Caverns Stability with More Than 10 Centuries in Prehispanic Excavations in Mexico

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ABSTRACT

In the archaeological region named Mesoamerica, there are cases of underground excavations for different purposes along several centuries. Some of them reach up to 9-meter depth and are in good conditions so there is motive enough to consider them as a historic case that must be analyzed in an Engineering point of view. From different cases, there were chosen two, Teotihuacan and Xochicalco, due to for these there are notorious relations between both sites, the most important is that these caverns were used as an astronomic observatory. In addition, for Xochicalco is possible to make analysis with the geometrical and geotechnical information in order to study the stability. This paper includes the main data, analyses and conclusions from engineering and archaeological topics; in fact conclusions must be applied for both disciplines.

INTRODUCTION

In the prehispanic world, caves or underground excavations, were used for different uses, protection, habitat, fertility, water or death god's habitat, rock sources, cemeteries, ceremonial sites and even astronomic observatories. Morante (1996) shows a general classification for underground excavations according with the use of each case, and he thinks that the use of the underground space could have been changing in different periods in the same excavation.

Both excavations used in the analysis for this paper are in the last case on those described before, astronomic observatories. From now on, excavations included in this paper are pointed with the name of the archaeological zone in which are located, Teotihuacan and Xochicalco, both are very close from Mexico City.

In Mexico there are seven underground excavations related with observatories, five in the rock or subsoil and two in the body of structures made by the man. In order to respect the extension of the work, the only observatories analyzed are the two indicated yet.

The paper includes a general description of the geotechnical and geometrical conditions in each site, remarkable concepts about engineering and astronomic knowledge that were transferred from the first chronological culture to the second, this is one of the main conclusions obtained.

TEOTIHUACAN OBSERVATORY

Teotihuacan is an archaeological zone located 60 km to the northeast from Mexico City, in Mexico State. The site is in a volcanic zone. Barba (Barba et al, 1990) believes that a quickly cooling could have generated a lot of steam, creating voids that allowed the formation of caves after the lava solified. Local inhabitants found these spaces and them prepare the caves to make them bigger than the originals ones.

At site there are soils formed from continuous volcanic materials, ash, sand and tuffs from the domes very close, some of them with recent activity, even at the Pliocene and Pleistocene. Meanwhile in that environment occurred alluvial deposits.

Teotihuacan Valley is the place where the biggest demonstration on the use of the underground space has been registered in opinion of many archaeologists.

The cavern analyzed is part of a system with three caves with the same characteristics and maybe with the same functions. These excavations are located 270 m from de Sun pyramid in the south-southeast direction. The period in which these were excavated is the Classic, between 200 and 350 A.D. (Morante, 2001).

From this group it has been chosen one cavern for this paper. The floor is 4,35 m depth. The chamber has in the bottom part 5 m in the east-west direction and 6 m in the north-south axis. It has 2,40 m high and coverage of 1,50 m (Soruco, 1985). The shaft is smaller than 1 m diameter, excavated in the rock except the first 33 cm from de surface because there is a soil layer (Fig. 1).

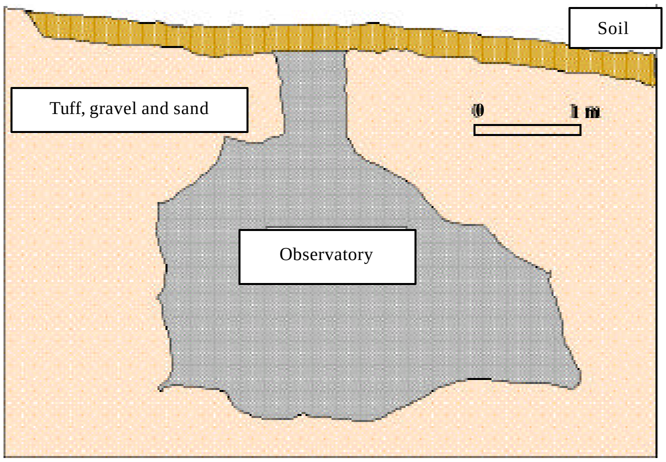

Fig. 1. Teotihuacan observatory. Cross-section.

The excavation geometry shows a relation between coverage and width of 0,30; this relation is very low and is not common in the tunnels engineering practice.

Stratigraphy described by Soruco (1985) includes different layers, as gravel, sand and earth materials without massive rock. Morante (1996) says that caves are located in general in the tuff, except the upper layer, which are soils.

There is not available information about the rock mass classification, but due to the materials are pyroclastics, cavern stability could be obtained by the natural compaction of the material and the arch formation. This one is the best explanation to understand the cavern stability. In that case the arch must be formed in approximately 1,50 m of coverage.

