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EARTHEN-BUILDING CULTURES AND SEISMIC HAZARD: CHILEAN TRADITIONAL ARCHITECTURE

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Theme 1: Latin-American Architecture at Risk: Earthquakes, Rain and Flood Damage
Keywords: Building culture, earthen-architecture, seismic hazard

Abstract

This article will disclose the partial results of a doctoral thesis developed between 2009-2012 within the Department of Technology of the Faculty of Architecture of the University of Florence. The final results, were presented during TERRA 2012 conference.

The core aim of the thesis is the seismic-risk assessment of different building cultures in Chilean territory that use earth as the predominant building material, in order to propose retrofitting techniques to reduce the threat. The research is inserted within the context of recent major earthquakes that have affected Chile, which have been particularly destructive to earthen buildings, raising the need to develop preventive actions to preserve this relevant heritage.

1. PRESENTATION OF THE RESEARCH

1.1 Introduction

Two thirds of the Chilean territory have abundant earthen architectural buildings, both in rural and urban areas, from the north (lat. 18, 11'S) until the beginning of the Bio-Bio Region (lat. 36 8'S), down to the south, i.e. between latitudes, where arid-dry and Mediterranean temperate climates prevail.

This long building tradition dates back to pre-Columbian times, when earth was used as molded earth in highland regions of northern Chile (1), and with the *quincha* technique by indigenous people of the central region. The use of adobe, introduced with the Inca conquest of the Northern Territory in the late 15th century, was greatly expanded during the period of the Spanish colonization (16th-19th centuries), when the technique became virtually the only building system used for founding cities. Mixed systems, meanwhile, were developed from the 19th century onwards, incorporating wood, aimed at gaining height, slimness, formal expression and better seismic-resistant behavior, relegating adobe to in-filling of walls.

The long tradition of using earthen construction materials experienced a decline in post 1940s, following the earthquakes of Talca in 1928 and Chillan in 1939 in the southern central region of Chile. Historic adobe buildings were blamed for the numerous deaths. As a result of both disasters, the first General Regulation for Urban Planning and Construction (1929) and seismic-resistant regulations (1940) were created, respectively. Both regulations abolished the use of earth as building material, leading to the massive use of industrial constituents, and to the consolidation of modern architecture.

Since then, earthen construction has diminished but not disappeared altogether. Nowadays in Chile, there is still an important presence of earthen monuments (churches, factories), and a large number of houses, mostly inhabited, that constitute settlements of architectural and environmental significance.

According to the analysis made by Karmelić (2009) based in the Inventory of Cultural Heritage Property (2001) prepared by the Ministry for Public Works, it is estimated that 40% of the Chilean architectural heritage is built of earth, mainly adobe (Karmelić, 2009, p. 212). This number is significant when taking into consideration the high seismic activity that characterizes the Chilean territory, which has propelled the development of seismic-resistant techniques throughout history.

1.2 State of the art

Despite being a rather anonymous architectural heritage, little researched and the focus of ever greater criticism after each earthquake, in present-day and subsequent the earthquake of February 2010, there has been an interesting process of appraisal of the traditional architecture built of earth, recognizing that this is an important part of the Chilean identity (Ministry of Public Works (2010). This process has contributed the following factors:

- The recent concern of the Chilean State for the protection of cultural heritage, reflected in the development of the first program for enhancement and conservation of architectural heritage, the Enhancement of Heritage Program (2007).
- The recent appreciation of earthen architectural heritage by the communities, which inhabit a house or a neighborhood, built of earth.
- The damage caused by earthquakes in the years 2005 and 2007, the criticism of the reconstruction processes responsible for the disappearance of entire settlements built of earth, and inadequate interventions in monuments that have revealed ignorance in the use of the material, and the immediate need to train technical and professional experts.

