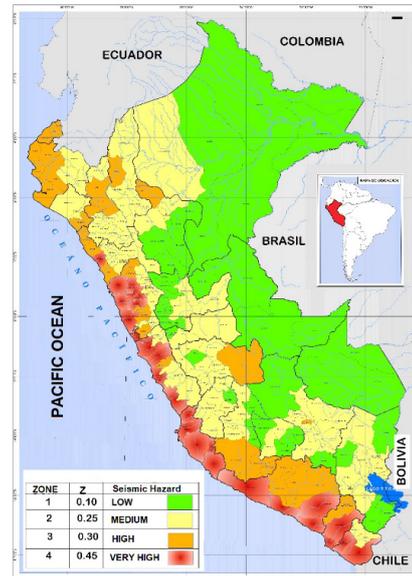


Figure 10. Seismic Map and Seismic Hazard of Peru (Source: adapted [34])

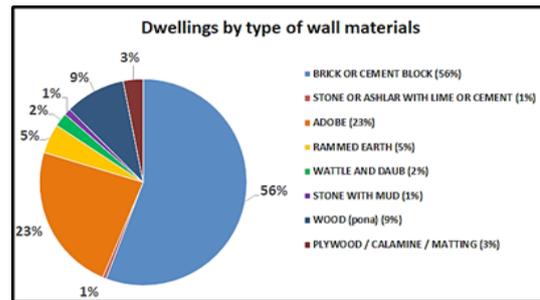


Figure 11. Peru Housing Census 2017 (Source: Own elaboration, 2021).

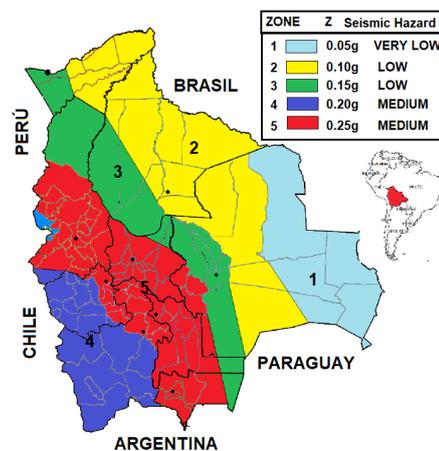


Figure 12. Seismic Map and Seismic Hazard of Bolivia (Source: adapted [37]).

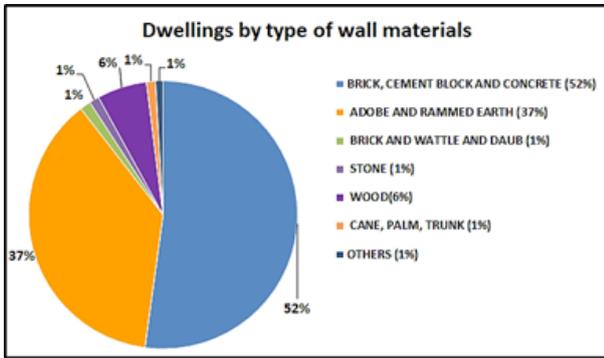


Figure 13. Housing Census of Bolivia (Source: Own elaboration, 2021).

3.5 Chile

Chile is one of the South American countries with the highest seismic hazard, reaching values of 0.40g over the entire area in contact with the Pacific Ring of Fire, Figure 14. On February 27, 2010, the central area of the country experienced one of its most significant earthquakes, with a magnitude of 8.8° (Richter), which originated due to the sudden displacement of the Nazca plate under the South American plate in an area extending approximately from the Arauco Peninsula in the south to the north of Pichilemu and covering about 450 km in length in an almost north-south direction for a width of about 150 km: approximately 200.000 dwellings were destroyed. During the post-earthquake surveys, it was found that most of the damaged buildings were made of earth, including heritage buildings, 40% of which were built mainly with raw earth materials such as adobe, adobillo and wattle and daub, and that most were located in the central area of the country [38,39]. However, the damages and in some cases total collapse of the earthen constructions were not entirely due to the seismic movement. The expert audits revealed that the main causes of damage and/or collapse were due to the passage of time and the gradual lack of maintenance. In addition, it was observed that poor repair practices with inappropriate techniques caused the buildings to be even weaker during an earthquake than at the time of construction, leading to the imminent collapse of the architectural works. Likewise, cases of good structural behavior in historical earthen constructions were observed, such as in some of the larger houses in the Chilean central Valley that had received the proper maintenance practices for earthen constructions.

