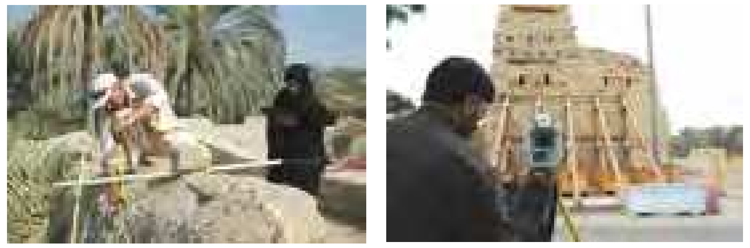

Fig.6 and fig.7 Documentation of Jimi Walls and monitoring of Abdullah Bin Salem Al Darmaki House (credits: Salman Muhammad © ADACH, 2010 - Ali Malekabbasi © ADACH, 2011)

they were not experienced in addressing the urgent need for conserving a large number of buildings at the same time, while no disaster-preparedness plan was in place. In such situations, approaches developed for the EC program can be used as a high-level model and a starting point. They address planning and prioritization, implementation, documentation, monitoring, data management and awareness-raising.

Planning and prioritization are done firstly building by building to understand typical conservation issues, followed by a task-based approach across many buildings. This is a two-way process. Once urgent issues are dealt with, a building-based approach is again used to identify and address mid-term conservation issues.

Implementation is carried out according to one of two approaches according to the authenticity of the fabric and the historic significance of the heritage. For buildings and sites of high significance and authenticity, a policy of minimum intervention is implemented after scientific investigations, studies and diagnosis. While for those that have been extensively reconstructed and are of low historic significance, a traditional master builder's approach to repair is adopted with the aim of conserving the 'tradition' as opposed to the 'fabric'.

The level of precision of documentation and monitoring is defined according to both significance and vulnerability. A regime for managing monitoring tasks across buildings guarantees control of possible deterioration and triggers appropriate actions in good timing.

A data-management system is set and a chain of task records is designed to regulate and record the whole procedure for all tasks. An internship program is designed to train students and young professionals, while dissemination through publications, group visits and public lectures raises awareness and interest in the program.

On a detailed level, approaches and methodology that were developed by the EC program can be relevant for emergency-conservation situations in the Arabian Peninsula, and possibly, the Middle East. However, the limitations of the model should not be undermined by differences in typology of the heritage fabric, construction materials and systems, environment and climate, socioeconomic and socio-cultural contexts.

7. CONCLUSION

ADACH's EC program has been successful in rapidly assessing and stabilizing a large number of threatened earthen buildings. Within the framework of the program, the Conservation Department established a planning system, documentation and monitoring protocol, materials-production workshop and skilled-labor force, and an interdisciplinary team of specialists.

In the future, the EC planning process will allow conservators to evaluate their work through quantifying and monitoring completed interventions. By tracking materials used, type and number of tasks performed, manpower, and the long-term stability of conservation interventions, future cycles can be modified and improved. The EC program is, however, only the beginning of a long process. As the EC cycles progress, less urgent issues are scheduled and priorities shift to longer-term conservation and management challenges, such as sheltering roofless buildings, reuse and/or opening the site to visitation.

The EC planning process is applicable to other regions facing a similar group of at-risk buildings or as a framework for disaster-preparedness planning in heritage areas. As the program was designed for the earthen heritage and conditions of Abu Dhabi, it must be adapted to suit different building materials, climates, and heritage-management contexts.

Notes

(1) See Malekabbasi and Sheehan (2011). Hamad bin Hadi al Darmaki House and the cultural landscape of Hili Oasis, Al Ain, UAE. Submitted for TERRA 2012 (Ref. T4-023).
(2) This opportunity was part of an internship program used to train the young Emirati female students in documentation of old walls with traditional measuring techniques.

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SEISMIC RESISTANCE IN THE CORE OF CARAL, PERU

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Theme 7: Ancient/Historic and Innovative Solutions for Damage Prevention and Performance Improvement
Keywords: Pyramids, stability, seismic resistance, reinforcement

Abstract

The great antiquity of the city of Caral and the level of engineering found in the pyramids leads to the conclusion that its construction technologies influenced the development of the ceremonial architecture of Peru and America. A first realization is that the pyramids were structurally secure due to the stability of their nuclei. The pyramids were stable as stepped platforms, resulting from the burial of previous structures, which was the religious and spiritual conception associated with the structural design. These buildings were treated as living beings that wanted to immortalize themselves with their deities, and once their stage of life came to an end, it was buried to generate yet a greater stepped-pyramid structure.