1.3 Objectives

The overall objective of the research is the identification of the different earthen building cultures in Chile, and the determination of a methodological framework for seismic-risk assessment in each of them, in order to prevent that threat. The specific objectives are to:

Establish a method able to systemically understand the origin and the development of each culture, elucidating and codifying local knowledge;

- Identify the different architectural and technological typologies belonging to each of the building cultures;
- Identify the conservation status of each of the building cultures, and to determine their vulnerabilities and threats;
- Identify the intrinsic critical points of each architectural and technological typology;
- Recommend priority-intervention models for each building type, in order to prevent seismic hazard;
- Propose verification tools for the safety of each building culture after priority interventions.

2. CONCEPTS

2.1 Local building cultures

The various examples of earthen architecture in Chile are part of numerous local building cultures. Building culture refers to a particular architectural technology developed in a specific place that is not only a constructive technique and a repertoire of materials, but a set of functional, constructive and structural solutions that intertwined respond to the problem of living in a human group, where every decision is a synthesis of unwritten rules, which in turn reflects the cultural (the social structure, beliefs, traditions, language) and environmental contexts (geography, climate, available resources, risks), in which a building is erected. For this reason, within a building culture resides countless knowledge about the place, the environment and the rational use of local resources to develop the built environment (Tonietti, 2010, p. 24).

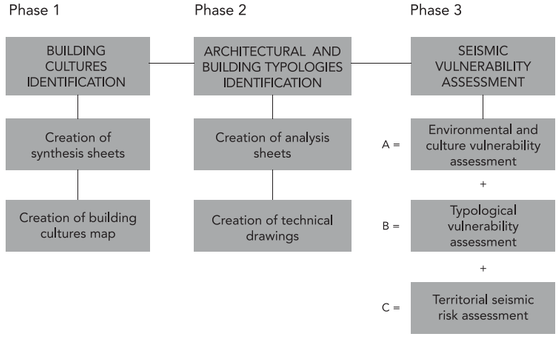

Fig.1 Scheme of the research-analysis phases, leading from the identification of building cultures, up to the evaluation of its seismic vulnerability (credits: Natalia Jorquera, 2012)

The definition of building culture must be holistically understood within the universe of new definitions developed in recent decades for cultural heritage, such as vernacular architecture, cultural landscape, intangible heritage; these are all concepts that emerge as complementary tools for the valuation of earthen architecture. A certain building culture can itself be an example of vernacular architecture, and it can also be a cultural landscape, while the survival of a building culture depends largely on how alive that intangible heritage is, which gave birth to it.

2.2 Seismic risk and local seismic cultures

In contexts of high seismic activity, local communities developed management strategies for such risk early, adapting all its available resources to create accurate seismic-resistant rules, constituting not only a particular building culture, but also a local seismic culture. The earthquake becomes part of the experience of the community, and part of the collective identity of the group, uniting their efforts to achieve stability in the built environment (Dipasquale and Jorquera, 2010, p. 112). The seismic risk remains in the memory of the local community, which together creates a series of simple unwritten rules, clearly read in the building's construction features.

Chile is one of the highest seismic prone areas in the world due to the 4,300 kilometers of coastline that is constantly pressed by the Nazca plate that descends under the South American plate, giving rise to three seismic areas parallel to the coast, of decreasing intensity from ocean to mountain ridge (Chilean Standard Nch433). The country has the unenviable record of registering the earthquakes of the highest magnitude recorded in history. In the 20th century alone, more than 30 earthquakes exceeded a magnitude of 7. For example, the earthquakes of 1906 in Valparaiso with a magnitude of 7.9; 1928 in Talca with a magnitude of 8.3; 1939 in Chillán with a magnitude of 8.3; 1960 in Valdivia with a magnitude of 9.5 (considered the largest earthquake in history); and the recent earthquakes of 2005 in Huara with a magnitude of 7.9; 2007 in Tocopilla with a magnitude of 7.7; and of 2010 in Cauquenes with a magnitude of 8.8.