According to the 2017 population and housing census [40], Figure 15, Chile has a total of 5.508.441 occupied private dwellings. The census showed that the most used material in exterior wall enclosures is cement block, stone

or brick, with a percentage of 44% (1.234.116 dwellings), while 24% (1.307.189) have exterior walls that are made of light partitions with cladding on either side. In fifth place, with 2% (121.756 dwellings) are those with adobe, mud, wattle and daub and pirca walls; a percentage that may seem insignificant with respect to the other materials used for enclosing walls, however, it is important to remember that a great majority of these earthen constructions are not only part of a historical heritage but also serve to keep part of the country's culture alive. They have remained intact in spite of the seismic events they have had to withstand, and are examples of good practices in earth construction in seismic zones, whether with adobe, tapia or wattle and daub technique.

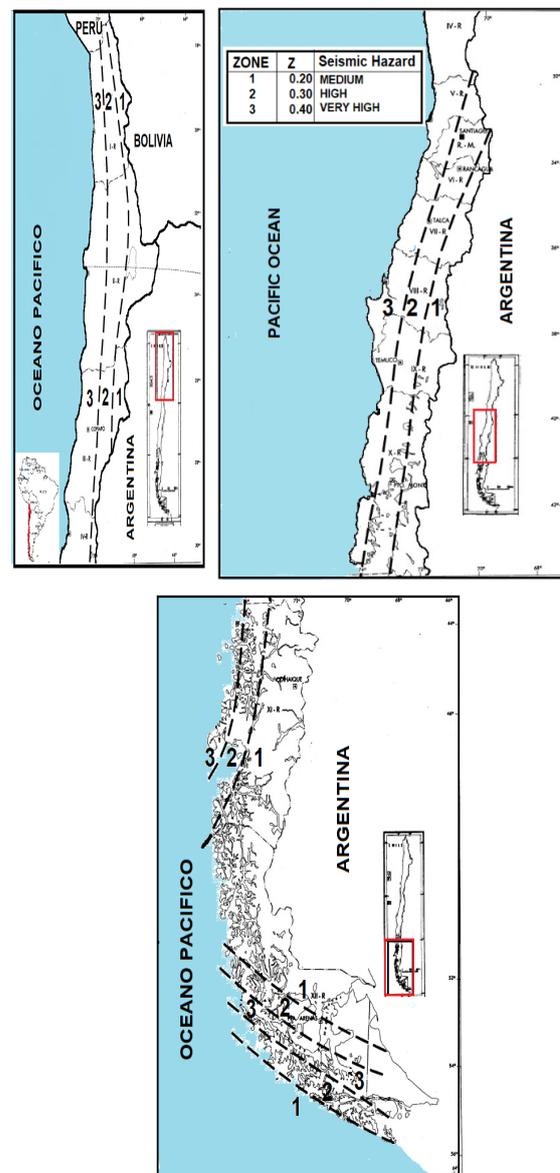


Figure 14. Seismic Map and Seismic Hazard of Chile (Source: adapted [41])

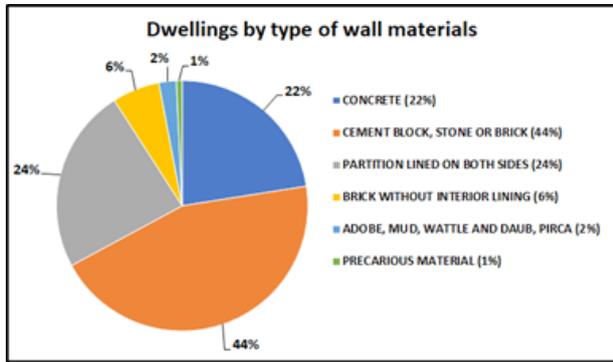


Figure 15: Housing Census of Chile (Source: Own elaboration, 2021).