Burials of the pyramids were carried out with specific materials and technologies developed to achieve the overall stability of the pyramid against seismic events. Platform nuclei were formed through trial and error, with materials of increasing internal friction and greater percentage of voids (angular stones), aimed to increase lateral stability.

The greatest revelation was the use of tension reinforcements. Builders invented bags of vegetal fiber containing stones in a stable equilibrium, which produced a strong earthquake resistant behavior in the cores of the pyramids. These were the forerunners of today's gabion technology. The façades of stone and earth were, for aesthetic purposes, plastered and decorated. They were the mutable skin of the immortal structure.

Additionally, in Caral, the technology of wood, cane, vegetal fibers and earth was developed, known as quincha, which was later re-used in the colonial architecture of Lima, as an earthquake resistant solution following the catastrophic earthquakes of 1687 and 1746. This paper is presented by the structural group of Caral, part of an interdisciplinary team, which describes the details of the research carried out at the pyramid called '*La Galería*', where significant progress in earthquake resistant engineering has been ascertained, developed in Peru over 5,000 years ago.

1. INTRODUCTION

The European outlook for the 'New World' could potentially be misrepresented to its pre-Hispanic Mudéjar history. The meeting of Europe and America did little to save the cultural value and the historical content of the new space found beyond the seas. Native art and building techniques were undervalued.

The discovery and study of historic sites during the past 15 to 20 years, such as Sechin Bajo, Caral, Ventarrón, Chavín de Huántar, Kotosh, Huaca Prieta, which are between 3,500 and 5,000 years old, demonstrate that these are buildings, temples, ceremonial places, pilgrimage centers and cities contemporary with the dynastic works of ancient Egypt. This is, however, a fact that has only recently been revealed, effectively changing the history of Peru and America. These grandiose monuments also transcended the human dimensions and contain secrets of advanced technological knowledge. Specific natural occurrences of this area of the world include the huge seismic activity and the El Niño phenomena. These translated into recurring disasters, exacerbated by the vulnerability of the first buildings that were made with the most accessible materials: earth and stone.

The Caral pyramids were contemporaneous with adobe mastaba, an ancient Egyptian tomb in the time of their first dynasty in 3000 BC, also the time of the first pyramids of large dimension stones. The technology of Caral was so outstanding that despite earthquakes, rains and droughts, Caral maintained the same level of development as in ancient Egypt, where seismic activity is only mild to moderate (Dahy, 2010).

However, the Caral civilization lasted only about 1,000 years. Other natural disasters took their toll, like El Niño, which created periods of rain and prolonged drought that devastated

Fig.1 La Galería Stepped Pyramid, Caral, Peru, constructed of stone and earth around 2700 BCE. Signs of deterioration (credits: J. Vargas, C. Iwaki, A. Rubiños)

agriculture and fisheries with catastrophic events that changed the location of the coast, while in Egypt, 31 dynasties developed their construction technology uninterruptedly.

Consider the following comparison. By the year 2750 BCE (in the second Egyptian dynasty), the first stepped pyramid Saggara, was erected and was built only of carved stone. The increasing size of the stones used (megaliths), representing architectural grandeur, required the use of earthen mortar on masonry joints. Stability was achieved based on the size, weight and friction.

In the mountainous areas of Peru, this process was also similar, except for the elimination of the earthen mortar. It reached the same level of development. However, it did not last only 500 years as in Egypt, but seven times more, i.e. 3,500 years passed between Caral and Tiahuanaco, which also managed to work with megalithic stones for grandiosity without using earthen mortar. This technique of dry stone construction was then transmitted to the Incas, who built monumental megalithic works without earthen mortars in Ollantaytambo, Cusco, Machu Picchu and other places.

The difference in rapid technological development can be explained by the recurrence of natural disasters suffered by the western areas of the South American continent, particularly earthquakes and El Niño. Every great earthquake caused the collapse of the structure, which had already been cumulatively damaged from recurrent earthquakes of lesser severity, which were much more frequent.

The technological advances in construction was made possible by a process of trial and error, but this occurred at a much slower pace than in areas of low seismic activity and natural disasters. Earthquake resistant structural engineering is far more complex than structural engineering for areas without seismic activity. The understanding of this complexity also relates to the criteria and methodology for built heritage conservation. Caral is thought to have been abandoned, as many later Peruvian and American cultures, by a combination of disasters that caused famines and epidemics. In reality, heritage preservation in the world should be divided into two types: seismic areas and non-seismic areas. It could also be divided into areas of natural disasters, and areas without these phenomena. Peru and Western America require heritage conservation criteria different from those universally adopted elsewhere.