3. METHODOLOGY: SYSTEMIC KNOWLEDGE AS A KEY FOR THE SAFEGUARDING OF CULTURAL HERITAGE

3.1 Systemic analysis and knowledge management for the identification and classification of building cultures

The identification of different cultures was performed through a systemic analysis that took into account all environmental and cultural factors that gave rise to the built environment. It integrated direct analysis (visits to 40 villages built of earth between latitudes 18° and 36°; accomplishment of architectural and technological photographic surveys; and interviews with residents, builders and local authorities) and indirect analysis (review of records from the Inventory of Cultural Heritage Property of the Ministry for Public Works; review of records of Historical Monuments and typical areas built of earth from the National Monuments Council; and review of literature sources).

Additionally, since the ultimate problem affecting the conservation of earthen architecture is the loss of local knowledge (ignorance or inconsistent local knowledge regarding the construction, maintenance, preservation, and repair), tools of knowledge management were used for the recovery of such information, identifying tacit and local knowledge, then documenting it in order to transform it into transferable data (Stiglitz, 1999, pp. 12).

3.2 Evaluation of seismic vulnerability of each architectural-technological typology

The evaluation of the seismic vulnerability of each architectural typology belonging to a certain building culture was approached from a holistic perspective, and considered environmental, cultural and technical aspects. Seismic vulnerability was evaluated by gathering of three factors: a) the environmental and cultural vulnerability of the building culture to which it belongs; b) the critical points intrinsic to the architectural typology (from problems associated with the choice of material, the construction process, the construction and maintenance of the building); c) the seismic risk of a certain territory where the building culture is located, which, with reference to the Chilean standard Nch433 of 1996, will result from the sum of the seismic zoning plus the classification of the building according to its use, plus the effect of the foundation soil, topography and characteristics of the earthquake.

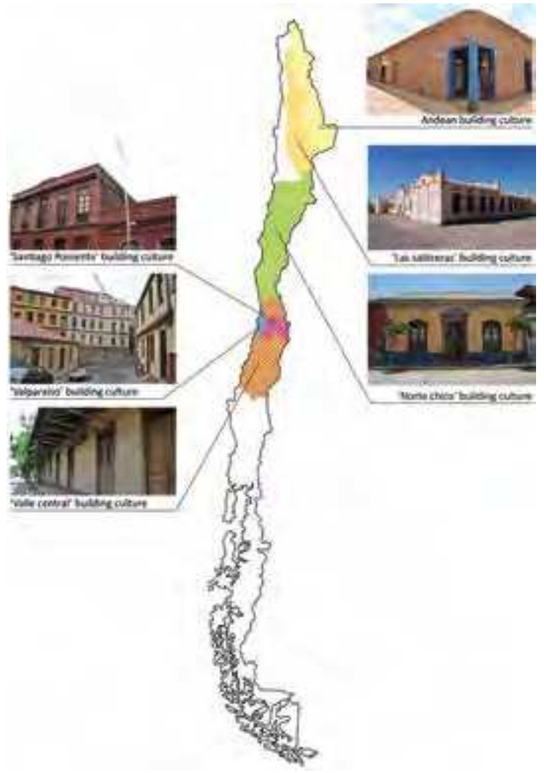

Fig.2 Map of earthen building cultures in Chilean territory (credits: Natalia Jorquera, 2012)

4. DEVELOPMENT OF THE RESEARCH: EARTHEN-ARCHITECTURAL LANDSCAPES AND LOCAL BUILDING CULTURES

4.1 Origin of the building cultures

The continental Chilean territory (2) has a great diversity of climates (according to latitude and altitude), vegetation, topography and landscapes (starting from the Atacama Desert to the north, and finishing in the eternal ice of Tierra del Fuego at the southern end). The country is divided into 15 regions, and five major climate sub-areas: the **Norte Grande** (lat. 17 56 '- 25 ° S) of desert climate and high steppe; the **Norte Chico** (lat. 25°17'- 29°11 S) of semi-arid steppe climate in the valleys, and cold temperate in the high mountains; the **Central Valley** (lat. 29 - 36 S) of favorable Mediterranean climate; the **Lakes Area** (lat. 37 - 44 S.) of cold climate and abundant rainfall throughout the year, the **Patagonia** (lat. 44 - 56 S.) of cold weather and almost polar region in the far south.

