

Geotechnical Rehabilitation of the Cathedral of Mexico in 2020-2021

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ABSTRACT

Between 1989 and 2001, the Cathedral of Mexico underwent a rehabilitation program to address significant damage caused by large-scale differential settlements resulting from subsoil consolidation, exacerbated by the overexploitation of deep aquifers. The work carried out within the scope of geotechnical engineering resulted in a significant reduction in both differential settlement and the rate of its growth. While this geotechnical program was in progress, structural interventions were implemented to address deficiencies in the structure, such as lateral cover connections, cracking in vaults, walls, and columns, and, finally, foundation reinforcement. The works continued into the first decade of the 21st century. Eventually, a lack of financing led to the suspension of maintenance work and of automated structural performance monitoring. The strong earthquakes of 2017 caused damage to the cathedral complex that was classified as low severity. Consequently, a rehabilitation project was undertaken to repair earthquake damage and perform foundation maintenance. As part of this project, updated topographic surveys were conducted, readings were taken from the installed instrumentation, and new estimates of future settlements were prepared. Finally, a maintenance and remediation strategy was proposed based on the building's current condition.

Keywords: *Differential settlement; regional subsidence; CPTu; piezometry; control piles; heritage structures.*

INTRODUCTION

The Metropolitan Cathedral of Mexico City and its religious complex—which includes the *Sagrario Metropolitano* (Parish of the *Sagrario*), the *Capilla de las Ánimas* (Chapel of Souls), and the *Curia*—have experienced structural distress due to significant differential settlements since the earliest stages of their construction in the sixteenth century, as they were erected in part on the remains of ancient Aztec temples that were themselves founded on very soft soils. In addition, the area comprising the Historic Center of Mexico City has been subject to more than a century of region-wide subsidence induced by groundwater extraction from underlying soil strata. This condition has exacerbated structural damage, resulting in cracks and distress in pillars, columns, and other structural elements.

The Metropolitan Cathedral was built between 1571 and 1813 and comprises five naves: the central nave, bounded by 16 columns and divided by the choir; two processional aisles running the length of the church; and two lateral chapel aisles enclosed by the perimeter and transverse walls. The central dome, 65 m high, is supported by four columns. The two bell towers are 60 m in height. The church is

126.7 m long and 60.4 m wide; the average height in the central nave is about 25 m. Its total weight is approximately 1,270 MN, and the average bearing pressure transmitted to the subsoil is about 166 kPa (Ovando-Shelley & Santoyo Villa, 2019). The *Sagrario Metropolitano* was constructed between 1749 and 1768; in plan, it forms a Greek cross, with the walls at the four corners constituting the principal load-resisting elements, and its dome resting on the four central columns. The building occupies a square footprint measuring 47.7 m on a side; its weight is approximately 300,000 kN, and the average bearing pressure transmitted to the subsoil is approximately 132 kPa (Ovando-Shelley & Santoyo Villa, 2019).

The Metropolitan Cathedral was built on part of the natural island inhabited by the Mexica, which stood slightly above the lake level. The Mexica ceremonial center was located on this island; consequently, the Cathedral's foundations contain remnants of pre-Hispanic structures. The Sagrario was constructed over pre-Hispanic remains associated with the pyramid of the sun god, Tonatiuh. The ground surface beneath the Cathedral was reinforced by driving approximately 22,500 short timber piles, on top of which a masonry platform (stone fill platform) measuring 140 m in length by 70 m in width was placed. These dimensions exceed the footprint ultimately occupied by the Cathedral. The thickness of this platform—averaging 0.90 m—increases toward the south, indicating an intentional thickening to compensate for the differential settlements observed since the earliest stages of construction. On top of the platform, a grid of masonry tie-beams was built, approximately 3.5 m high, 2.5 m wide, and up to 127 m long, to support the walls, pilasters, and columns (Figure 1).