Recent research (Hsiang, Meng, & Cane, 2011) statistically supports the possible relationship between social conflicts or civil wars and natural disasters. In the tropics and sub-tropics, El Niño makes certain areas warmer and drier where, statistically, societies affected by famine become violent. Indeed, after the 1789-1793 El Niño, the French Revolution occurred, and after 1983-85 El Niño, "Sendero Luminoso" violence from Ayacucho exploded in Peru. Similar circumstances occurred in Angola, Haiti, Burma and several other countries (Hsiang et al. 2011).

2. THE CITY OF CARAL AND LA GALERIA PYRAMID

The city of Caral was part of one of the six oldest civilizations in the world, being the oldest on the American continent. It originated about 5,000 years ago in central-northern Peru. It was established in the valley of the Supe River, in the province of Barranca, 184 km to the north of Lima. The city was located 24 km from the coast, 350 m above sea level and occupied 66 hectares (Shady, Cáceda, Crispín, Machacuay, Novoa, & Quispe, 2009). Caral was composed of a dozen pyramidal public buildings, from which the Mayor Pyramid Building, the Central and La Galería stand out.

The La Galería pyramid is the third largest structure of the sacred city of Caral. It reaches 18.6 m in height, and has a volume of approximately 30,000 m3. It is believed that this pyramid fulfilled political and administrative functions (Shady et al., 2009). It is representative of the materials and technology used in Caral. The building consists of overlapping platforms bounded by stone and earthen masonry walls, with stairs accessing the different levels.

The platforms were built in different phases. These were initiated by the burial of the structures of the previous phase, and ended with the construction of new perimeter walls and new levels of pavements. The burials were usually composed of organized fillers to improve stability based on earthquake resistance concepts. The external walls were only aimed at fulfilling the function of façades, and not that of containment. This structural configuration is explained later in greater detail.

3. SEISMIC-RESISTANT STRUCTURAL NUCLEI IN LA GALERIA PYRAMID

The age of the sacred city of Caral suggests that the technologies developed in this place were the basis of the technological development in Peru and much of the Americas. Early research shows some common structural criteria with other contemporary ceremonial buildings, such as Sechín Bajo,

Fig.2 Reed *shicras* providing stability to the fill. There are fills with balanced vertical flat edges, which supported the upper overburden and the expansion of the *shicras*' area (credits: J. Vargas-Neumann)

Las Haldas, as well as later cultures, such as Ventarrón, Kotosh, Chavín de Huántar (which, at the time, was considered the parent civilization), Cupisnique, Moche, Nazca, Tiahuanaco and, finally, the Incas.

One of the most interesting structural concepts is related to the burying of the preceding structures: a spiritual-religious concept combined with technological concepts. The building was considered a living being to be respected once it had fulfilled its life, and was buried instead of being demolished. The result was a pyramidal structure composed of successive structural burials. Earthquakes destabilized these pyramids and forced, through trial and error, the improvement of the materials and technology of their nuclei.

In Caral, it seems that initially cobbles were used to form the nuclei. These stones were sourced from riverbeds; and are characterized as having a very low friction angle and, therefore, high lateral thrust, unfit for the dynamic (seismic) stability of fillers. To gain roughness, the rounded edges of the stones were broken using fire (heat-fractured stones), and the stones were mixed with earth to increase stability. Then, angular-stone quarries, with even more roughness, were used. Another important step was to stem the use of earth in the nucleus, significantly increasing the percentage of voids, which reduced the specific weight of the filling mass and, therefore, the lateral thrusts, which are the ones that determine the stability of the nucleus. At some point, the technology to stabilize the nuclei made an important qualitative leap, a change that even today is astonishing. The inhabitants of the Caral area were farmers and fishermen, they knew cotton, woven fabrics and fishing nets, knew the reeds, cattails and later, sawgrass, a stronger type of reed brought down from the highlands. They created open-weave bags for transporting objects, thereby creating shicras (Asencios, 2009). They found that *shicras* could work as reinforcement for the nuclei of pyramid platforms (Vargas, Iwaki, & Rubiños, 2011).

The fibers and the fiber bags had tensile capacity, better than the fragile materials (lumps of dried earth and stones), which were plentiful and accessible. To combine them together was very innovative, as a bag filled with stones became a structural unit of great virtues. It was easily transportable, and the traction of the fibers controlled the tendency of stones, placed upon each other, to fall apart or roll.