This climate and geographical diversity together with the cultural diversity of Chile (the presence of pre-Columbian ethnic groups and the high number of European immigrants from the mid-19th century onwards) has led to a wide range of architectural forms and technological solutions, through the use of earth and stone in the far north, to mixed techniques in the central valley, up to the massive use of wood in the south. Earthen architecture is abundant in the first three sub-climate regions, appearing with a fairly homogeneous exterior architectural language, especially in residential architecture, but with important typological and technological deviations that respond to climate diversity, natural resources available, and the characteristics of earth as a construction material.

4.2. Building cultures and earthen types

Six building cultures were identified, each with a distinct territorial extension from which a name was assigned. Established for each were: the architectural and technological typologies that form it, the period of historical development, the conservation status (some are "lively" cultures, others instead are in the process of decay and almost vanishing), and the threats (environmental and socio-cultural) within which the seismic risk is the common denominator. Thus, a fundamental aspect within the classification was the identification of earthquake-retrofitting strategies of the building culture.
Ordered from north to south, these are:

Andean-Culture Typologies: Andean church, Andean housing and the "pre-cordillera" housing:

These are located in the Andean region of Norte Grande (highlands and inland valleys of the Andes region, and the regions of Arica and Parinacota, Tarapaca and Antofagasta). The birth of this culture dates back to pre-Columbian times and further development occurred during the Spanish Colony so that architecture is the result of the fusion of Andean and Spanish world visions. The earthquake-resistant strategy is based on the addition of elements attached to the main volumes (buttresses, reinforced-plinth course, terracing) and/or thickening of the main walls. It is a gravitational static principle rather than a dynamic one.

Conservation is critical and the culture is at risk of disappearing, mainly because of the social changes that occurred during the first decades of the 20th century, when a great part of the population left the Andean villages to work in mining industries in the area. Currently, the main threat is the shortage of water, used by numerous mining industries in the area that has contributed to a further desertification of the valley, inhibiting cultivation, and thus survival. The earthquakes of 2005 and 2007 have worsened the situation, destroying the few well-preserved settlements.

Culture of "the Saltpeter" Typologies: Workers' housing, housing for mine owners and civil buildings:

Located in the various mining towns in the Atacama Desert, this culture based their productivity in the extraction of sodium nitrate, the so-called "saltpeter". These mining encampments were established in the late 19th century and most of them closed in the mid-20th century. Its special value is that they represent a single case of industrial architecture built with earthen materials, using mixed systems of iron and earth. At a cultural level, it represents a particular case of a community made up of two opposing groups: the mine owners (British and American), and the mining workers belonging to the lower classes of Chile. The earthquake-resistant strategy was based on the inclusion of tie-rods (metal devices horizontally located every few rows) that complemented the work of the adobe masonry, helping to counteract horizontal thrust.

Currently, only the Maria Elena Saltpeter Mine remains in operation, so this culture is almost extinct due to natural changes in production systems that have led to the closure of most encampments. The earthquake of 2007 affected particularly the city of Maria Elena, which was at risk of completely vanishing, but thanks to its prompt declaration as a Typical Zone, it has been protected and most of its emblematic buildings have been restored.

Culture "Norte Chico" Typologies: Semi-urban housing and rural chapels:

Located in the oases of the interior valleys of the regions of Atacama and Coquimbo, the population of the region originates from the Molle pre-Columbian culture, but it was consolidated as an inhabited area only in the late 17th century after the rise of agricultural production. This culture has less-defined features than the others, but its remoteness from urban centers has allowed it to remain partially alive, keeping typical customs of rural life and, therefore, also the use of traditional techniques even in contemporary architecture. The earthquake-resistant strategy is the incorporation of timber-tying elements (llaves, trusses) within the adobe masonry, which, because of their small size, are unable to efficiently connect the different parts of the building.