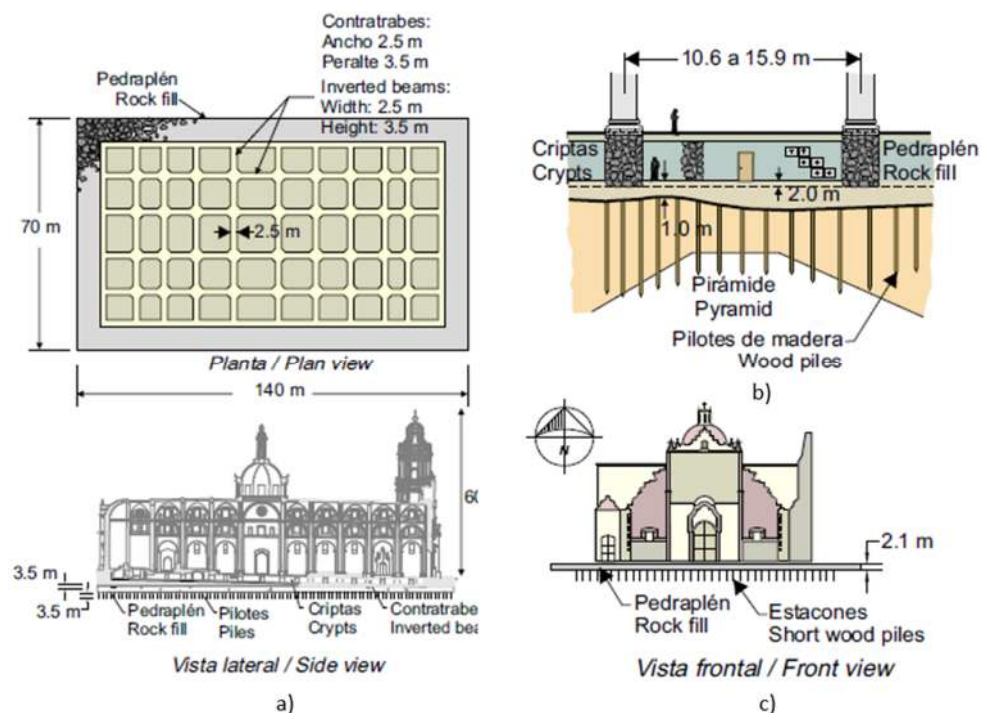


Figure 1. Schematics of the foundation of the Metropolitan Cathedral and the Sagrario. (Ovando-Shelley & Santoyo Villa, 2019).

SITE STRATIGRAPHY

The subsoil underlying the Cathedral complex consists predominantly of lacustrine deposits formed by highly compressible soft clays, resulting from the deposition and physicochemical alteration of alluvial materials and volcanic ash (Figure 2). These deposits are interbedded with layers of volcanic ash, pumice beds, and soils derived from the weathering of volcanic, fluvial, alluvial, and glacial deposits. This stratigraphy yields an ordered sequence of soft-clay strata separated by stiff lenses of clayey-sandy silt, desiccation crusts, and basaltic or pumiceous sands.

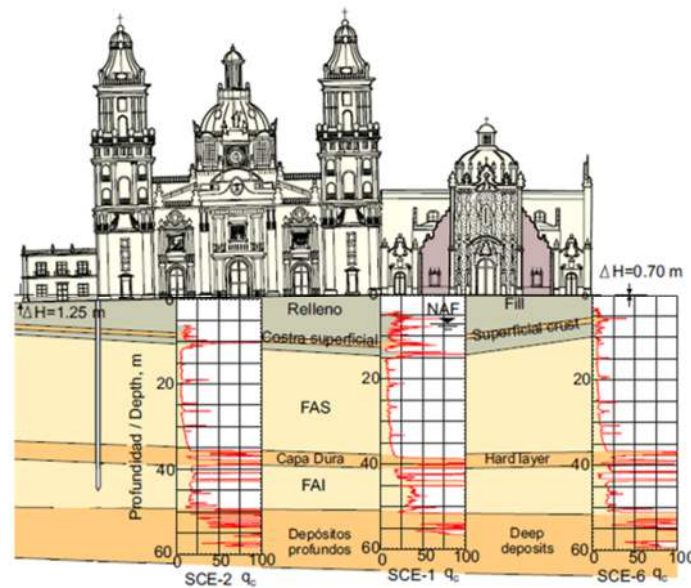


Figure 2. Stratigraphic profile of the front portion of the religious complex (Santoyo Villa & Ovando Shelley, 2008)

GEOTECHNICAL INTERVENTION IN 2020–2021

The following sections summarize key aspects of the geotechnical intervention conducted in 2020–2021 at the Metropolitan Cathedral and the *Sagrario*.