Manzanilla (1990) thinks that the underground excavation had to be used to obtain rock for different constructions and they used them sometimes for funeral occasions. In addition, teotihuacanos could have excavated a tunneling system in order to use materials from the underground world and to reach the volume necessary for the pyroclastic pieces in their constructions.

The walls were not covered with "stucco", a kind of mixture of dust, calcium and water, this is a difference with Xochicalco as is described latter. The reasons because the walls were without this kind of protection are not known, but it is true that excavations are in good conditions nowadays despite the effects of the weathering and even the earthquakes.

Manzanilla (1990) confirms that there are evidences of the pyroclastic materials underground excavation and has a specific reference about the use of the rock pillars to contribute to the roof stability.

To the east of the Sun Pyramid, there is a big area, at least 3 hectares where is notorious a lower lever of the surface, to give an evidence of the material extraction and the possibility of tunnels collapsed.

In fact, Barba (Barba et al, 1990) comments about the existence of collapsed caverns in Teotihuacan, identified each one because it is possible to see areas with 3 to 5 m depth like a trench and in their walls is possible to see the entrance to caverns or tunnels

Morante (1996) explains in relation with the collapsed caverns that some of them could have failed first in small holes, which latter teotihuacanos could have opened to use it as an underground observatory, and he is very emphatic in postulate that all the excavations used by teotihuacanos, were adapted by themselves.

In the observatory, there is evidence in which teotihuacanos opened a first chamber and after that with a small tunnel, they prepare a new chamber. Both chambers have a hole in the upper part to use it as observatory.

Nowadays chambers are without problems about drainage, because at the surface there are channels to discharge the rainfalls. This is a reason to think that teotihuacanos kept in mind this incidence and how they avoid the entrance of the water to the excavation.

In the center of the observatory there is a kind of altar, which was used as a reference of the shadows and the light from the sun, moon and Venus. These three bodies are the ones that can produce a projection in the earth.

The observation of these bodies allows identifying specific days in the calendar, for instance the Zenith for the Sun and the Moon, as well as other dates with complete precision.

XOCHICALCO OBSERVATORY

Xochicalco is located 120 km to the south of Mexico City, in Morelos State, in a zone with sedimentary rocks. Limestone is the main rock in the site. There are evidences of the water flow, which produced small caves, at least twenty with different dimensions.

The observatory was excavated approximately in 700 A.D. and there are registers about the observatory since the end of the 18th century, when the cave was named "Gruta del Sol" (Sun Cavern).

In the whole arrangement, of the tunnels in the observatory area, there are four spaces well delimited: the tunnel access, the main chamber, the observatory and a contiguous chamber, which was closed by xochicalcas.

The tunnel access is similar to an aisle, 1 m width, 17 m long and 2,50 m height.

The main chamber is a big hall, rectangular shaped, 28-meter large, 10-meter width and 2,50 m height. In three points there are a kind of entrance in the walls. These representations of structures were made with stone masonry very well built (Picture 1). Actually the main chamber has a mesh and small bolts to avoid a failed block over the visitors, but it is not for the roof stability.

Picture 1. Masonry in a main chamber wall.

In the same chamber there are three inner columns, square shaped, 3,50 m width approximately. The inclusion of these columns is a very important success in the stability and to understand the relation between Teotihuacan and Xochicalco.

At the end of the main chamber, there is an oval chamber, 6 m diameter named the astronomers chamber, the observatory that now is available to visitors, is twice depth in relation with Teotihuacan one. In this case it reaches up to 8,70 m depth, from the surface until the floor of the observatory, (Fig. 2).

In this observatory the arched roof is a semi - spherical shape, in its upper part there is a shaft formed with masonry. It is 5 m height, and reaches the surface. North and south walls has a very short tilting and the other two walls are completely verticals.

The cross section of the shaft is oval one, and is very curious that it has a width shorter than 43 cm, including the masonry (Picture 2).

The constructive process must have been excavating a shaft with a bigger diameter, at least to allow a man to be there and to continue excavating. After that, at the end of the excavation, the shaft was protected with the masonry and the pieces of the coverage were put in the right place in order to allow the operation of the observatory. The space between the line of the excavation and the masonry must have been filled and compacted because the masonry has been in very good conditions.

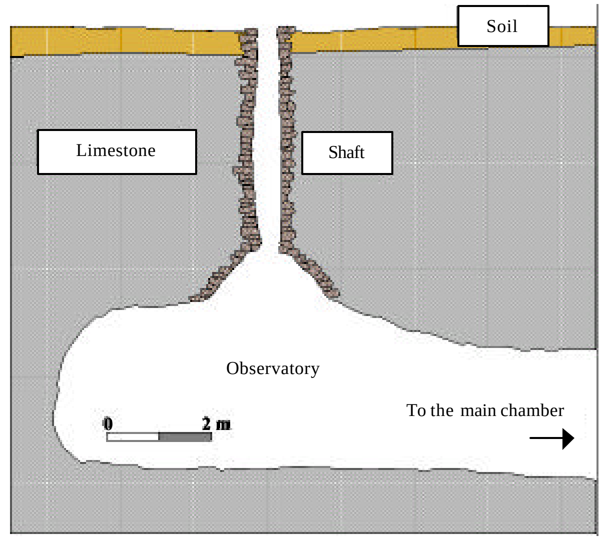

Fig. 2. Xochicalco observatory.