Urban Culture "Santiago Poniente (2000)" Typologies: three to four-story style palace:

Located in the western area of the historic center of the capital, Santiago, this culture emerged in the mid-19th century, when, after independence from Spain, the capital welcomed immigrants from different parts of Europe, who built multi-story palaces using mixed techniques of wood and earth, this being the only major type (with some variations). From this culture remain the architectural expressions, but not the community that gave life to it, as it migrated to the upper sectors of the capital. The main threat to this culture has been the depopulation of the center of Santiago by the mid-1950s, the consequent urban decay, and finally, the great real-estate speculation affecting the area since the mid-1980s, when newer buildings of greater height built within the blocks has modified the structural behavior of the housing assemblage. The earthquakes of 1985 and the recent one of 2010 destroyed palaces that were already in a state of great structural vulnerability. The response strategy to earthquakes in the past was based on the one hand, on the use of mixed techniques where wood conferred elasticity to the building, and on the other hand, in the concept of each palace as a part of a structural assembly shaping the entire block, matching the height and size of the mezzanine diaphragms and the global height of the buildings.

Culture of Valparaiso Port Typologies: Multi-family residential complexes of several floors:

Located in the historic area of the city of Valparaiso and established in the mid-19th century in close relation to the cultural exchange, it was the main Pacific harbor. The only recurring types are multi-family residential complexes of several stories, built of the mixed technique of balloon-frame with a wooden skeleton and in-filled with earthen blocks called adobillo (adobe of smaller dimensions embedded in the uprights). The decay of the culture coincides with the opening of the Panama Canal in 1914, which relegated the seaport of Valparaiso to the background, causing social change and a major economic crisis that is only being overcome in recent years thanks to the tourism developed from the designation of the city as a World Heritage site in 2003. The mixed system developed has enabled these structures to efficiently respond to the numerous earthquakes that have affected the city, recording no major damage with the last earthquake in 2010.

Culture of the Central Valley Typologies: Factories, continuous semi-urban housing construction, colonial churches and chapels:

Located in the interior valleys (between the Andes and Costa mountain ranges) of the metropolitan areas of Valparaíso, O'Higgins and Maule, this is the culture of greater territorial extension. Its origin dates back to the first decades of Spanish colonization and the landlord agriculture-production model. Despite the social changes in the production system over the course of the 20th century, this culture remains quite alive keeping the rich traditions and the entire intangible heritage related to the rural world, even though, similar to the other cultures, local knowledge related to earthen construction has been gradually lost. The earthquake-resistant strategy is the appropriate geometric design (symmetry, in respect to proportions) and the incorporation of timber elements, such as llaves and other connecting elements (like tie-rods) in the adobe masonry. Unfortunately, due to the lack of maintenance or modification of the original structures throughout the centuries, a large part of this rich architectural heritage suffered serious damage after the last earthquake in 2010.

The various levels of analysis of each of the cultures and their associated typologies were summarized in fact sheets for greater understanding. These were:

- Factsheet 1: Photographic and plan survey of each of the architectural types that make up the different building cultures;
- Factsheet 2: Summary table of the six building cultures, with their types and the summary of the construction techniques used;
- Factsheet 3: Synthesis of each building culture, with the analysis of the physical context, the cultural context, and the predominant technology;
- Factsheet 4: Analysis of every architectural typology from an architectural and technological (constructive-structural) point of view, towards an earthquake-resistant solution and criticism.

Fig.3 Example of summary fact sheet of the Andean building cultures (credits: Natalia Jorquera, 2012)

A) Assessment of environmental and cultural vulnerability of the building culture:

The building culture is in a great state of environmental and cultural vulnerability. Scarce resources, especially water, have led to a profound change in the production system based on agriculture, generating not only migration to urban centers and the abandonment of settlements, but also adverse changes in the characteristics of local construction materials. The infertile land has lost its clayey features, and the crops of paja brava (straw), useful for roofing and manufacture of adobes, have almost disappeared. To this add the loss of constructive knowledge related to building with earth. A process of disengagement with the house itself is then confirmed, which results in lack of maintenance, and replacement of the original typology with other architectural and technological forms. The introduction of modern materials (such as steel-sheet metal on the roofs) has worsened the already weakened structural behavior of the housing.

