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INTERVENTION ROAD OF THE AQUEDUCT IN QUERETARO CITY

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Abstract. *Boulevard Bernardo Quintana in the Santiago de Queretaro city was opened in 1962, their two-way pass under two of the arches of Queretaro and other intermediate leaving free, road were excavated around 3 m below the original ground level; the four adjoining pilasters were given an exaggerated structural protection and therefore the vehicular road was only a two-lane with 8.9 m wide total, narrowness originating severe circulation problems. The project to enlargement the road to three lanes was based on extending the width 11.5 m, through the optimization of the protection of the pilaster by placing tangent piles of 50 cm in diameter lower below grade level, which make up a wall for this linked from the top with a head beam.*

The challenge was to ensure that the aqueduct was exposed to deformation of a few millimeters; to do this, an ingenious system of protection was installed in the five arches that could accuse any deformation, formed with steel drag beams located on the gutter of the arches above pilasters and radial strand cable was placed that supported curved arc. A system of monitoring and instrumentation was installed to determine the behavior during the enlargement, in order to work within the ranges of security imposed by a colonial structure as important as the aqueduct of Santiago de Querétaro city.

1 DESCRIPTION OF THE AQUEDUCT

It is said of Don Juan Antonio de Urrutia y Arana thanks to his technical knowledge on the subject drew and directed the construction of driving water spring near the Cañada; the first section of the project is a channel length of 5 km was known as El Socavon because it was covered with stone slabs. The section in archery has east-west direction, extends for 1,259 m with 74 arches; at its end becomes a channel on a wall along almost 430 m, reached the Convent of the Holy Cross located in Sangremal hill, the highest point of Querétaro.

The aqueduct is uniform modulation of masonry; average clearing the arches is 13.0 m and the average measured between the key Arches and the channel is 1.6 m; pilasters are 3.36 m and 3.38 m from the front line. At the top of the pilasters to the breadth is reduced in steps on both sides, to match the width of the aqueduct at the top (1.10 m); the caño is 24 cm base and 27 cm high. The height of the arch is variable, with a high of 28.42 m is between Calle del Indio Triste and Puente de Alvarado while in the section where it crosses the Boulevard Bernardo Quintana, Arches 25-28 have an average height of 16.45 m, Figure 1. The Aqueduct has required several repairs as the first arc destroyed during the Battle of Querétaro Reform War.

2 GEOTECHNICAL SCOPE

The geotechnical project was done in three stages: a) It began by defining in detail the stratigraphic site characteristics, the strength and deformability of soils. b) four wells were excavated to know the protections that were built on the foundations of the four pillars that were intervened in the 1960s and c) Identify options for a less robust protection, to give the assurance that none of the arcs suffer damaging deformations.

The objective of the study was to design subsurface protection elements of the pilasters foundation adjacent to the widening to three lanes of the underpass. This protection is based on confining the unground part of the foundation with piles cast in place.

3 SUBSOIL EXPLORATION

For the stratigraphic sequence of the site fourteen standard penetration soundings were conducted Figure 2, SPT-1 to SPT-14, to a maximum depth of 14.2 m, this test is to drive into the soil by percussion a tube half-round standard dimensions and a standard power ramming that allows obtaining representative soil samples for visual identification. The strength and compactness of subsoil is done by correlation with the number of blows N required for driving the tube 30 cm. Once detected the rock, a barrel with diamond drill was used a sampler to rescue specimens 3 inches in diameter basalt, located underlying soils at a variable depth.

To set the parameters of soil design strength (cohesion and angle of internal friction) and the difficulty involved in obtaining undisturbed samples were carried out field tests in two borings consistent with the appliance known as Phicometer, these were designated SPH-7 and SPH-10.

Additionally four open pits (PCA-1 to PCA-4) were excavated to a maximum depth of 4.3 m, with these knew the characteristics and depth of subgrade foundation of the pilasters of the aqueduct they and determined by direct observation, surface stratigraphy and geometry of each, in particular clarify the enlargement that have the base. Also they allowed to check visually that the foundation meet the two old rules of construction: a) the walls or pilasters were placed at least two Castillian varas deep, the rudeness of the pilasters is on average 3.81 m (4.5 varas) b) the enlargement in the base of the pilasters of the arches is 27 to 30 cm, as was usual in the sixteenth century, As regards the concrete walls of the road was found that traditionally were cast with false work and its width is 35 cm and are separated on average 1.96 m of the shaft of the pilasters and 1.66 m of enlargement. These data were important because they are asserted to have been cast as usual trench walls in the subway in Mexico City

