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Damage Assessment of Historic Earthen Sites after the 2007 Earthquake in Peru

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Abstract: The Pisco earthquake of August 15, 2007 resulted in 519 deaths and 1366 injured, with a total of 650,000 people affected and 80,000 dwellings damaged. Preliminary reports indicated that significant earthen sites were damaged. A few months after the earthquake a rapid assessment to better understand the failure of the affected sites was performed by a multidisciplinary team convened by the Getty Conservation Institute (GCI) in response to a request from the Instituto Nacional de Cultura del Perú (INC). This paper presents the highlights of that evaluation and its implications for the future design and retrofit of earthen buildings.

Key words: Earthen architecture, earthquake, seismic damage, damage assessment

Background

The existence of earthen architecture in Peru goes back to the formativo temprano or initial period (1800/1500–900 BC). It has been a construction technique used all over the country for over more than 4,000 years and has proven to be a sustainable resource for the evolution of Peruvian culture. In response to their understanding about the effects of seismic activity on earthen structures, early Peruvian cultures wisely choose to build their sites over rocky soils and developed reinforced construction techniques to dissipate the energy generated by seismic events (Williams 1980, Bryce 1980).

The Pisco earthquake tragic human losses resulted from the collapse of buildings in the states of Ica, Lima, Huancavelica, Ayacucho and Junín among others (Johansson et al., 2007). The damages have been described by several national and international organizations that traveled to the affected region immediately after the earthquake. From October 28 to November 2, 2007 the GCI in collaboration with other Peruvian institutions lead a multidisciplinary team of national and international earthquake engineers, preservation architects and conservators, visiting a total of 14 buildings (Fig. 1). The main objective of the GCI rapid assessment was to evaluate the damaged sites while recording pre-existing conditions (abandonment, deterioration or structural interventions) that might have affected their seismic performance.

The Pisco Earthquake

On August 15, 2007 at 18h 40min 59sec (local time) a M_W 7.9-8.0 magnitude *inter*plate earthquake occurred off the coast of central Peru. It had a maximum local Modified Mercalli Intensity (MMI) of VII-VIII (Instituto Geográfico del Perú – IGP) and its epicenter was located at 13.35S and 79.51W at a depth of 39 km (USGS). The earthquake was generated in the boundary between the Nazca and the South American plates, in which the Nazca plate slid underneath the American one (Alarcón 2007). A total of 18 accelerometer stations recorded the time histories of Pisco earthquake indicating a total duration of approximately 300 seconds. The principal explanations for the duration and distribution of these ground motions are the rupture model having two zones of large displacements which generated the two packs of motions (Tavera et al. 2009).

There have been numerous studies carried out by several national and international institutions to define the geology of the affected area (Lermo 2008, CISMID et al. 2008). According to those, most of the visited sites were located over alluvial deposits from the Quaternary era, not suitable for constructions unless with reinforced, strong and expensive foundations; and where geotechnical effects such as liquefaction and landslides could have occurred. These types of soils amplified the

energy frequency or the ground motion acceleration generated by the earthquake producing even more damage to the sites.

Earthen Architectural Heritage in theAffected Area

Post-earthquake assessments offer an opportunity to understand why buildings fail and provide information that can serve as the basis for the improvement of seismic performance. Lessons learned from earthquakes and other natural disasters are used to advance construction techniques. More recently, such lessons have fostered the development of the engineering and historic preservation disciplines, as well as the testing and review of current building codes and disaster management policies. This section of the paper presents information to characterize the structural damage observed at the visited sites (Fig. 1) during the assessment performed by the GCI team.

Figure 1: Location of visited sites in relation to the Pisco earthquake epicenter
From left to right: 1. Church of Chilca, 2&3. Hacienda Arona y Montalván, 4. Church of Coayllo, 6. Church of El Carmen, 6. Tambo Colorado Archaeological site, 7. Hacienda San José, 8. Cathedral of Pisco, 9. Church of Huaytará, 10. Church of San José, 11.Church of San Javier, 12. Cahuachi Archaeological site
(Credits: The J. Paul Getty Trust, 2007)

Damage Assessment Typologies Adobe typically used to build thick and massive walls is a low-strength building material best to resist compression but weak to stand tensile forces. The stresses absorbed by an adobe wall during an earthquake normally exceed the wall's tensile strength developing cracks and isolated blocks that pound against each other until the structure suddenly collapses. *Quincha* on the other hand is a relatively high-strength building construction technique with flexible membranes. The wooden frame and the cane structure can absorb tensile stress. Collapse normally occurs when the decayed and disconnected wood and the cane elements are unable to function structurally.

Tolles et al. (1996) stated, the extent of earthquake damage to an adobe structure –and *quincha* in the Peruvian case一"is a function of (a) the severity of the ground motion, (b) the geometry of the structure, i.e., the configuration of the adobe walls, roof, floors, openings, and foundation systems, (c) the existence and effectiveness of seismic retrofit measures, and (d) the condition of the building at the time of the earthquake."

