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The Intervention of Earthen Heritage in Seismic Areas and the Conservation Charters

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Abstract Earthquakes are recurring natural phenomena that cause cumulative damage to earth constructions that can lead to their collapse. The discovery of earthen architectural heritage in Peru, has led to the re-exposure of adobe buildings, increasing their vulnerability to seismic activity. How can we prevent protect them from further damage their loss and?

Due to their gradual and progressive destruction, earth constructions located in seismic areas constitute a critical and unique case. The structural response of stone masonry joined with mud mortar depends on the weakest of their construction materials: earth.

This paper presents the criteria for structural conservation of earthen architectural heritage and tools for seismic-resistant reinforcement developed by field experts during the last 25 years. The concepts of reinforced earth and liquid mud injection, developed by the Pontifical Catholic University of Peru (PUCP) with support from the Getty Conservation Institute (GCI), are also included in this work.

The article also analyzes recent cases of the re-intervention of earth monuments initially restored during the last century and re-destroyed by more recent earthquakes; offers solutions to this situation, ranging from the safest and friendliest to the most aggressive ones. Finally, I concludes expressing the urgent need to reassess the conservation criteria accepted by the International Charters ratified by ICOMOS and UNESCO regarding earthen architectural heritage located in seismic areas.

Keywords: Earth architecture, earthquakes, conservation charter

Destruction of Earthen Architectural Heritage Located in Seismic Areas

It's evident that the effect that earthquakes have on architectural heritage is more destructive in constructions built using earth or stones joined with mud than in those built using any other material. To understand this problem and prevent the loss of architectural heritage, there are three main considerations that should be taken into account:

The unique character of constructions built with earth or stones joined with mud mortar, due to their weakness and vulnerability to earthquakes.

The tragic correlation between the areas in which earthen constructions are built and the areas with strong earthquake activity.

The Conservation Charters ratified by ICOMOS, which provide technical guidance regarding the intervention of architectural heritage built in areas of seismic activity, particularly the specifications on constructions using earth or stones and mud.

Seismic Vulnerability Constructions built using earth or stones joined with mud have low tensile strength. The impact of earthquakes on them can be quite destructive, causing them to crack or collapse. Consequently, earthen architectural heritage is more easily damaged than structures built from other materials.

Fig. 1 is an important photograph of Acllawasi, part of the Pachacamac complex, which is located close to Lima. The image is a good example of the destructive effect that earthquakes have had on earthen architectural heritage throughout the centuries. The photograph shows what was left standing of Acllawasi (built around the XII Century) in 1941 and the destructive impact of earthquakes on this great Inca maiden temple, built on earth, with stones foundations, steps and water wells.

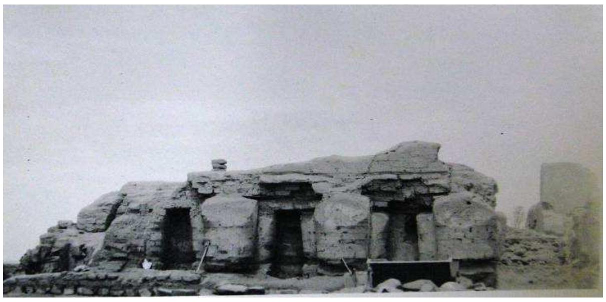

Figure 1: Pachacamac, Peru. Moon Temple. Detail view of the three niches, 1941 (Credits: Archive from the archeologist Julio C.Tello. National University of San Marcos)

The temple of Acllwasi was completely rebuilt by Julio C. Tello between 1941 and 1945. It was dramatically destroyed by the earthquakes of 1966, 1979, 1974 and 2007, and is currently closed to visitors for safety reasons.

Laboratory tests show that adobe masonry is approximately 10 times weaker than brick masonry (according to Peruvian National Buildings Regulations). The recent earthquake in Pisco evidenced the vulnerability of earth constructions, especially when compared to buildings made from other materials (Blondet et al. 2007).