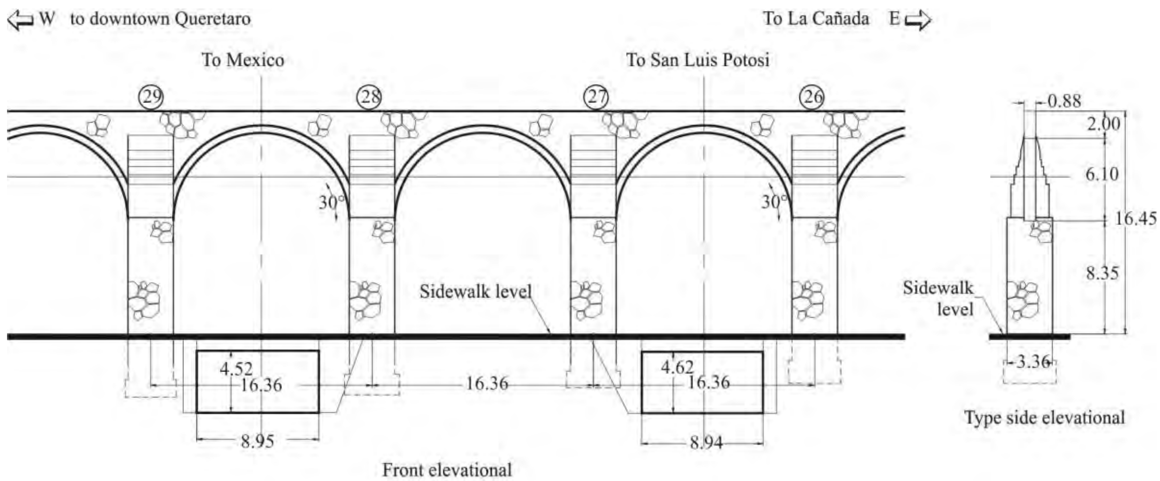

Figure 1 View of arches 25 to 29, dimensions in m

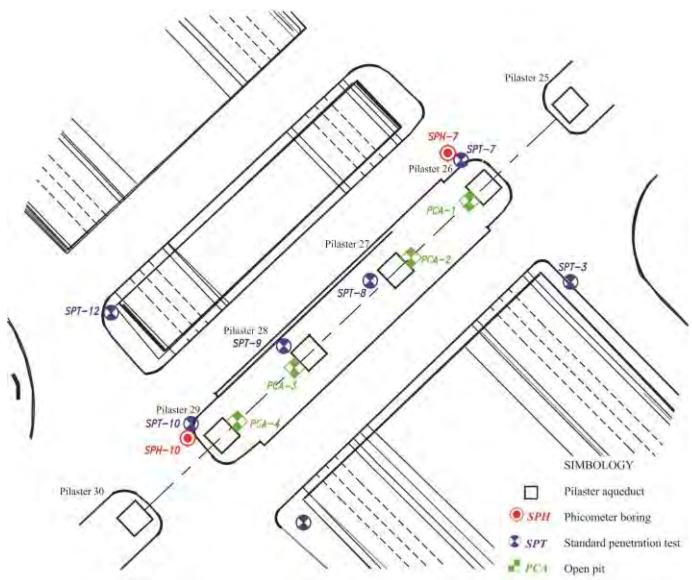

Figure 2 Location of exploration borings

4 LABORATORY WORK

In the samples obtained in the borings of standard penetration test following properties were determined: natural water content and visual classification. With the rock samples of basalt and volcanic rock were carried out in simple compression test.

5 SITE STRATIGRAPHIC CONDITIONS

According to the borings conducted and its interpretation, the stratigraphic sequence is described below and shown in Figure 3.

Heterogeneous fills. They were placed to give the final levels of the ground of the Avenida de los Arcos; have thicknesses ranging between 1.20 and 6.80 m are composed of a mixture of brown sandy clay; in some borings were found: gravel, caliche lumps, fragments of volcanic rock and mortar and even tree roots. The average value of blows in standard penetration test was 30, with minimum values of 2 and maximum of 60.

Organic Soil. Underlying heterogeneous fills and these deposits are part of a surface layer with a thickness ranging from 0.4 to 1.2 m, consisting of dark coffee high plasticity clay (CH) forming expansive agricultural soils in the area.