The bags full of stones were used to form the nuclei of the pyramids. These bagged stones did not convey lateral pushes to their neighbors. Therefore, they could create mounds of bagged stones, which had stability on their own and stabilized the nuclei, which improved the structural behavior of the fill, especially under vibrations and forces of lateral inertia during earthquakes. Caral is a precursor of the modern gabion technology.

These bags of vegetable fiber (junco, white grass, etc.) contained a volume of stone and were called *shicras*. These are a constructive element, that is a very advanced concept for its time, which could be efficiently used in modern times for slope stability and control of landslides. The volumes of the *shicras* found can weigh between 15 kgf to 2,000 kgf. The result of their use was the successful construction of assembled piles of mounds or stable pyramids, with optimal earthquake resistant features. The pattern of *shicras* fill was determined. These differ in their disposition, quantity and their interaction with other materials, such as gravel and large stones.

The concept of assembled piles is a precursor of stability concepts in modern times. It is a structural criterion associated with movement control through reinforcement, instead of increasing the resistance of the constituent material, which collapses when earthquakes produce large forces and efforts greater to the resistance of the impacted materials.

Modern building codes use, for different materials, design criteria based on the performance or movement control, rather than design criteria based on resistance (Vargas et al., 2011). This technological leap surpassed that of the contemporary Egyptians. Some Egyptian adobe masonry mastabas have traces of pieces of wood used as local reinforcement (lintels), but no reinforcement distributed throughout the nucleus. In Caral, this was due to the need for the nuclei of the pyramids to be earthquake resistant and not simple fills.

The structural feature of the nuclei caused the walls or the façades not to have a significant structural function. Their purpose was to provide a surface for plastered or painted decorative features, and to define the building. The nuclei withstood earthquakes and the pyramids were stable. The walls were vulnerable, but their collapse did not affect the overall stability of the pyramids.

Research carried out in the field, measured the slenderness of the walls and the volumes of the associated structural nuclei, and it was determined that due to the geometrical and physical characteristics, the walls would not be able to withstand lateral thrust, if there were no *shicras*. The nuclei were stable against earthquakes, but the walls could collapse and be rebuilt (Vargas et al., 2011).

The second type of nucleus structure adds a stone wall of large stones with no mortar, which separated the shicras core and the angular gravel fill. For practical reasons on very long walls, the angular gravel fill, glued to the wall façade, was also bagged in *shicras*. These were, possibly, reconstructions situations, where the facing is remade into a new position to the outside.

The third type of structural nucleus seems to correspond to the earliest periods, before the use of *shicras*. Indeed, the nucleus contains loose angular stones, a solution of high coarseness and low unit weight (an improvement which prevails over the technique of the first fillings with rounded river stones and earth, cut rounded stones and earth, and quarried angular stones and earth). These are found only in the lower parts of the pyramid building. This type of fill was far surpassed by *shicras*.

4. STONE AND EARTHEN-MORTAR FAÇADE WALLS

The walls were not structural elements intended to contain fills and nuclei; rather they were decorative elements of the façade system. The resistance of the pyramids was entrusted to the nuclei and not the walls. It was understood that the nuclei withstood earthquakes, and the walls did not, which could be more easily repaired.

The lower wall resting on the ground was generally composed of large stones (1.00-1.50 m). The joints were filled with small wide stones of about 200-300 mm, known as pachillas. These allowed the insertion of smaller areas of earthen mortar within the joints, which ranged between 20 to 50 mm, thereby more efficiently controlling cracking due to shrinkage of the earthen materials. The height of these walls could be 3.0 m with a thickness of 400 to 700 mm. The largest stones were placed at the corners. The stones were of very different sizes, but the largest stones were chosen for the base. This was intuitive and can be explained by the difficulty of raising the largest stone. The stones for the corners were valuable and re-used with each subsequent expansion. It has been verified that the walls of this style are positioned on natural soil in a layer of 100-150 mm of gravel and earth.

The facing of the upper platforms is typical and the most common. It consists of a relatively homogeneous arrangement of stones of sizes between 300-500 mm. The shapes of the stones, though irregular, tend to be rectangular and their bases horizontal, clearly the result of good carving abilities. Between the stones, there are pachillas of 100-200 mm wide to decrease earthen mortar thickness to 20-50 mm. These were used in the stepped platforms resting on earlier platforms, and not on grade. The height of the existing walls is about 1.60 m, reaching in some areas a maximum height of 2.10 m. The thickness varies between 350-400 mm.