Picture 2. Shaft seen from the bottom of the astronomers chamber to the surface.

Behind the main chamber, there is a second chamber, which was closed and filled intentionally by the inhabitants of Xochicalco. It was 4,70 m width, 6,80 m length and 5 m height. This information is very important and will be used as a reference during the analysis of the information.

The stratigraphy is composed by a layer of soil with 80 cm width, immediately continue with 80 cm of weathered rock. Under this one there is a 3-meter layer with rock very jointed and for the deepest zone the rock shows better conditions.

In general, there are three joint systems, which produce semi-cubic wedges.

Coverage in the case of the main chamber has a relation of 0,62 between cavern width and depth of the roof in a section out of the inner columns, twice respect to Teotihuacan. But if the columns are considered then the relation reaches 1,77. This one is a value too much closer to the general empirical recommendation of maintain 1,5 to 2,0 times the width as a coverage in underground excavations.

Morante (1993) says that in Xochicalco excavations is common to see walls or columns with a masonry protection or with stucco, as a kind of reinforcement. In some of them stucco was used to cover the roof, the walls and the floor. In addition, it was found that the floor has a slope to allow the drainage and conduce the water out of the chamber zone.

In other caverns an application of sludge or lime sludge was used for some walls or columns. Morante (1993) suppose that the columns were planed as a contribution to the roof stability, and in fact the contribution has been there for centuries. The constructors must had excavated the complex tunneling system keeping in mind the experiences of Teotihuacan, excavated 5 centuries before.

The astronomers chamber is one in which evidences of the use of stucco were found. Today there are just small parts with the original application.

Xochicalco observatory has not an altar as a reference for the light pass; due to in this case the light is more exact with respect to the previous observatories.

Morante (1993) says that the actual conditions of the tunnels are very similar to those in which were found by the first explorers, Alzate in 1791, Marquez in 1804 and Robelo in 1885. The last one was the first in comment something related with the real use of the observatory.

Rock mass properties

Due to in Xochicalco is possible to obtain the basic information to classify the rock mass, for this site the Grimstad and Barton (1993) criterion was applied to obtain the rock mass quality index Q as is described next:

$$Q = \frac{RQD}{Jn} \times \frac{Jr}{Ja} \times \frac{Jw}{SRF} \quad (1)$$

Rock Quality Designation (RQD). Based on the continuity and spacing of the joints, it was considered that in a cubic meter could be 6 joints; it means 2 by each direction. In that case a volumetric joint count Jv = 6. Then due to the lack of boreholes, RQD was calculated with Palmström equation (Palmström, 1982):

$$RQD = 115 - 3{,}3Jv \quad (2)$$

The result was RQD = 95%.

Joint set number (Jn). There are two main systems and one secondary, so in this case Jn = 6.

Joint roughness number (Jr). Joints are in general slightly rough and planar, so Jr = 1,5.

Joint alteration number (Ja). The most of the cases are unaltered joint walls without filling, so Ja = 1,0.

Joint water reduction (Jw). In general there is a lack of seepage, it can be assumed a Jw = 1,0 which allows the case of dry excavation or even small flow without charge.

Stress Reduction Factor (SRF). The tunnels have a thin coverage, so low stress is the case, and was chosen the value of SRF = 2,5.

Rock Mass Quality Index (Q). Including these values in equation (1), the result was Q = 9,50, which is related with a fair mass quality, very close to the limit for good one.

Stability analysis.

Maximum width supported by itself. With equation 3 (Barton et al, 1974) was calculated the width that does not require support:

$$B = 2(ESR)Q^{0,4} \quad (3)$$

The result was B = 4,92 m for the value of Q index (9,50) considering excavation support ratio ESR = 1, to avoid any excessive consideration of the own resistance of the masses.

With this criterion, it means, that the main chamber of Xochicalco has been stable due to the pillars. In case these were not there it could be possible that the excavations could have collapsed during its long life.

Talking about the chamber behind the astronomers' chamber that is now closed and filled, maybe the reason because xochicalcas had to do that could be in relation with the maximum width for self-support. In fact the explorers report that it is 4,70 m, very close to the value of 4,92 m.

In the case of the astronomers´ chamber the width is bigger than 4,92 m, but the geometry of the roof and the masonry must be contributing to the stability.