Volcanic toba. They are composed of carbonated silty sands with different coffee pinkish tones in some areas has inclusions of red tezontle. The thicknesses grows south and east of the site (borings SPT-1 and SPT-2) and range between 0.6 and 7.4 m and the number of blows in the standard penetration test varies from 10 to 100. This subsoil is where the pilasters 26, 27 and 29 of the Aqueduct are supported.

Tezontle. Is the top of the basalt and consists of sands and gravels pinkish brown in different tones and dark gray. In some areas has caliche inclusions; the thickness of this layer shows significant variation, being thicker to the north and east of the site (soundings and SPT SPT-3-7).

Basalt. Underlying the tezontle; is an intermediate andesitic basalt lava emerged from Cimatario volcano, its color varies from pinkish gray and dark gray, its natural fractures presenting caliche and its appearance varies slightly porous to mass. The 28 is the only pilaster that rests on this material [1].

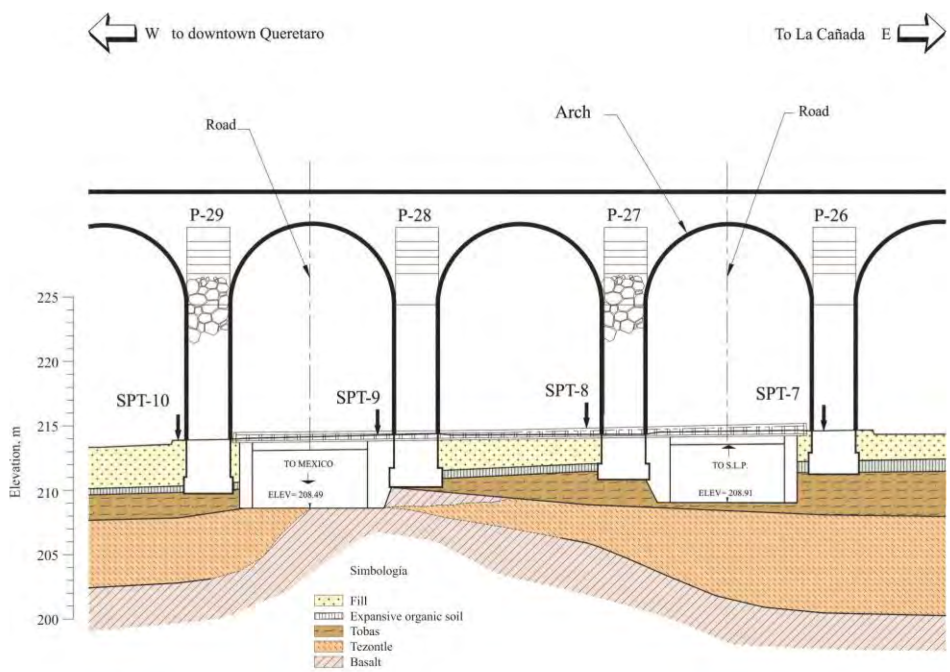

Figure 3 Stratigraphy between pilasters 26 - 29

6 PROTECTION OF THE PILASTERS OF THE ARCHES

The extension of the road from its original width of 8.94 m to 11.5 m, to have three lanes in both directions, was possible thanks to that space between the pilasters and box was 1.96 m, before mentioned; where they could enter piles of lateral support the pilasters and then proceed to the demolition of the existing drawers to make enough space to accommodate the new concrete box with three lanes.

The foundation of the four pilasters is surrounded by 18 concrete piles 50 cm in diameter, embedded within one meter in basalt about 7 m deep; these piles were placed around the perimeter of each pilaster, 11 at front, 4 at side and 3 on the back; 11 at front are installed tangents to the enlargement of the pilasters within a false work to prevent concrete to adhere to the pilasters' masonry, Figure 4. Piles were attached to each pilasters foundation by a rigid concrete beam, the safety factor with which this solution was designed is 3, a higher value is justified because the aqueduct is an important monument; concrete of this element was isolated masonry plates fiberboard.

The enlarged view of the road at 11.5 m wide section will by building four walls made with tangent piles of 50 cm diameter recessed below the current ground level and on top of these walls a beam clamped head is placed.

To follow through on the road of Avenida de los Arcos were placed reinforced concrete slabs supported by concrete heads beams and its foundation was made by piles 60 cm in diameter also embedded in the layer of basalt.