Partition wall with cladding on both sides: This wall is thin and must have a supporting structure on the inside (sometimes not visible), which can be made of wood or metal profiles. The cladding or coating, both internally and externally, can be: wood planks or boarding, gypsum board, fiber cement, plastic, siding, tin or zinc. These last three are usually used only on exteriors and another type of coating on interiors.

3.6 Argentina

The western part of Argentina represents a zone marked by high seismic hazard, Figure 16, having been the scene of several destructive earthquakes throughout its history. In Mendoza in 1944, most of the adobe houses collapsed, causing deaths and injuries [15]. In 1977, an earthquake in San Juan with a magnitude of 7.4 on the Richter scale, caused great damage to the north of the province of Mendoza, where more than 50% of adobe buildings were destroyed. Eight years later, in 1985, Mendoza was again the scene of a strong earthquake (magnitude 6.3 on the Richter scale), where the greatest damage was caused to old adobe or brick buildings [42]. In spite of these seismic events, earthen constructions are currently being undertaken in different geographical regions of Argentina; namely a FONAVI (National Housing Fund) neighborhood in the Quebrada de Humahuaca (Jujuy province), as well as school buildings, offices and rural infrastructure in several localities, the main construction techniques being traditional adobe, walls reinforced with reeds and earth-cement blocks, and mixed roofing with improved poured earth roofs [43].

According to the National Institute of Statistics and Census (INDEC), in the 2010 census it was observed that out of a total of 12.174.069 dwellings, 93.3% had brick, stone, block or concrete exterior enclosures with and without plastering, and in the case of adobe, with and without plastering, the figure was 1.9% (230.185 dwellings), Figure 17. In this case, all earthen enclosures came under the

same classification category as adobe, preventing us from knowing how many houses specifically use tapia, BTC or quincha techniques. In Argentina, the Cuyo Northwest area and the Northern region are the most exposed to seismic events, considered Zones 3 and 4 according to INPRES, nonetheless, 63% (143.952 dwellings) of earthen constructions are located in these regions.

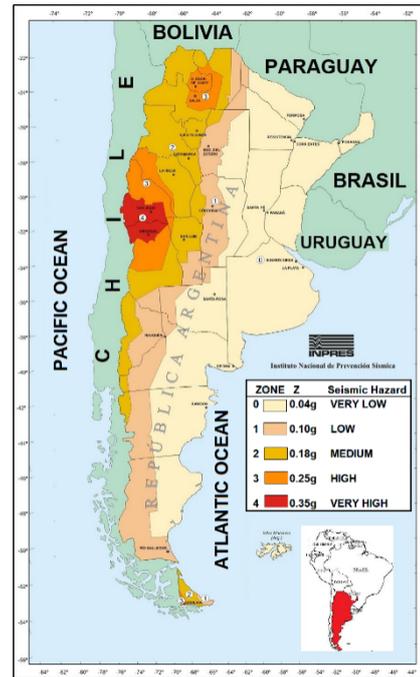


Figure 16. Seismic Map and Seismic Hazard of Argentina (Source: adapted [44])

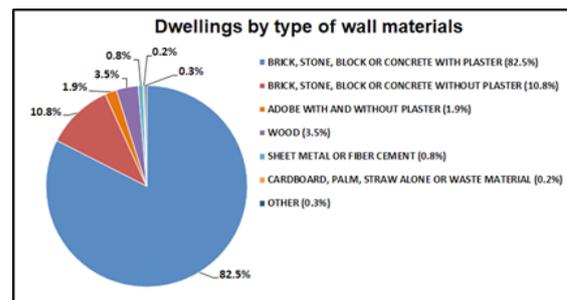


Figure 17. Housing Census of Argentina (Source: Own elaboration, 2021).

