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Constructive and earthquake-resistant aspects of modelled-earth, a technique in ancient Peru

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Topic: T1.3. Studies of traditional techniques and materials

Abstract
Modelled earth was a pre-Inca construction technique used extensively in ancient Peru. It comprised placing portions of mud in horizontal rows to build walls and large buildings. It comprised placing portions of mud in horizontal rows to build walls and large buildings without the aid of molds, unlike the rammed earth of European origin. Unfortunately, there is a lack of written, graphic or oral evidence that would help to better understand how pre-Columbian walls were made. Therefore, the research was based on the study of the buildings to plan hypotheses about the construction procedure and their structural performance, given that the area where they were built is highly seismic. The research showed that the ancient Peruvians used seismic-resistance strategies in their buildings comprising the use of segmentation of the earth structures, with the criterion of keeping the blocks joined to each other using support planes to form the final architectural volume. The article suggests that seismic energy was dissipated through these joints, and it got a greater deformation capacity without the total collapse of the structure.

Keywords: *Seismic behavior; pre-Columbian constructions; structure; traditional buildings.*

1. Introduction

Modelled earth was a building tradition used in ancient Peru that comprised placing superimposed layers of mortar in a damp state, without using compaction or molds. In Peruvian archaeological sites, it is possible to see the layers or courses that show how the mortar was laid. In pre-Inca times, this technique was used to build walls and massive structures. On the Peruvian coast, and especially in the city of Lima, there are examples of the use of this construction technique. Modelled earth was not used after the Spanish Conquest and was replaced by rammed earth, a European technique, since then, the modelled earth was forgotten.

1.1. Historical and geographical context

The constructions studied are on the southern coast of the central Andes in present-day Peru. Architectural evidence was restricted to the altitudinal level known in Peru as costa or Chala (Pulgar Vidal, 2014), which in cauqui, a language originating in Peru, means a sparsely inhabited place with sandy soil. The coastal zone of South America registers intense seismic activity, because of the phenomenon of subduction between the Nazca Plate and the continental plate of South America.

As for the temporal development of this construction technique, using the classification of the archaeologist John Rowe (Ramón Joffré, 1994), in the period from 800 A.D. to the 15th century, it should be noted that this classification takes the ceramic styles as an indicator and not architecture. As for the civilizations that used this construction procedure, we can mention the Yschma and other coastal lordships, such as the Collique. They also used it in Inca times, although with changes.

Fig. 1. A segmented wall, built by modelled earth in Tambo Inga archaeological site - Lima (Source: Torres, 2021).

2. Methodology

It was necessary to compile information on the archaeological sites. The search began with bibliographic sources, scientific articles, publications in magazines, books, images from archives, etc. Precious were the books of European travelers of the 19th century who, with a particular vision, described in great detail the pre-Hispanic architecture in the surroundings of the city of Lima. The publications on Peruvian architecture during the 20th century, whose descriptions were useful for this work, were invaluable.

Visits to the archaeological sites were part of this research, which included measurements, observations, photographic recordings, diagrams, drawings, etc. The state of conservation and deterioration, the processes of degradation of the earth material, were registered.

It is important to note that most of these settlements have not been excavated, but this had not restricted their evaluation for this research. The walls have several meters high, which facilitates recording.

For the visits, we had the support of various professional archaeologists who allowed to enter the sites under protection the Peruvian Ministry of Culture, such as the huacas of the Maranga complex, La Huaca Centinela, the Fortress of Campoy, or the Sanctuary of Pachacamac. In other cases, Several sites haven´t been protected by the authorities, it hope will soon be protected and conserved.

It is important to mention that many archaeological sites that would have been part of the record of this work have disappeared throughout the 19th and 20th centuries because of the urbanization process of the city. The *huacas*, how archaeological sites are called, that formed part of this research were:

- Pyramid with Ramp III in Pachacamac
- Huaca Tambo Inga
- Huaca Tres Palos
- Huaca La Palma
- Huaca Mateo Salado
- Huaca Mangomarca;
- Fortress of Campoy;
- Walls of Chuquitanta
- Palace of Oquendo
- Huaca Cerro Respiro.

3. Constructive features

The monolithic construction of the earthen walls was developed by placing portions of mud in a humid state in horizontal layers. According to the observations made at the sites visited, the texture of the mortar used in the modelled earth walls corresponds to mud in a humid plastic with light manual pressure and without the use of compacting tools for its construction. They placed it in horizontal layers of varying thickness, ranging from 10 to 20 cm in height. This technique was used to build walls and platforms, essential elements of the Andean architecture. In archaeological contexts today, it is possible to see the horizontal bands of mortar overlapping each other.

The surfaces were worked to get a smooth finish. In the enclosures, the walls were plastered by covering the joints of the mortar layers, achieving the appearance of a monolithic wall. The stacking of the mortar in courses was important to increase the compressive strength of the wall. Upper rows were placed like layers of sediment, compacting the lower tiers of mortar. This procedure did not completely prevent the wall from cracking because of shrinkage during the drying process.