The procedure that is proposed to achieve the projected width involved the design and review of the containment system which would ensure that the pilasters did not suffer displacement during excavation, so the following aspects were reviewed:

a) Stability of the supports of the pilasters of the aqueduct.

b) Elements of retention.

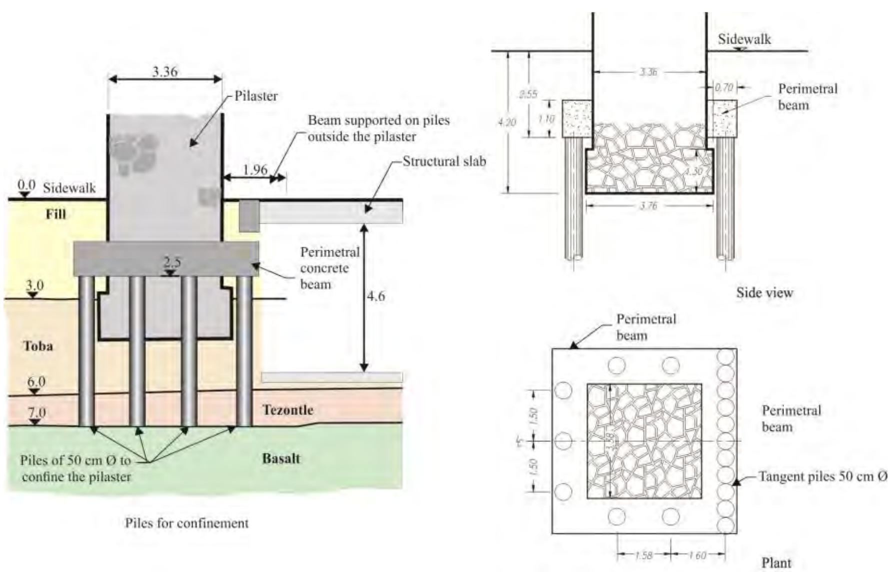

Figure 4. Confinement of the pilasters

7 STABILITY OF THE SUPPORTS OF THE PILASTERS

Considering the depth of the base of support for each of the pilasters of the aqueduct varies from 3.4 to 4.6 m from the level of the traffic island of Avenida de Los Arcos, so to prevent discovering the support thereof, was performed partial excavation to a depth of 2.5 m which allowed the construction of the concrete beam, called “cinturon de concreto”.

The capacity of the soil supporting the pilasters of the Aqueduct, considering that losing confining, a failure could occur was calculated, Figure 5 shows the geotechnical analysis model for the most unfavorable condition corresponding to the Pilasters 26 in which its width is 3.75 m and depth of 3.4 m support for the excavation of 2.5 m required to place concrete beam above, with expressions of soil mechanics ultimate load capacity of 750 kPa was calculated. This value exceeds the 384 kPa concluded by Dr. Fernando López Carmona that transmits the pilaster whose weight is about 5.4 MN [2].

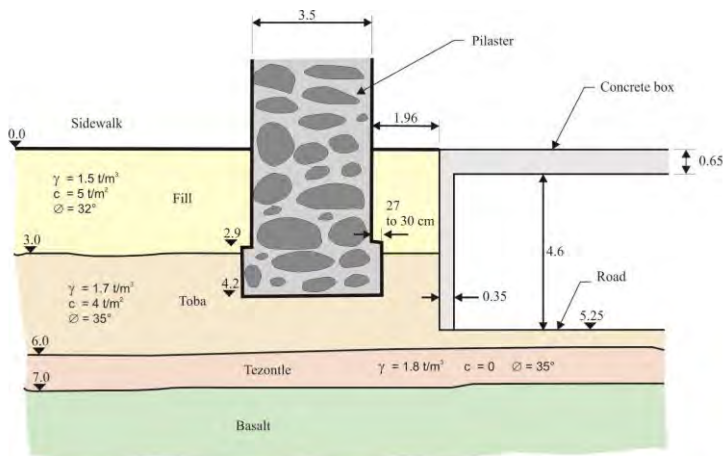

Figure 5. Foundation of the pilasters

8 RETAINING WALLS

The concrete boxes were demolished to extend the existing rails. The characteristics of the soils found in the project area as well as the benefits from the construction point of view, the use of a system of tangent piles of 50 cm diameter was projected to form a longitudinal wall on all four sides of the three lanes and which functions as retainer against lateral earth pressure. The piles were embedding at least 2.0 m below the current ground level of depressed. In Figure 6 shows the beams constructed for the stability of the pilasters and the new overpass.