Piezometric conditions in July 2021

In July 2021, a CPTu test was performed, and pore-pressure dissipation tests were conducted; readings were also taken at the piezometer stations and in the observation standpipe. Figure 3 presents these results and compares them with piezometric records from 1999. The comparison indicates that over the last 21 years, the depth to the groundwater level (GWL) has not changed significantly and that, from approximately 7.5 m (the current GWL) down to 38 m (the depth of the hard layer), pore pressures remain essentially hydrostatic. Although pore pressures between 38 m and 49 m show drawdown relative to hydrostatic conditions, they have not changed appreciably during the past two decades. This observation is consistent with the interpretation that the main drawdown driving regional subsidence in the Historic Center occurs at greater depths (>50 m), as documented in prior hydrogeological assessments.

Execution of CPT soundings

A comparison of the CPT-2_Ing (2021) sounding with earlier CPTs performed at the base of the West Tower of the Cathedral in 1989 (SCE-1989) and 2001 (SCE-2001) shows higher q_c values in 2021, attributable to soil stiffening induced by subsidence associated with groundwater withdrawal (see Figure 4).

Measurement of water levels inside the shafts

The results in Figure 5 indicate that, overall, the shafts exhibit minimal fluctuations in water level, consistent with the site's geotechnical conditions. However, the water levels in shafts L-09, L-12, and L-16 differ by up to 2 m, warranting a detailed site review to rule out possible leakage in the piezometer tubing.

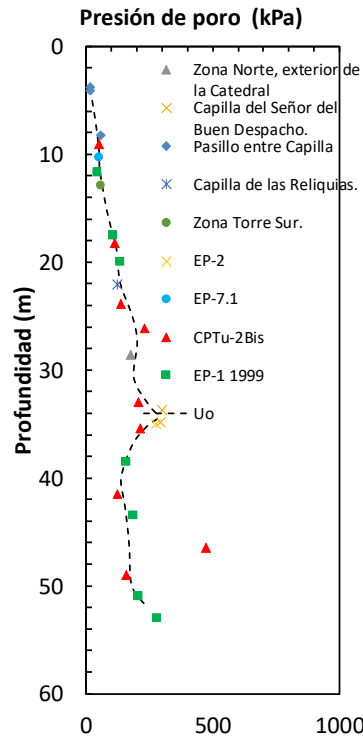


Figure 3. Pore-water pressure records from 1999 and July 2021.