Fig. 2. Mud layers in a wall, it can see the concavity formed. Palace of Oquendo – Lima (Source: Torres, 2021).

The layers show a concavity both towards the center of the wall's plane and the center of the longitudinal axis of the wall. This concavity is a sign of the weight that the upper course exerted on the lower course when the mass was fresh. It should be noted that if excessive weight was placed on the lower course, there would be a risk of cracking because of excess weight or crushing. Two or three courses of a maximum thickness of 20 cm could have avoided exceeding the stresses on the lower layers in the drying process.

Once the mortar courses of the wall had been laid, the surfaces were treated, as the fingerprints of the workers could be found on the walls. The work was probably carried out by applying a layer of very fluid mortar to fill the voids that formed on the sides of the wall. It carried this work on facing out on all the faces of the block, including the one that was to receive the adjacent block.

Fig. 3. Modelled earth blocks, with segmentations. Fortress of Campoy- Lima (Source: Torres, 2021).

3.1. The planning of construction

In the archaeological sites visited and others of which there are bibliographical references, modelled earth blocks presented common elements in their structural design, finding earth blocks that order, confine or adjust the structure.

Guide blocks

It was the trapezoidal blocks, which formed the first construction phase of the wall. From this, other blocks were added, which were attached to it, forming the large masses of the final structure.

It is so-called because it has inclined sides that "order" the other blocks that are added to it, and this block is recurrent in the constructions recorded, including others that were built with adobe masonry.

It can have different dimensions and is formed strictly with inclined sides with variable angles of inclination, maintaining a joint with the adjacent blocks that start at the base at the upper end, guaranteeing continuous contact.

This block can comprise several construction phases that finally form the trapezoidal section.

Confined blocks

These blocks are those that are built attached to the computer block in the form of inverted trapezoids, parallelograms, and other irregular shapes and are generally confined and compressed by the adjustment blocks.

Adjustment blocks

They could be defined as trapezoidal-shaped blocks of molded earth with the minor base downwards, which serve to give adjustment to the other adjacent blocks by behaving like a wedge or keystone. These were placed at certain points foreseen with a clear purpose of adjustment of this mega-masonry, according to the stratigraphic analyses carried out on several archaeological walls, they were built as the last phase of the wall in such a way that their construction was important for the stability of the structure.

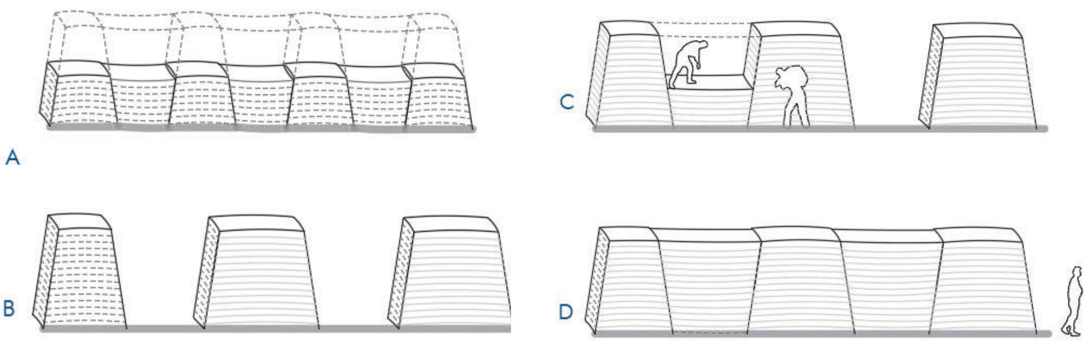

Fig. 4. A sequence of possibilities in the construction of segmental walls. A: Blocks built simultaneously. B, C, and D: Alternating construction (Source: Torres, 2021).

4. Structural hypotheses

Earth structures can only develop properly under compressive stresses and, even then, they are extremely fragile. Once cracked, because of seismic vibrations or the drying process of the mud, they lose their initial stability conditions to behave unknown.

Thinking and analyzing this phenomenon to give stability to these constructions could be the way to the design of the segmental walls. The deformation capacity of monumental earth structures once they crack is of an uncertain magnitude. A real structure does not behave as in a laboratory test with perfectly known or controlled conditions.

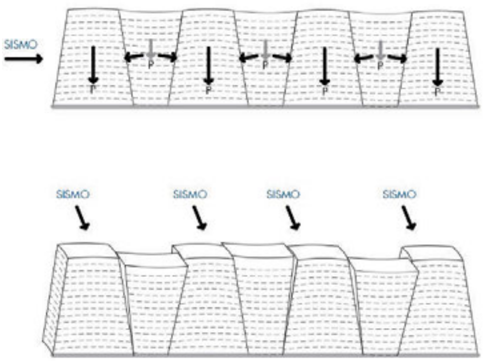

Fig. 5. Forces act on the walls when they are built-in segments (Source: Torres, 2021).