The new wall is subjected to earth pressure and its stability was reviewed and the conclusion was to place horizontal anchors in its crown to prevent lateral movement whit a load of 159 kN.

9 GEOTECHNICAL INSTRUMENTATION

9.1 Introduction

Expansion works at Bernardo Quintana Boulevard under crossing Avenida de Los Arcos to three lanes was essential to monitor the structural behavior of the arches, to ensure that at no stage of the work settlements or crashes were generated. It was essential to know with certainty the effects of the intervention on the geometry of the monument, as it was the only way we could assess the safety with which construction work was performed.

This monitoring consisted of a measurement campaign: a) topographic precision that would allow to verify that a geometric change of the arches, b) convergence is presented, of course bows to state whether they were expanding or reducing its light measurements were made in five arches, the boulevard and the other two sides c) measurement of inclination of the pillars with plumbline [4].

Topography brigade. The measurements were carried out by a brigade under the command of Resident Engineer of the work, the Surveyor engineer was a competent and knowledgeable technical craft, devices available were: a) a laser surveying station in excellent condition and newly calibrated b) a topographic level of accuracy. With both instruments reliable measurements were obtained on a millimeter. Measurements were taken every third day in the morning before the sun and heat were a factor of uncertainty.

Figure 6 Overview of the beams

9.2 Topographic leveling

In order to define the extent of any settlements that might present the pilasters of the aqueduct, topographic leveling was performed, for which required the measurement points were fixed and they could leave as reliable references very long term.

References are stainless steel bolts 5 cm length, 6.3 mm in diameter, housed in a bore diameter of 9.5 mm and fixed with epoxy glue type Figure 7; should protrude 5mm to support the state or strip measurement. One of these is placed in each of the corners of the pillars 25 to 30.

The leveling were referred to a fixed bench. Measurements were performed with a topographic level of ± 0.01 mm resolution and invar bar code to achieve an accuracy of ± 1 mm with two measurements at a distance of 1,000 m.

Settlement values defined from the topographic leveling performed were the order of 1 mm but two references that apparently moved during construction 4 mm.

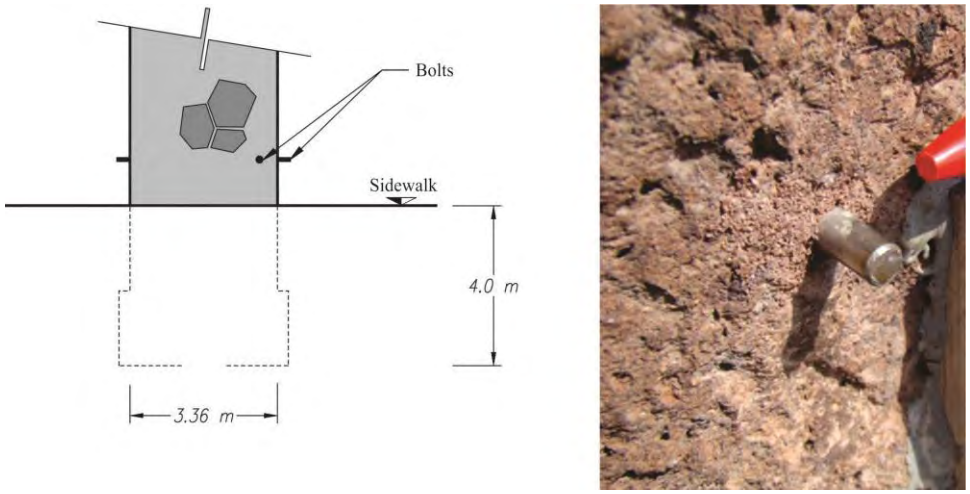

Figure 7 Topographical references

9.3 Convergence measurements

The term convergence measurement was developed for the construction of tunnels and consists of the determination of changes in spacing between pairs of fixed points on a certain date. The same technique is applied to measure the distance between pilasters or columns of a monument. The standard is to measure horizontal distances in three different heights.