4. Results

It was observed that the Latin American countries located in the Pacific Ring of Fire are prone to seismic movements with high accelerations in a large part of the territory, as can be seen in Figure 18, and that the seismic hazard of the countries analyzed in this work coincides with the areas with the highest number of earthen dwellings. According to the data obtained from the censuses of

the Latin American countries of Colombia, Ecuador, Peru, Bolivia, Chile and Argentina, the percentages of earthen constructions, while in some cases low, when translated into number of dwellings are evidently high enough to warrant seismic regulations as well as the training of qualified professionals to carry out proper supervision and intervention of the works. The percentages analyzed are as follows: Colombia 5.3% (714.478 dwellings), Ecuador 8% (383.086), Peru 31% (2.390.625), Bolivia 37% (1.037.473), Chile 2% (121.756) and 1.9% for Argentina (230.185 dwellings). Here Peru, in spite of being one of the countries with the highest seismic risk, represents the country with the highest number of earthen dwellings. Furthermore, in cases where earthen constructions were damaged during an earthquake, the original material was reused for the repair or reconstruction of the affected dwellings, showing the perseverance of the inhabitants and their interest in continuing to live in earthen houses.

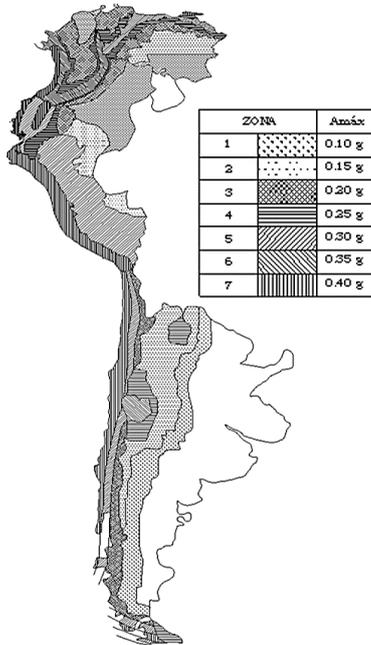


Figure 18. Seismic zonation in Venezuela, Colombia, Ecuador, Peru, Chile and Argentina in 2003 [45].

5. Conclusions

There is no denying that the countries situated in the seismic zone in the Pacific Ring of Fire are exposed to constant threats. All of them have been the scene of earthquakes of different scales and magnitudes, causing from slight damage to earthen dwellings to the total collapse of heritage buildings. However, these destructive events have not prevented their different cultures from continuing to build with techniques whose main component is earth and

that are an integral part of the footprint of the cultural traditions of each country.

There is a question regarding earthen constructions that many people ask themselves: Why do people continue to build with earth in areas of high seismic vulnerability? Perhaps for some the answer lies in the idea that they are economic, sustainable and thermally comfortable constructions, but the reality in many cases is simply that in all these areas the need for a decent dwelling carries more weight. At the same time, the ancestral knowledge, the culture and the history that defines them, are an important distinctive mark that has a bearing on each country and on the occupants of earthen constructions; so much so that after a seismic event where damages or destruction has occurred, most people and in most cases, immediately rebuild their dwellings with the same earthen materials and constructive techniques. For this reason, it is important to introduce regulations and train professionals to carry out the necessary designs, calculations and supervisions to enable new constructions located in seismic zones to comply with the necessary requirements on seismic resistance and safety for their occupants.

In the case of existing constructions, such as heritage buildings, it is necessary to preserve the historical, architectural and cultural legacy through appropriate and compatible interventions with the techniques originally used. Nowadays the use of new construction materials for the restoration of earthen architectural works is very common; however, ideally in this situation there should be a workforce skilled in traditional techniques to be able to perform the correct repair or restoration, otherwise, we will be faced with Theseus's paradox "...Would we be in the presence of the same ship if each of the parts of the ship had been replaced one by one? ...", which, applied to vernacular earthen architecture, will mean that slowly, with each seismic event, restoration or poorly performed intervention, a piece of the history, culture and identity of each country will be destroyed.

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