One response to the condition of stiffness and fragility of earthworks seems to have been the modulation or use of wall segments. There are examples of constructions that employed it, both with adobe and modelled earth walls.

Their appearance was mistaken for drying cracks in the mud. However, the archaeological record has made it possible to verify that they are not. Chronologically, the criterion of segmentation and modulation was used from around 200 AD. Today, the triangular-trapezoidal section blocks can still be seen, which are grouped, wedged, and adjusted by supporting each other as if they were wedges or keys to compress adjacent blocks. It carried the modulation to build massive structures (platforms) and walls (enclosures).

The present work proposes that this is an original construction system with seismic-resistant and well-planned virtues. This research has been directed towards walls made with this construction technique.

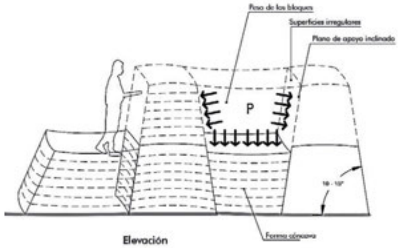

Fig. 6. Diagram of forces favoring transverse restraint in walls (Source: Torres, 2021).

It proposed that the geometric segmentation of the walls made the structure behave in such a way that it can be predictable and rational. The criterion was to establish how such a structure would behave during earthquakes, the stacking of blocks forming large walls responds to a need to convert a monolithic block of the earth of fragile into a ductile behavior. It is a criterion for solving the behavior of structures in a deterministic and simple way.

Segmentation was a procedure to provide the wall with sufficient strength to improve the response in case of earthquakes, in such a way that the contact joints between the blocks formed plastic hinges in predetermined locations to form a mechanism similar to a ductile behavior of the structure. The joints planes were formed on the sloping sides of the blocks, where it make contact. Through these joints, seismic energy was dissipated, and they got greater deformation capacity, each contact zone thus becoming an element capable of deformation.

The construction of walls divided into segments required foresight of their components. The arrangement of the construction segments with inclined sides ensures they converted lateral forces of seismic origin into compressive forces that were distributed along the length of the wall. It successively transmitted the force between blocks with compressive stresses, and as long as the blocks had the right dimensions, they could absorb these stresses and not crack.

Fig. 7. Joint between modelled earth blocks. Huaca Tres Palos – Lima (Source: Torres, 2021).

This type of structure was not physically embedded or articulated. Each joint there was the principle of a ball and socket joint, which allowed the dislocation of the structure, thanks to which it could experience some variations in profile and move without collapsing with small movements. This balance of forces shows how the bending stress because of the earthquake can be converted into compressive stress that guarantees the stability of the structure. An interesting detail is the wedge elements, the trapezoid-shaped segments with the smaller base facing downwards, which adjust the other blocks. They placed these at certain intended points with a clear purpose of adjusting the assembly. These wedges were used in massive platforms from the time of the Lima Culture and the mechanical principle is also very simple: the wedge element, because of its weight and the time factor, generates great forces perpendicular to the surfaces in contact, adjusting them similarly to the behavior of the keystone in a voussoir arch, exerting the compressive forces for the mechanical system to function. It achieved the transverse bracing of the walls in a more complex way because it linked several factors to achieve it. The horizontal earthquake restraint in the longitudinal direction of the wall, i.e. in the wall's plane, was because of the transmission of forces between blocks through the joints. In the transverse direction, i.e. for forces outside the plane of the wall, there were several factors that we can analyze.

Fig. 8. Modelled earth wall, showing the layers of mud and the segmentation that allowed the displacement of the blocks. Fortress of Campoy- Lima (Source: Torres, 2021).

5. Conclusions

Earthquakes have conditioned the development of architecture because of their recurrence and severity in a region with intense seismic activity. With a rational, deterministic, and simple way, it tried to resolve the stability of their buildings, although there is still a lot of research to be done in this respect.

An important feature to highlight is the use of "mega-masonry", which comprises the formation of a wall, with the successive placement of parts, fractions, or blocks that were made in situ and which were joined using diagonal and straight joints. It assembled the wall in an order that ensured the stability of the parts of the wall as if it were a large puzzle. The superimposition of the blocks can predict the order of placement of the blocks following a reinforcement model that takes advantage of the geometry of the parts to guarantee an adequate interlocking between the mega-masonry. This technique has been identified in Yschma walls, also built with adobe. Therefore, it is of "traditional" use. This mega-masonry owes its name to how the megaliths were used in the Inca walls, with which we suggest that there are certain similarities. The shape and proportions of these walls was conceived differently to how engineering is understood today, unlike what happens in the present where the material is chosen accord to the design of an object. It is an original, rational and natural way of finding a seismic resistance solution that the ancient Peruvians developed and which should be appreciated, studied and, perhaps, recovered as a useful lesson for today.

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