The measurement was made with an extensometer consisting of a steel tape mounted on a device with a spring constant voltage and bearing at their ends are strung on hooks eyelets permanently mounted on the shaft of the pilasters at different heights. The tape may have lengths of 15, 20 or 30 m with a resolution of ± 0.25 mm and ± 1.0 mm accuracy. Measurements were taken in the morning before the sun and heat were a factor of uncertainty

The measurement consists of: a) attaching the extensometer between the pair of eye hooks, b) the mark in the constant tension c) indicator adjusts the range reading is done, using the scale tape and cover the extensometer; then the equipment is removed and the operation is repeated scoring readings.

For the project of the underpass a pair of eyebolts were installed on the arches 25-29 to three different heights, 3.0, 6.0 and 9.0 m in relation to the level of the ridge, Figure 8.

All measurements show lower opening or closing the half-millimeter, so the values were within the accuracy of the apparatus. With exception of the arc 25 in which the end closure 3 mm in the lower section and the upper section of an aperture of 3 mm was obtained.

9.4 Plumb-line

In the pilasters brackets were installed up to the springing of the arches, pilasters 26-29, in which hung a plumb-line to determine any changes in the tilt.

The plumb line used is a metal cylinder about 7 kg weight hanging from a steel wire of 0.5 mm, the top of which hangs from a fixed bracket; The cylinder is immersed in a container of viscous liquid which reduces the influence of wind. The container is a portable rectangular tank focusing and leveling by bolts, as illustrated in Figure 9; the top of the tank is a framework with prescription rules 1mm and has two bubble levels to confirm it is in a horizontal position accuracy is ± 1.0 mm.

The measurement involves placing and leveling the tank in place, hang the cylinder, wait until the fluid stabilizes and plumb using a T-square to measure the position of the wire in two directions.

During the time that the work carried out no movements pilasters were detected.