Fig.4 Example of the constructive-structural analysis factsheet of the Andean-type housing (credits: Natalia Jorquera, 2012)

B) Evaluation of the intrinsic vulnerability based on the building typology:

The great vulnerability of all types belonging to the Andean culture is the "non-monolithic" behavior of the whole, due to the poor quality of the material used for adobe and associated mortar; errors during the execution of the work (as in the irregularity of the building, and the excessive thickness of the mortar); and construction errors, such as lack of interlocking between the party walls, and the absence of ties (between walls, and between walls and roof), which gives rise to an "accumulation of elements" rather than a structural unit. To this, add the excessive weight of the layer of mud and straw, used as insulated roofing, which generates an overload of around 300 kg/m^3, where the structure is weakest. The load is incorrectly transmitted to the walls, due to the misconfiguration of the trusses, which are composed of wood of little structural strength, small dimensions, and excessive horizontal spans that fails to create a triangular shape. Nevertheless, it is still a structure that generates thrust on the walls, which already have problems resisting their own weight. Despite these characteristics, the housing is not highly impacted by the seismic thrust, due to its small size, simplistic and symmetrical geometry.

C) Evaluation of seismic hazard of the territory to which the culture belongs (4):

According to Nch433, the Andean Culture belongs to Seismic Zone 1, which means that earthquakes are seen there with less intensity than in rest of the Chilean territory, and with an acceleration of 0.2 g. The foundation soil is generally rocky, so amplification of the seismic wave is not confirmed. According to its category of occupation, housing belongs to Classification II in degree of importance (importance increases from I to IV).

It could be established in summary that, in relation to the territory, the seismic risk of the Andean Culture, and especially of housing, is lower than in other cultures belonging to Seismic Zones 2 and 3. However, due to the special vulnerability status of its building culture and the intrinsic weaknesses of its architectural and technological typology, the risk turns out to be high, i.e., a shallow intensity and duration earthquake will devastate simple housing (which are already in poor condition, presenting conceptual design errors, even where static conditions are concerned).

Thus, the most recurrent damage observed after the earthquakes of 2005 and 2007, corroborates this thesis: fractures of corners and crumbling walls are related to the intrinsic defects of this typology, rather than to mechanisms triggered by seismic action.

5. CONCLUSIONS

The results achieved to date are:

a) The development of a database with building cultures and their architectural and technological typologies, emphasizing their vulnerabilities and critical aspects. In a hypothetical second phase of this research, it would be interesting to complement the database with a record of damage caused by seismic action for each building culture.

b) Determining a methodological framework for the evaluation of seismic vulnerability.

c) The recommended "priority interventions" for each building culture (a work in progress).

The interventions to be proposed are directly related to the intrinsic vulnerability of each type. For example, it is proposed that any consolidation/restoration project of a structure belonging to the Andean Culture should start to solve the problem of the lack of "monolithic" behavior, either through the employment of ties and/or outer reinforcements (reinforced-plinth course) that confine the elements, taking advantage of the Andean Culture's positive aspects, which is its geometry and the considerable thickness of its walls.

The integration of these three recommendations can become a powerful nationwide tool for seismic-hazard mitigation. Regional actions devoted to intervention (consolidation/restoration) on earthen-architectural heritage could focus on the preventive resolution of the critical issues of each typology, improving buildings' behavior under local seismic action.

Notes

(1) The current regions of northern Chile, Arica and Parinacota, Tarapaca and Antofagasta, once belonged to Peru and Bolivia respectively, during the Spanish colonial period and until 1883, when Chile won the Pacific War, and claimed these territories.
(2) The Chilean territory is formed by the insular Chilean territory and also the Antarctic Chilean territory.
(3) In the development of the thesis, the two most extreme cultures (Andean and central valley) were evaluated as an example, since due to the large geographical distance between them, they represent two contrasting examples from the environmental, cultural and earthquake-resistant response point of view, but also because these two cultures were affected by the recent earthquakes of this century.
(4) This point is still under analysis.

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