As a variable of these, some very untidy facings are present on upper platforms. These not only include irregular stones (less carving work), but have also lost the horizontal system of courses. It is possible that these variations depend on the

Fig.3 The first type of nucleus structure in La Galería pyramid (credits: J. Vargas-Neumann)

Fig.4 Alternative to the first type of nucleus structure (credits: J. Vargas-Neumann)

working staff, and the ages of the expansions that occurred to the different pyramids of Caral.

The walls were plastered and painted, which shows their function as finishes, as well as the architectural planning. The coatings were of high quality earth and straw to avoid shrinkage cracking. The builders knew how to avoid cracks by mixing earth with coarse sand particles, and controlling cracks with straw to prevent micro-fissures from drying (Vargas, Bariola, Blondet, and Metha, 1984).

5. *QUINCHA* SEISMIC RESISTANCE TECHNIQUE

Another very important technological development that originated in Caral is *quincha*, known in other parts of America as wattle and daub. *Quincha* is a construction technology that uses timber framing, cane or vegetal fibers, coated with earth to build walls, which are then plastered with earth and straw. *Quincha* walls are an elastic structure of narrow thickness and low weight, which has a very efficient earthquake resistant behavior due to its great capacity to dissipate energy caused by earthquakes.

Quincha structures found in the upper platforms of La Galería pyramid incorporated wooden trusses formed by vertical Huarango logs of 150-300-mm diameter, spaced approximately every 400 to 600 mm, along with horizontal elements comprised of bundles of four-six reeds with 25-40 mm diameter, 100-200 mm apart but tied together. These were

a) b)

Fig.5 The oldest example of *quincha* found in America. a) *Quincha* structures; b) Trusses (credits: J. Vargas-Neumann)

secured in place by vegetable fiber ropes. These are covered by earthen plaster placed in two or three layers of 50 mm. The first layer is composed of dark-gray earth that is less clayey. The second and third layers are formed with a yellow earth with a high plasticity and adhesive quality clay. All layers contained organic material (grass or straw). It is still possible to see in some parts that the finish was whitish-color paint.

The location of *quincha* on top of the pyramidal frustum is not accidental. Quincha was of a different material, lighter weight, higher elasticity and flexibility, and of different architectural expression. It had very good seismic behavior and its use must have been predicated by the needs of the spaces formed, for example, the probable existence of lightweight and safe covers, which provide shade and ventilation to environments used for extended periods of time.

6. CONCLUSIONS

The Galería pyramid is a structure of overlapping and staggered platforms, resulting from expansions and successive burials over an extended period of time, possibly around 1,000 years according to archaeologists. This pyramid is fairly representative of the rest of pyramids or mounds built at Caral. There, it is obvious the differences of geometric shapes and probable uses.

It has been shown that the most important structural element was the nucleus structure that provided stability to the pyramid. This stability was based on the use of reinforcement for its traction, which controlled dynamic forces caused by earthquakes. It has been shown that the walls did not meet the most important structural functions (except for their own stability). They role was only to demarcate the building's exterior and to provide a vertical surface that could be plastered, painted, or decorated.

The main reinforcement elements of the structural nuclei were the *shicras*. These controlled deformations and displacements similar to contemporary gabions. However, the shicras have undergone a process of deterioration that has caused the loss of their primal structural characteristics. Earthquakes of later centuries tore down the walls and exposed the *shicras* to weather and ultraviolet rays, reducing their durability and resistance. Even so, the *shicras* and the *quincha* walls are reliable and a robust development of earthquake resistant knowledge at Caral and in the surrounding Supe Valley.

The division of the world into seismic and non-seismic regions has recently raised awareness that there must be a fundamental difference in the structural concepts of conservation, which define intervention processes. This raises the need for new design criteria for heritage recovery, based on earthquake resistant structural performance. It means that movement of elements cracked by earthquakes must be controlled, especially those formed by fragile and vulnerable materials. This means the rational use of reinforcement (capable of resisting tractions) with minimal intervention characteristics, material compatibility, original technology and reversibility. In Peru, there is a movement that seeks to establish criteria or specific principles for seismic activity and the high vulnerability of the materials that make up Peruvian cultural heritage, such as earth, stone set in earthen mortar, quincha, etc. It is based on the principles that consolidation solutions to archaeological sites such as Caral must be sought. It requires training of inter-disciplinary teams to develop and discuss the alternatives for each situation. The sooner these are developed; the sooner decisions and results for preservation will be obtained.

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