The severity of the ground motion is impossible to control or prevent and is conditional to the type of soil on which the structure is built. Soft soils 一as the ones where visited sites are located一 amplify the ground motion acceleration generated by the earthquake inducing more damage to the sites. The geometry of a building influences its ability to withstanding seismic events. Tolles *et al.* (1996) as part of the Getty Seismic Adobe Project (GSAP) provides excellent descriptions 一similar to the ones observed during the 2007 Pisco survey一on how thicker, thinner, constrained or not-

constrained adobe walls perform during a seismic event. Complementary to the GSAP project, the Pisco survey focused on damage failures of *quincha* walls, vaults and domes and the impact of the building structural conditions on their seismic performance.

Quincha Deterioration Mechanism Most of the visited sites damaged by the earthquake were constructed with domes, vaults and walls made of *quincha.* Regular maintenance of these structures was expected during the Peruvian ancient and colonial times, including the occasional replacement of the wooden structural elements, cane reed and leather straps. With time and lack of maintenance, wooden elements were damaged by the presence of termites and the connections started to fail. The leather straps became brittle and the reed cane detached from the structure losing its flexibility and tensile strength. The state of deterioration of this construction system influenced the way buildings performed during the Pisco earthquake (Figs. 2-4).



Figures 2 (left): Detail view of cane reed after mud plaster detachment, Church of Chilca
Figure 3 (center): Detail of leather straps, Cathedral of Ica, Ica
Figures 4 (right): Detail of deteriorated wooden arches at Church of San José, Nazca
(Credits: Courtesy of INC Lima, 2007)

Shifts or Total Collapse of Domes of Church Towers At the Churches of Chilca, El Carmen, and Huaytara as well as the chapel of Hacienda San José, the difference between the flexible *quincha* pillars and the stiffed adobe tower during pounding precipitated the upper dome failure, shifting first, and collapsing later. Severe termite damage was observed under detached plaster in all the wooden elements and cane reed of the *quincha* pillars, vaults and domes.

Partial or Total Vault Collapse As mentioned before, wooden structural elements and the cane mesh of the *quincha* were heavily damaged by termites. In the case of the vaults, the damage was observed at the wooden arches and at their connections to the top of the adobe walls, pilasters and front facades. Another pre-earthquake condition contributing to collapse is the presence of a heavy layer of dirt or cement mortar over the vault, probably due to lack of or inappropriate maintenance respectively. At the moment of the earthquake, the vault tried to restrain the rocking of the walls, adding stress to the deteriorated trusses and their connections until failure (Fig. 5).

At the churches of Coayllo, Guadalupe and Humay, the presence of reinforced concrete arches at the end of the vaults stiffened the structure at both ends which in conjunction with the deteriorated arches induced the *quincha* vault to fail. At the Cathedral of Ica, the architectural configurations of the building as well as its maintenance helped to partially withstand the earthquake. The better seismic performance of preserved arches, the presence of the lunettes and side chapels between them prevented the total collapse of the vault (Fig. 6).

Out of Plane Collapse When entire vaults or domes collapsed, it was clear that walls (front facades or lateral walls) rocked until connections failed resulting in partial or total vault collapse. In the case of the Church of Guadalupe the concrete tower pounded the earthen façade until collapse of its upper section inducing partial collapse of the vault (Figs. 7, 8).

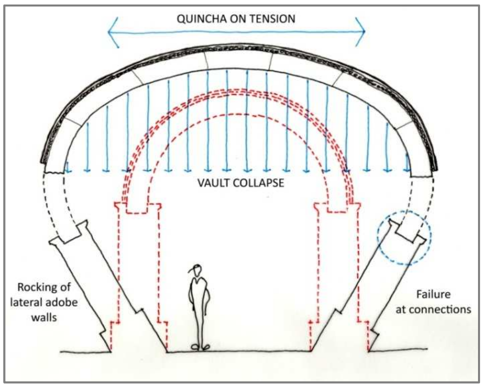

Figure 5 (left): Failure scheme mode of quincha vault
(Drawing, C. Cancino, 2009)
Figure 6 (right): Cathedral of Ica after the Pisco earthquake,
where arches and lunettes stopped total collapse of quincha vault
(Credits: J. Paul Getty Trust, 2007)

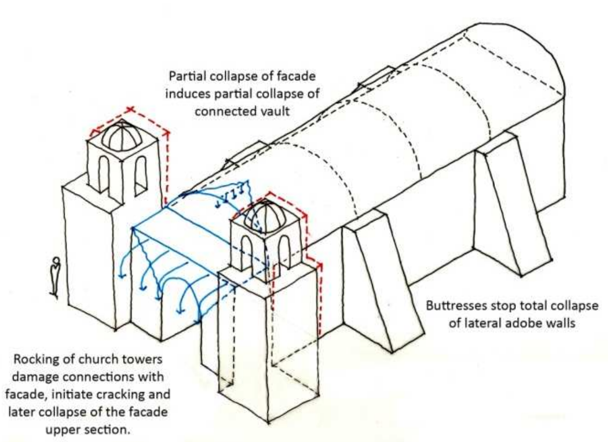

Figure 7 (left): Façade failure as seen at the Church of Guadalupe, Ica
(Drawing: Claudia Cancino, 2009)
Figure 8 (right): Church of Guadalupe after the Pisco earthquake where out of plane of collapse of front facade induced partial collapse of the quincha vault
(Credits: J. Paul Getty Trust, 2007)