Using the correlation provided by Bieniawski (1976) to obtain the RMR from the Q index as indicated in equation 4:

$$RMR = 9\ln Q + 44 \quad (4)$$

The result is RMR = 64, considered in Bieniawski classification as a good rock, very close to the fair zone rock. With this value the RMR system predicts a span without support required, for this case 3,20 m as a lower option and 5 m is the lower value for historic cases with roof falls in mining (Bieniawski, 1984). This span is absolutely close to Barton´s one.

Pillars stress. Xochicalco pillars have a tributary area of 6,25 m^2, for which the column of rock over each one is around 8 m. So the medium stress in a pillar is a compression 500 kPa. This is a very low stress, so pillars are free of stability problems.

OTHERS PREHISPANIC UNDERGROUND EXCAVATIONS

In Mexico there are underground excavations used for funeral disposals, especially in the cultures named "de occidente" (western cultures), which grown in Michoacan, Jalisco and Nayarit, states. In that area is common to find chambers for example the Huitzilapa cave which reaches up to 8,7 m depth, in hard tuff (Lopez L. and Ramos J, 1994). This excavations were made in the same period of Teotihuacan.

The excavations have a shaft and each one could be with one chamber or two chambers. A representation of this kind of cemeteries is shown in Fig. 3, taken at the Nayarit Regional Museum in Tepic, Nay., Mexico.

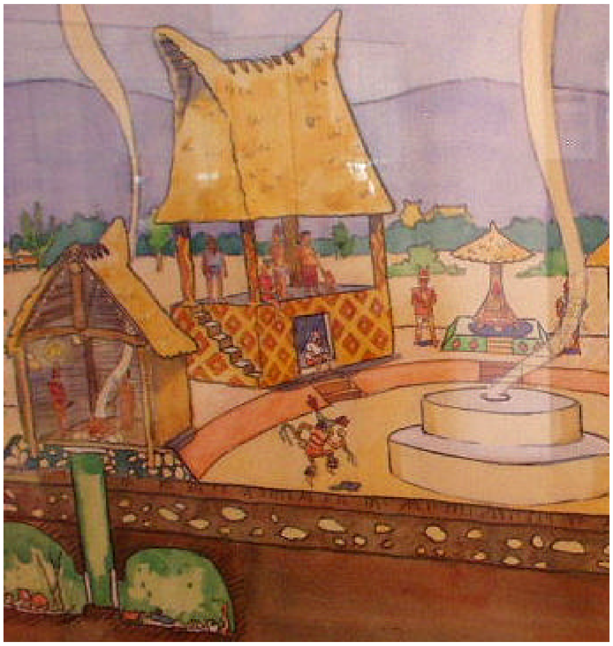

Fig. 3. Tomb representation as used in a Mexican Western Culture.

In other latitudes, for instance Tierradentro, Colombia, is a place with many chambers for funeral practices in tuff. In these cases the maximum depth is 6 m. The smallest ones are very simple, just a chamber, for those with medium dimensions were incorporated wall columns and finally in the biggest ones the pillars were included (Yanez, D. and Suarez, M., 2001).

CONCLUSIONS

The interpretation of the information compiled points to propose that in Teotihuacan there were a lot of experiences in tunneling construction. For instance, the problems with those excavations with very thin coverage and the incorporation of pillars to increase the roof stability.

This knowledge could have passed to Xochicalco, because in this place the constructors increase the depth of the excavations and included pillars especially in the biggest chamber.

This hypothesis is coincident with Morante´s opinion, (Morante, 2001), in which he is sure that the astronomic knowledge was transmitted from Teotihuacan to Xochicalco. The conclusions of the analysis and interpretation made for this paper points to postulate that it must be established that transfer of engineering knowledge was made as well as the astronomic one.

In fact, without the pillars, the main chamber in Xochicalco could have failed, as was described.

The use of masonry or stucco helped to avoid weathering in the walls and the roof. Especially for the astronomers´ chamber in Xochicalco, the masonry must be contributing significantly to maintain the stability in the roof and in the shaft.

In the actual conditions, Xochicalco and Teotihuacan are not in risk conditions, so stability must be for many years more.

At Teotihuacan, as well as Xochicalco, a complex system of tunnels was made by the man, in order to practice many functions, ordinaries, rituals and astronomic. In the last case both places are one of the most wonderful examples of underground engineering in the ancient world, especially because astronomic observation need an extraordinary precision and constructors had the ability and knowledge to satisfy the requirements.

In all the cases studied by Morante (1993 and 1996), was identified that the tunnels constructors obtained the calendar absolutely exact, it could be the best in the ancient world, with 365.24 days by year at the tropic, which is surprising close to that indicated today by astronomers, 365.24219.

This paper is an example of the relation between engineering and archaeology, in the specific area of underground excavations. It could be used for complementary or similar analyses and it pretend to promote the beginning of a new discipline, the archaeoengineering.

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