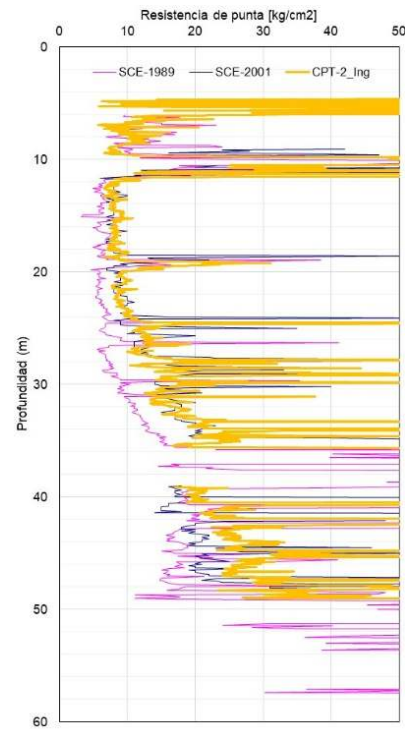


Figure 4. Comparison of the CPT- 2Ing, SCE-1989, and SCE TP-2001 records

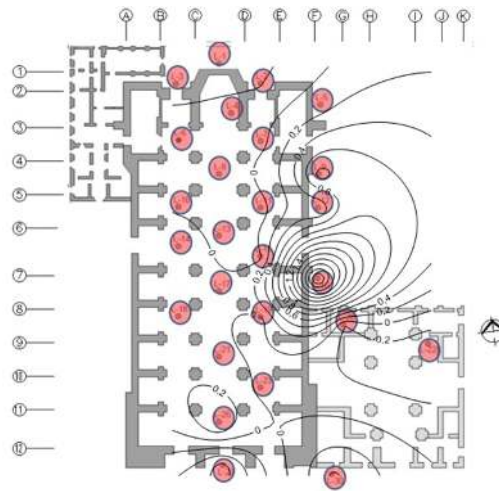


Figure 5. Water-level contours in shafts, referenced to the elevation of Shaft L06.

MAINTENANCE OF THE CATHEDRAL'S FOUNDATIONS

As part of the foundation maintenance activities for the Metropolitan Cathedral of Mexico City, the Institute of Engineering (II-UNAM) provided technical support, proposing methodologies and issuing pertinent observations and recommendations to mitigate and correct the differential settlements affecting the structure—attribution primarily to regional subsidence, the presence of pre-Hispanic remains in the subsoil, and specific structural features.

The works carried out on the foundations of the Cathedral and the *Sagrario* comprised: maintenance of the pile load frames (reaction frames) (Figure 6); trimming of pile heads that exhibited a significant apparent protrusion; replacement of the hardwood (*caobilla*) blocks used to maintain a constant load on the pile head; application of pile loads in accordance with the calculated values; and load testing on selected piles.



Figure 6. Pile load frames 17, 16 and 15.

Load Test

Initially, the Institute of Engineering (II-UNAM) designed and supervised the load testing of six piles along the south façade, each initially carrying 25 t (~245 kN). The piles were loaded in 10 t (~98 kN) increments up to 120 t (~1.18 MN), and the resulting displacements were recorded at each increment (Figure 7). They were then unloaded and set to the operating load specified by design. The tests verified shaft and toe-load transfer responses, enabling assessment of whether each pile was socketed into a hard layer or fully embedded in the clay strata. Load levels referenced in this paper are distinguished as follows: (i) proof-load test levels (up to 120 t) used to verify axial response; (ii) operational loads re-established after maintenance (e.g., 10–90 t) to control differential settlements; and (iii) analytical verification load cases (e.g., 50–95 t) used for limit-state checks.

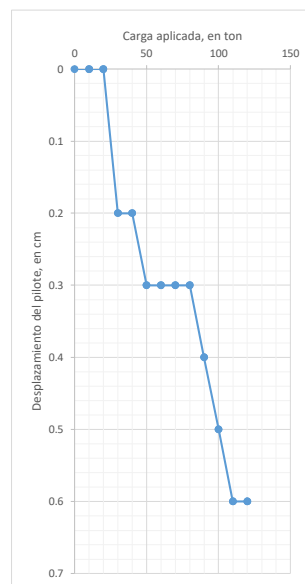


Figure 7. Example of load test of pile 54/205B

Pile reconditioning

The Cathedral has the highest number of piles within the religious complex; however, among the 417 control piles, only 28% have load-carrying capacity. In this context, control piles are foundation piles equipped with load frames and deformation cells that apply and maintain controlled axial loads to mitigate differential settlement. An initial review was conducted to determine the loads on the piles, from which it is known that the total load carried by these piles is 3,912 t (~38.4 MN), i.e., 3% of the structure's total load. As shown in Figure 8, 80% of the piles do not carry more than 50 t (~490 kN).

Lack of maintenance over an extended period led to marked deterioration of pile components, especially in the southwest sector: bolts, plates, and reaction frames with significant corrosion; wooden blocks

exhibiting deformations exceeding the allowable limits for this type of pile; and cases in which the timber is rotten.

To reduce the settlement rate in the southern zone, a loading protocol was designed. This protocol accounted for the load capacity identified in the initial review, the recorded pile emersions, and the mechanical characteristics of the wooden blocks to be used.