The intensity of seismic forces can modify the geometry of the earth's crust, causing the collapse of the vulnerable buildings made with stones or earth, materials that were widely used in the pre-Hispanic era. Valuable historic monuments, such as Caral, the Moon Temple, Chan Chan, Paramonga or Pachacamac, in Peru; or Paquimé, Zapotal, la Joya, Teotihuacan, Cacaxtla, Tula, Tizatlán, and Cholula, in Mexico, are under serious seismic risk.

Earthen Buildings in Seismic Areas The biggest problem of earthen architectural heritage is the tragic correlation between the location of most earthen constructions and the world's seismic areas. Fig. 2 illustrates this coincidence in the American western coasts and mountains, located in the circum-Pacific belt, which is the cause of almost 90% of the world's seismic energy dissipation. It also shows how this coincidence occurs in the Mediterranean and Middle East, located in the Eurasian belt.

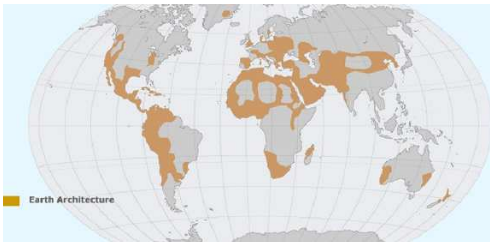

Figure 2: Juxtaposition between the maps illustrating seismic geography map and areas with earthen architectural heritage (Credit: De Sensi, 2003)

Conservation Charters and Earthen Architectural Heritage in Seismic Zones The Conservation Charters ratified by ICOMOS do not provide any technical guidance on the special intervention required by architectural heritage built in areas of high seismic activity, nor do they mention the special treatment required by earthen architecture. The universal criteria and recommendations do not make any distinction between methods that should be used in earthen architecture located in seismic areas and methods appropriate for constructions that are not under earthquake risk. The intensity of the damage suffered by architectural heritage in seismic areas, and the rate at which it occurs, are drastically different than in areas that are not affected by seismic activity. This limits the range of solutions required to solve this problem.

The only document that makes any reference to this situation is the Zimbabwe Charter (2003, www.international.icomos.org/charters), which tangentially mentions the recurring nature of earthquakes, although it doesn't mention, nor seems to understand, the cumulative damage caused by earthquakes to architectural heritage built using vulnerable materials, such as earth: 1.7 No action should be undertaken without having ascertained the achievable benefit and harm to the architectural heritage, except in cases where urgent safeguard measures are necessary to avoid the imminent collapse of the structures (e.g. after seismic damages); those urgent measures, however, should when possible avoid modifying the fabric in an irreversible way. It is not clear whether these urgent safeguard measures refer to emergency interventions that should be undertaken immediately after an earthquake, such as partial or total underpinning, or to permanent and reversible reinforcements, as this presentation will suggest.

None of the International Charters ratified by ICOMOS have acknowledged the seismic location of architectural heritage as relevant in differentiating its treatment from that given to buildings located in non-seismic areas. We should aspire to have a clear statement on the special treatment required by buildings located in seismic areas. Furthermore, it is also crucial to develop alternatives that include permanent reinforcements (not just emergency ones) that can ensure the structural stability of the structure and the safety of the buildings' inhabitants and visitors.

Based on the opinions expressed by the ICOMOS/UNESCO International Scientific Committee regarding climate change and in the possibility that technological change might allow us to find new solutions (Pretoria 2007, New Delhi 2007 and Quebec 2009 Symposiums), we should extend the same concern, precaution and foreseeing to natural disasters, such as recurring earthquakes, in seismic areas.

Local Conservation Measures in Countries with Seismic Activitiy

The Venice Charter (1964-65) establishes the following: "It is essential that the principles guiding the preservation and restoration of ancient buildings should be agreed and be laid down on an international basis, with each country being responsible for applying the plan within the framework of its own culture and traditions".

The safeguard of cultural heritage built with earth or using stones joint with mud mortar, should acknowledge the area's ecology, geography, history, tradition and local seismic activity, as well as consider any previous experiences regarding damage observation and assessment. In Peru, for example, regulation NTE 0.80 Adobe is currently under revision; the intention is to transform it into a modern tool for construction and conservation of earth architecture and to include a chapter that will offer specialized guidance on heritage conservation. To that end, the state office in charge of revising the aforementioned regulation (SENCICO/Department of Housing) is currently considering the participation of the Getty Conservation Institute (GCI). They are also working with the Chilean committee, responsible for creating a regulation regarding the conservation of earthen architectural heritage in Chile, in order to share projects and experiences.