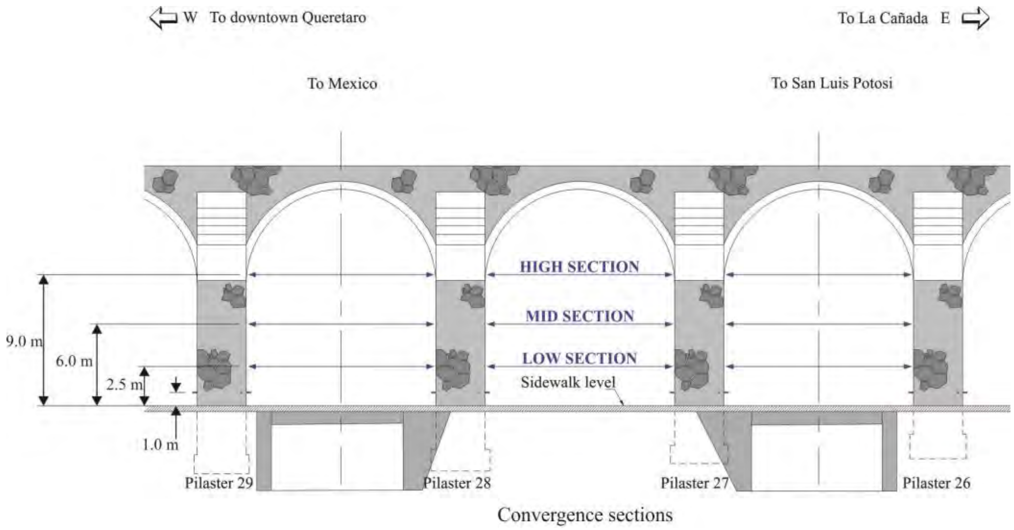

Figure 8 Convergence sections

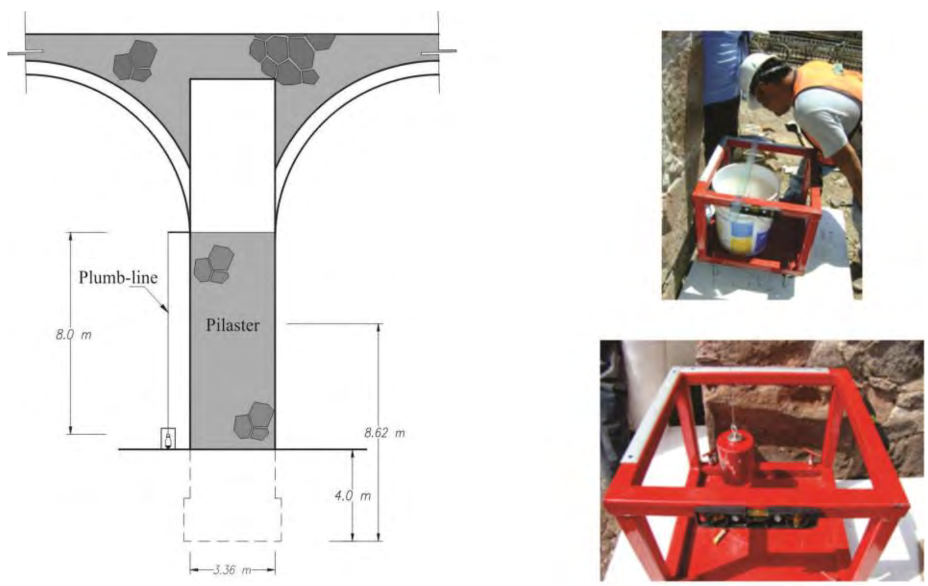

Figure 9 View of plumb-line

9.5 Conceptual framework for acueduct safety

The fundamental conditions that were agreed with the Coordinación Nacional de Sitios y Monumentos INAH, to allow the work of Bernardo Quintana Boulevard extension were: a) To assume a very large safety factor against overturning risk b) that the deformations will induce Arcos could be tolerable for that structure. To verify that these conditions are met the settlements of four adjoining pillars and one on each side, and the opening or closing deformations between columns, known as the convergence measurements were measured.

The overturning of a structure is a theoretical concept that can be applied to the Arches as defined in any book of structures; however the definition of tolerable deformations may be subject to discussions, so it is suggested that the experiences of the Geometric Correction of the Metropolitan Cathedral and the Pisa Tower could be taken as a guide to define tolerable for Arcos; which can be considered valid because the two monuments are significantly more sensitive to deformation than the arches of the aqueduct of Queretaro.

9.6 Tumbling geometric condition

The most likely direction in which one of the pillars could be turning in the direction orthogonal to the structure, Figure 10 shows a cross section on the axis of a pilaster hanging type with both sides of the arches 5.4 MN. The classic rule defines a structure that will turn when the vector of its mass, linked to its center of gravity (centroid at 8.62 m from the base of support) pass outside the middle third of the base. This geometry defines the weight vector would 0.56 m off-axis of the pilaster, without taking into account the enlargement of the foundation.

$$\tan\theta = \frac{0.56\cdot m}{8.62\cdot m} = 0.0649, \text{ so that } \Theta = 3.71°$$

The displacement for the above angle would have to be: dp = 800 tan 3.71° = 52 cm; this number is so large that it is unimaginable that could cause such deformation to induce failure.

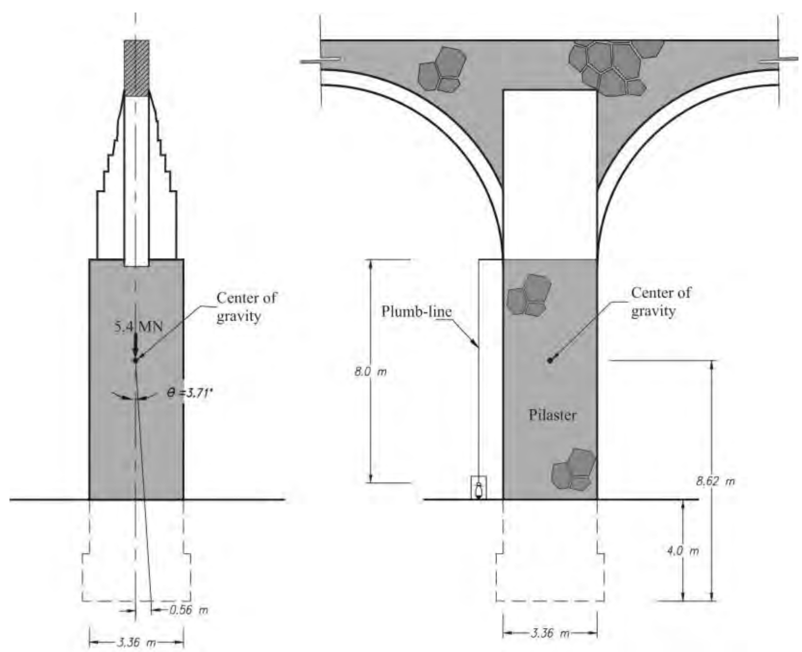

Figure 10 Geometric model to define the maximum tolerable rotation

9.7 Tolerable angular deformations

The angular deformation were tolerated by the structures of the Cathedral of Mexico and the Tower of Pisa were taken as a guide; beginning with the experience of the Cathedral, because its structure is the most sensitive, endured two immediate turns between arches 1/1000 without being induce cracks, it began to appear with spins 1/500. Another important concept is that the structures of both monuments tolerated a maximum rotation of 0.5 ° (as a ratio = 1/114.6).