In the case of the Church of Coayllo, partial out of plane collapse of later walls contributed to the total collapse of the vault triggered by its deteriorated arches. A much more obvious example of this type of failure however, was observed at the stand alone walls at the Church of Chilca and the main house and worker residences of the San José and Arona y Montalván estate respectively where walls sections collapsed. In both cases, the slenderness ratio of the walls didn't resist the rocking during the earthquake.

Damage on Columns and Pillars In the case of the Cathedral of Ica, the hollow pillars constructed with wooden frames and cane mesh plastered with mud and gypsum suffered from plaster detachment at their bases. It seems that the *quincha* pillars were able to absorb most of the energy and only plaster detachment at the bases was recorded. In the case of the Arona y Montalván main estate house, it seems that the roof of the veranda moved in two directions: Parallel and perpendicular to the building facade. A resulting gap was observed at the roof of the building between the veranda and the main house as well as a crack between the veranda and the main tower. The plaster detachment at the upper section of the columns could be the result of the rotation of the columns. The colonnade balustrade and bases prevented the whole structure to collapse.

Plaster Detachment Although plaster detachment is not structural damage, it is important to mention as a condition worth study and repair. Well maintain plaster layers contributes in a major

way to the overall coherence of the structure. Many plaster detachments were observed on vaults, domes, walls, columns, and pillars of the visited sites. Furthermore, and most importantly, previous non-repaired plaster detachments left the wooden elements of the *quincha* roofing systems, as well as columns and pillars, exposed to the environment generating termite damage, as observed at the Churches of San José and San Javier de Ingenio in Nazca. When previous plaster detachments were repaired with non-compatible materials such as layers of cement over the *quincha* vaults or domes, heavier loads were applied to the earthen walls inducing out of plane collapse. That was probably the case at the Church of Coayllo and the Cathedral of Pisco.



Figure 9: Upper dome of Hacienda San Jose Chapel: Connections deteriorated inducing loss of structural integrity (Credits: J. Paul Getty Trust, 2007)
Figure 10, center: Beetle damage at the adobe walls at the worker residences of the Hacienda Arona y Montalván (Credits: INC Lima, 2007)
Figure 11, right: Termite damage on wooden framework at Cathedral of Ica, Ica (Credits: J. Paul Getty Trust, 2007)

Impact of the Lack of Maintenance on the Structure: The seismic behavior of the visited sites was affected by maintenance issues that significantly reduced the structural integrity of the building including:

- Loss of structural integrity and lack of connections between damaged wooden elements of *quincha* vaults, pillars and walls, which isolated parapets, partitions, and façades, affecting their stability. (Fig. 9)
- Non-repaired structural cracking and weak mortar-block adhesion strength.
- Moisture damage to the *quincha* and adobe walls.
- Beetle damage in adobe blocks that reduced wall strength. (Fig. 10)
- Termite damage on the wooden framework of the *quincha* walls, which contributed to partial or total collapse of entire structures. (Fig. 11)
- Addition of different building materials and systems into the structure.

Recommendations

1. There are already a certain number of technical options available to build safely with earth and to retrofit historic earthen sites located in earthquake zones based on scientific research that is worth disseminating.
2. There is potential to develop less invasive alternative retrofitting techniques by adapting traditional methods and materials. Scientific data needs to be acquired to apply engineering concepts and values to traditional retrofitting systems.
3. There is a strong need to develop guidelines for seismic retrofitting using local materials and low-tech solutions for its implementation. A program of intervention for minimal strengthening methods, easy repair techniques, and site maintenance would reduce loss of life and damage in future earthquakes.

Conclusions

- Earth construction in Peru represents a great piece of its cultural and vernacular heritage and is one of the main materials for the construction of its settlements. Over centuries, earth has been used alone and as a part of sophisticated building systems (e.g. *quincha*), demonstrating the abilities of Peruvians to develop appropriate solutions to seismic activity.
- Modernization at the end of the XIX century introduced new industrialized building technologies to the main cities, leaving earth as the predominant construction material in rural areas. Local knowledge on maintenance declined over time leaving earthen buildings prone to decay and susceptible to earthquakes.
- Concerns about the life safety and seismic performance of earthen buildings have been the impetus for banning earth as a suitable contemporary construction material. Nevertheless, earth remains the predominant building material in the existing buildings stock. Effort is needed to develop solutions to reduce the vulnerability of significant existing earthen sites.
- During the August 2007 earthquake, seismic damage was a result of the accumulative effects of seismic activity, lack of maintenance and repair.

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