Existing Design Criteria for the Conservation of Earthen Constructions Located in Seismic Areas

The earthen structures located in seismic areas that have managed to survive for many centuries have massive architecture, characterized by thick walls that are able to resist their weight and the effect of earthquakes. Structures that include large windows, pillars, arches, vaulted ceilings and minarets, on the other hand, have proven to be quite vulnerable.

The structural damage caused to architectural heritage by periodic seismic activity is cumulative. Each earthquake worsens the construction's global stability, which had been previously weakened by previous earthquakes. This process produces cracks on the walls, which multiply and become thicker. The sections of wall between cracks lose stability, the walls are no longer monolithic, and finally the structure collapse, which leads to a total loss of heritage.

In the specific case of constructions built with adobe or stones joined with mud mortar, the estruction process is considerably faster, which makes the intervention more urgent and complicated.

There several criteria for the design of interventions on earthen architectural heritage. Their objectives are based on three different design philosophies:

a. The oldest criterion used is based on strengthening the walls to prevent future cracking. This can be done by increasing the walls' width, building buttresses o rebuilding (partially or completely) a damaged wall. This criterion should not be applied in seismic areas.

b. A more modern criterion is based on maintaining the structure's overall stability. The objective is to control cracking and separation of the structural elements after an earthquake. To do this, strong tensile reinforcements should be applied. Moreover, a good design should also add deformation capacity to the structure after the cracking. This criterion was studied and applied by PUCP in low-income houses since 1972 to this date and by the GCI's Getty Seismic Adobe Project (GSAP) during the 90's, particularly in projects involving historical buildings (Vargas et al. 1978; Vargas et al. 2005; Tolles et al.2002).

c. A criterion recently developed attempts to recover the original strength of the fissured walls. The idea is to repair the existing cracks (usually caused by seismic activity), in order to seal the gaps on the walls. It is necessary to repair the structure after every earthquake, in order to prevent the accumulation of damage. This criterion was developed by PUCP with GCI's support (Blondet et al. 2007a,b, 2008)

These criteria can be used together in seismic areas. The harshness of seismic activity forces us to contemplate and consider the use of every possible strategy in order to prevent collapse.

Intervention Methods and Strategies in the Conservation of Earthen Architectural Heritage in Seismic Areas

Over the last forty years, in response to the loss of life and property caused by earthquakes, academia, governments, professional institutions have developed research programs to minimize the vulnerability of earth structures through use of reinforcements and damage repairs. Three of the most important researches are described below:

Research Developed by PUCP Following Criteria of Stability, Behavior or Reinforcement The reinforcement developed by PUCP since 1972, was mostly intended for low-income housing projects and in communal constructions and considered the use of collar beams and some kind of mesh for additional reinforcement. There are four types of reinforcements, but only the most modern ones should be applied in the conservation of architectural heritage:

- Internal cane meshes. 1974-1985 (Vargas J. 2005, p4 and p6).
- Electro-welded meshes inlayed into cements and sand settings.1985-2005 (Zegarra L 1997).
- External meshes of cane and rope and geomeshes (Torrealva 2005)
- Polymer geomesh with mud settings. 2004-2009 (Blondet et al. 2007).

The use of the first three solutions is recommended in areas with moderate seismic activity. The geomesh reinforcement has proved to be quite efficient in allowing the structure's ductility, so it can be safely used in areas that are under strong seismic activity. This system has been previously used in the intervention of architectural heritage in Peru, particularly in walls with no pictorial value. The reaction from the international community towards this kind of reinforcement has been mostly negative, as the use of this mesh destroys any previous setting on the wall.

Research Project Conducted by GCI Following a Stability or Reinforcement Criterion The Getty Seismic Adobe Project (GSAP) was developed in California and Skopie (Macedonia). It began in 1990 and had as its main goal improving the stability of earthen architectural heritage.