Any changes in the verticality of the pillars of the aqueduct was measure whit plumb cushioned against the wind with a viscous liquid, Figure 9, at a height of eight meters on average. With the above parameters, turns the level of support pilasters to 4 m depth and the following table was derived.

Table 1 Turns tolerable for Arcos de Querétaro

Angular deformation	Angular relationship	Turn in arcsec	Displacement in the plumb of 8.0 m
Very conservative	1/1000 = tan 3.44’	3"	8 mm
Conservative	1/500 = tan 6.87’	7"	16 mm
Induced monuments	θ = 0.5°	30"	70 mm
Acceptable fot arcs	θ = 0.25°	15"	35 mm

9.8 Differential settlements on the pilasters

For differential settlement of acueduct parallel to all sides involved pilasters were installed as fixed references 4 bolts stainless steel, Figure 7, with measurements of differential settlement level are defined, whose plant is square in section 3.36 m side, differential settlement Δh of each was determined in accordance with the tolerance parameters defined above, settlements are in the following table.

Table 2 Tolerable differential settlement for the pilasters

Settlement	Relation	To pilasters	Differential between bolts
Very conservative	1/1000	3.36/1000	± 3.4 mm
Acceptable	1/500	3.36/500	± 6.8 mm

9.9 Convergence measurements

Acceptable opening or closing deformations are measured at a controlled belt tension is set between two pins on the inner sides of the arc, Figure 8. As for the tolerable values, the criterion mentioned in his book Professor Jacques Heyman, which are also of the order of 1/1000 and 1/500 was adopted; well for whose arches of the Aqueduct clear in the operated area is 13.0 m, are those contained in the following table.

Table 3 Tolerable values for the convergence of the arches

Deformación	Relation	To pilasters	Differential between bolts
Very conservative	1/1000	13.00/1000	± 13 mm
Acceptable	1/500	13.00/500	± 27 mm

9.10 Safety warnings and risk

During construction the framework adopted for tolerable deformations are summarized in the following table, to monitor the behavior of the monument during all work intervention.

Table 4: Warning about safety and risk

Status	Movement plumb	Differential settlement pilasters	Convergence
Safely	± 7 mm	± 3.5 mm	7 mm
Caution	± 15 mm	± 5 mm	± 14
Preocupation	± 30 mm	± 6.8 mm	± 28
Failure	520 mm	----	----

NOTE: Preocupation means that when any of these parameters is reached may continue the work, but under careful supervision to prevent any of them increases.

10 CONCLUSIONS

Reference values and acceptable settlement and rotations by INAH are very conservative and are implemented to verify the safety of the protection of the pillars for the expansion work Bernardo Quintana Boulevard.

As for the term "preoccupation" as shown in Table 4 meant that when any of these parameters could be reached to continue the work, but under careful supervision to prevent any of the listed values are increased. It was just around that could be making a mistake during the process of construction, which should be detected and removed early.

The decision to continue the work if any of the values of "Caution" is exceeded would be subject to a technical analysis would show that was tolerable for the arches of the aqueduct.

Measurements made with geotechnical instrumentation described showed that the strains were in the range of accuracy of the equipment, so: a) changes in the defined vertical sinkers were less than 2 mm, b) measurements of convergence, openness or closure of the arches, were less than 0.5 mm and c) differential settlement between the sides of the piers was less than the level and accuracy of topographic instrument used.

Vibration measurements taken with accelerometers placed at various points of the arches, acceleration peaks were observed when one of the bits with which the hole was drilled to confinement piles reached the basaltic rock and / or ran into some edge of the foundation pilaster, these became accelerations of 0.6 g were lasting only a few milliseconds and therefore had no effect on the structure of the arches.

All this showed that the intervention of Arcos de Querétaro not induce any change in its state of stress and safety conditions and implicitly that the project successfully met the safety and conduct of the aqueduct, which was observed and approved by supervisors INAH technicians.

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