The effort made by the GSAP project between 1990 and 1997 (Tolles et al. 2003) was mainly focused in the use of confining elements that would allow for some kind of ductility and improve the walls' overall stability. Thinner walls, on the other hand, demand more aggressive solutions. The following are the most recommended reinforcement strategies:

- Wooden collar beam
- Details from the wall-ceiling connections
- Wooden diaphragms, in the case of constructions with tympanums
- Top and/or bottom horizontal lasso, made from a synthetic material or from flexible steel (cables)

- Vertical lassos close to the corners, windows and doors, and made from a synthetic material or from cables
- Combining collar beams and horizontal or vertical lassos
- Central steel or synthetic bars fit into circular drillings and fixed into place with some kind of grout

As with the Peruvian examples, the projects developed in California using these reinforcement techniques have received negative criticism from the international community, as they are considered aggressive conservation strategies, especially the core centers' solution, which is irreversible. (Barrow et al. 2005).

PUCP's Ongoing Research Following a Criterion of Structural Restitution. Crack Repair Using Mud Grouts Crack repair in walls and earthen structures by injection of liquid mud (*grout*) has been studied and developed by PUCP since 2005 with the support of the Academic Research Unit. During its second year of existence, the project also received support of the GCI (2007). The preliminary results were presented in the "First Experts Meeting on Seismic Repair and Refroit for Earthen Buildings Structural Grouting Research" organized by GCI in Lima, 2007.

Field Application Examples

Reconstruction of the Mateo Salado Archeological Complex, Lima, Peru The complex was built by the Ichzma Culture (XII Century) using earth and stones and was later occupied by the Incas. It features several layered unfinished pyramids. Each layer is 2.5 meters high and is made of grids of round-shaped stones held in place by mud fillings and perimetral containment walls featuring mud walls with vertical layers.

The containment walls were destroyed by previous earthquakes, which caused the loss of stability of large sectors of the archaeological complex. Mud mortar joints were restored by injection of previously screened liquid mud, both in transversal cracks as in longitudinal separations between the layers of the mud walls. Local materials were used for this non-aggressive intervention. Before injecting the mud grout (screened soil with a high water content), permanent mud seals and planks were used to hold them in place.

Fig. 3 shows one of the cases in which a containment mud wall has lost stability and strength after its vertical layers fell apart, worn out by the pass time. It is well known that a wall formed by three unjoined layers is much weaker than a solid wall.

Figure 3: Weakened containment wall, injected with mud grouts to increase its strength to side filling tension (Credits: Mirna Soto, 2008)

The mud injection increases the wall's strength without having to use any kind of reinforcement. These friendly solutions were applied by the archeologist in charge of the restoration works, Pedro Espinosa, from the INC (National Institute of Culture), 2009, with the structural guidance of Julio Vargas N.

Restoration Workshop in Acllawasi, in Pachacamac, Lima, Peru The archeologist Julio C. Tello rebuilt Acllawasi, using the original local materials and technology. The subsequent earthquakes of 1966, 1970, 1974 and 2007 destroyed it again. A program from UNESCO, Peru, studied the historic archives of J.C. Tello and began restoration works in a small sector from the vast complex, as part of a workshop to train local archeologist and technicians on the use of new restoration techniques by liquid mud injection. Fig. 4 shows the crack repair conducted by the archeologist Sofia Rodriguez Larraín in Acllawasi, as part of a multidisciplinary team directed by archeologist Edgar Santa Cruz, with structural guidance from the engineer J. Vargas Neumann.

Figure 4: Crack repair by liquid mud injection in Acllawasi. Heritage friendly solutions. Credits: Sofía Rodríguez Larraín, 2008

Intervention of the Casa Marrou, Lima, Peru An interesting restoration project was conducted in the old Casa Marrou in Barranco, Lima. Geomesh were used, as well as reversible reinforcement and crack repair by liquid mud injection. The archeologist and conservation expert Sofia Rodriguez Larraín was in charge of the project in 2008, with the structural guidance of engineer Julio Vargas N. The waterproof cement setting was removed and polymer mesh was held in place by a mud and straw setting coat, which allowed the adobe walls to "breath".

Intervention of the Adobe Mansion of Las Flores, in California, USA A team of conservation experts, directed by Jake Barrow, performed this restoration intervention in California in 2004. Methods developed by GSAP were used, such as top confinement reinforcements (steel cable, reversible solution) and the use of core centers (which is a non-reversible solution). The use of this last method caused a negative reaction and might discourage other conservation experts of using other solutions given by GSAP.

Model of Recent Intervention in the Bam Citadel, Iran Due to the recurrent seismic destruction in the area, a reconstruction process in the citadel of the Fortress of Bam, in Iran, was started in 1970, using local materials and technology, as in the case of Acllawasi, Peru. In 2003, while the restoration works were still in progress, an earthquake destroyed the whole citadel.

A new intervention method was recently applied in Bam, which generated controversy and negative reactions, as it's based on more aggressive reinforcement criteria. One of the 38 towers of the Arg-e Bam fortress was intervened by an Italian team, presented by engineer Valter Santoro in Lima. The method used included the drilling of the tower, and the use of glass fiber rods, joined by liquid mud grout. Figs. 5 and 6 show this method, which is quite similar to the core centers proposed by GSAP, although more aggressive and irreversible.

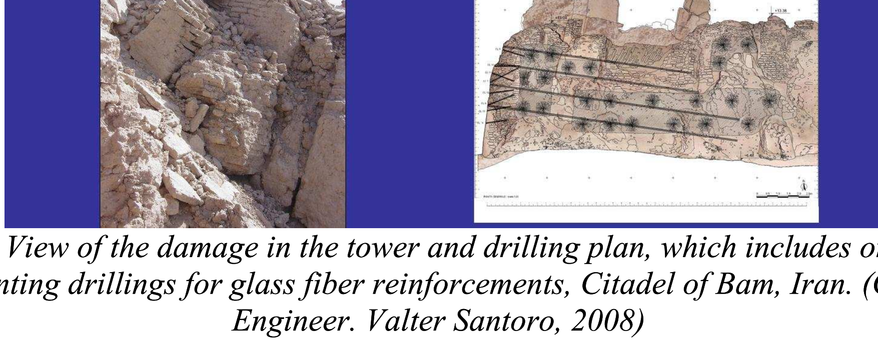

Figure 5: View of the damage in the tower and drilling plan, which includes orthogonal and slanting drillings for glass fiber reinforcements, Citadel of Bam, Iran. (Credits: Engineer. Valter Santoro, 2008)

Figure 6: Scaffolding, drilling and placement of glass fiber rods. Bam Citadel, Iran (Credits: Engineer. Valter Santoro, 2008)

International Conservation Charters (ratified by ICOMOS)

The International Conservation Charters could help put an end to the destruction of architectural heritage, built with earth or using stones and earth, located in seismic areas. They should, however, acknowledge the profound differences between materials and structures in their strength and vulnerability to earthquakes.

A fact that can no longer be ignored is that seismic activity divides the world. The technological advances of seismic resistant technology from the last 50 years evidence the failure of treating all architectural heritage with the same generic recommendations.

The continental drift theory is now widely accepted, which explains the causes of earthquakes and can help to define a seismic geography, where the effects of seismic activity can be studied through the use of modern probabilistic technologies. Thanks to the historical and statistical research, it's now possible to comparatively estimate the planet's seismic vulnerability, and to create seismic risk maps.

The earthquakes produce inertia on the buildings, which are already under permanent vertical strain due to gravity. The stress produced by seismic forces is dynamic and has variable intensity with different frequencies in time.

Although we are used to gravitational forces, we not always fully aware of the magnitude of seismic forces. This is reflected in the low earthquake-resistance of the buildings created by humankind in the past. Seismic activity produces strain, cracking and faults in structural elements that haven't been designed properly, which can lead to their collapse during earthquakes.

Materials with low tensile strength, such as the ones used in adobe constructions, crack under less strain than those built using bricks or stone held by lime and sand mortar. Weak materials can also suddenly collapse, which means that the safety of the building's inhabitants is under constant risk.

The recurrence of seismic activity produces cumulative damage in the structure, which can lead to its collapse and to the subsequent disappearance of the architectural heritage. This demands either the permanent and constant repair of damage after each earthquake, or the use of permanent structural reinforcements with high tensile strength, which should also be compatible with the materials that were originally used.

Based on the conservation charters' criteria, archeologists have used the sites' original materials and technology in the restoration projects. These methods have turned out to be inefficient. Thus, there's been a repetitive and recurring cycle of conservation versus damage, which has led to the gradual loss of architectural heritage and caused a threat on human life. This is what happened in Arg-e Bam Citadel and in Pachacamac's Acllawasi, just to mention two distinctive cases.

In order to protect earthen architectural heritage in seismic areas, it's imperative to include in the conservation charters ratified by ICOMOS the possibility of using compatible and permanent reinforcements, following criteria of reversibility and minimum strain.

Conclusions for seismic areas

1. It's imperative to stop the destruction of earthen architectural heritage, caused by frequent and severe earthquakes.
2. The techniques of crack repair by liquid mud injection need to be improved and made available to other professionals in the conservation field.
3. The criteria recommended by the current international charters produce damage-intervention-damage cycles, which is evidenced by the restoration works conducted in the past, as well as during this century.
4. It's necessary to improve the current international conservation charters, to allow the use of permanent reinforcements made with materials with high tensile strength and that are compatible with earthen constructions in seismic areas, following a criteria of reversibility and minimum intervention.

References

[1] Barrow, J, Porter, D, Farneth, S, and Tolles, L (2005). "Las Flores Adobe Seismic Retrofit: A Case Study Using GSAP Guidelines and Development of Compatible and Reversible Grouts," in *International Conference Sismo Adobe 2005*, Lima, Peru

[2] Blondet, M, Vargas, J, and Tarque, N (2007). "*Behavior of earthen structures during the Pisco earthquake, Peru."* Pontifical Catholic University of Peru, Lima

[3] Blondet, M, Vargas, J, Ginocchio, F, Morales, K, and Iwaki, C (2007a). "*Estudio Preliminar del Uso de Grouts de Barro para Reparar Fisuras Estructurales en Muros Históricos de Adobe."* AdobeUSA 2007, EEUU

[4] Blondet, M, Vargas, J, Ginocchio, F, Villa Garcia, G, Morales, K, and Iwaki, C (2007b). *"Reparación de grietas en construcciones históricas de tierra en áreas sísmicas, Informe Final DAI.*" Pontifical Catholic University of Peru.

[5] Blondet, M, Vargas, J, Ginocchio, F, Villa Garcia, G, Sanchez, K, Fernandez, C, and Chang, J (2008). *"Reparación de grietas en construcciones históricas de tierra en áreas sísmicas, Parte II, Informe Final DAI.*" Pontifical Catholic University of Peru

[6] De Sensi, B (2003). *Terracruda, La Diffusione Dell'architettura Di Terra* (www.terracruda.com/architetturadiffusione.htm)

[7] Santa Cruz, E (2009). "*Proyecto de intervención en el sector del Acllahuasi del Sitio Arqueológico de Pachacamac, Informe Final."* UNESCO, Peruvian National Cooperation Committee, UNESCO, Lima, Peru

[8] Tolles, EL, Kimbro, EE and Ginell, WS (2002). "*Planning and Engineering Guidelines for the Seismic Stabilization of Historic Adobe Structures." GCI Scientific Program Reports*, The Getty Conservation Institute, Los Angeles

[9] Torrealva, D and Acero, J (2005). "*Uso de materiales naturales y de polímeros en el refuerzo sísmico de construcciones de adobe."* SismoAdobe2005, Lima, Peru

[10] Vargas, J, Bariola, J, Blondet, M, and Metha, P (1984). *"Seismic Strength of Adobe Masonry."* Pontifical Catholic University of Peru

[11] Vargas, J, Blondet, M, Ginocchio, F, and Villa García, G (1978). "*La vivienda Rural de Adobe.*" Pontifical Catholic University of Peru

[12] Vargas, J, Blondet, M, Ginocchio, F, and Villa García, G (2005). "35 Años de investigaciones en sismo adobe: la tierra armada,"in *International Seminar on Architecture, Construction and Conservation of Earth Buildings in Seismic Areas,* SismoAdobe2005, Lima, Peru.