However, during field inspections, the installed blocks exhibited inferior mechanical properties (indicated by the red dashed line). In those cases, and in subsequent maintenance, the issue was remedied, as evidenced by the solid green lines in the figure. Final pile loads after maintenance were determined based on calculations of column and façade out-of-plumbness (tilt) to mitigate these effects. The applied loads were 10 t (~98 kN), 30 t (~294 kN), 40 t (~392 kN), and 90 t (~883 kN), as appropriate (Figures 9 and 10).

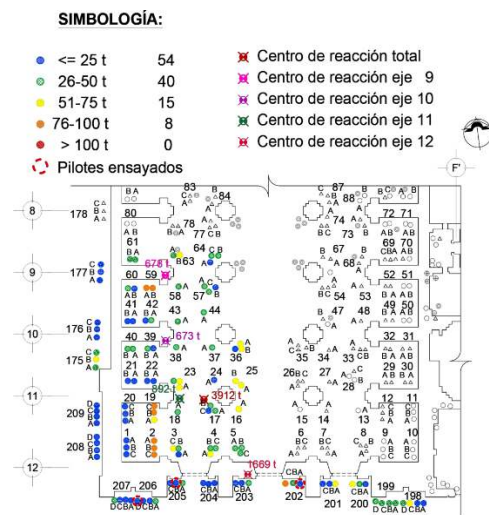


Figure 8. Load on the control piles before maintenance

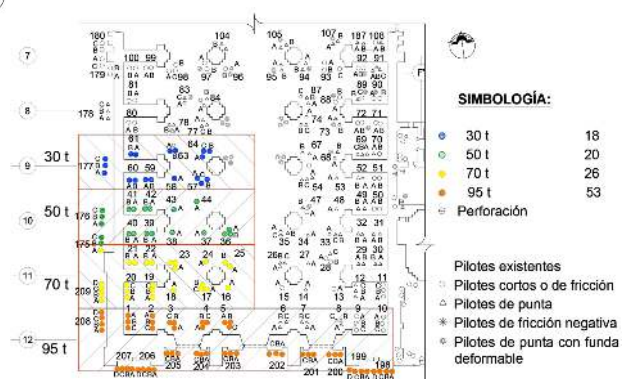


Figure 9. Loading protocol designed for control piles



Figure 10. Load application at 90 t. Pile 54/205B.

ANALYTICAL REVIEW OF THE BEHAVIOR OF THE CONTROL PILES

The performance of the end-bearing and friction-control piles (diameters of 0.40 m and 0.45 m) installed in the southern sector of the Cathedral was evaluated. The review verified compliance with the ultimate limit state (ULS) requirements of the Complementary Technical Standards for the Design and

Construction of Foundations (NTC, 2017), using the loads specified in the II-UNAM test program. In addition, the criteria of Tamez (2001) and Zeevaert (1983) were applied to assess end-bearing behavior.

It is necessary to consider that, due to the uncertainties of the mechanical properties of the Hard Layer, the length of many of these, the working conditions by tip, and the load loss due to buckling, mainly, for which analysis is carried out of the cases that are considered possible, and the most probable working situations of the piles are determined.

Tamez Criteria

Tamez (2001) proposed several criteria for evaluating the performance of control piles. In a static analysis, he considered that for a control pile to function correctly under static load, two conditions must be encountered (Martínez, 2017):

- The foundation slab must settle at the same rate as the adjacent ground surface. This implies that the load transmitted by the slab to the soil, plus the negative frictional force induced by the regional subsidence, must equal the pile's frictional bearing capacity.
- To prevent the pile tip from penetrating the resistant stratum, the tip's bearing capacity must be greater than or equal to the sum of the yield load of the deformation cell and the lateral bond bearing capacity multiplied by a safety factor.

Zeevaert Criterion

In 1983, Zeevaert analyzed the behavior of an end-bearing pile under negative skin friction generated by a load applied to the ground surface over a specific tributary area, without accounting for the load applied to the pile head by the traditional control device.

Zeevaert deduced that the total load acting on the pile equals the load applied by the control device plus the negative skin friction generated by the surface load acting on the pile, including the effect of subsidence.

Review of the failure limit state according to NTC (2017)

The review of the safety of foundation elements under a failure limit state consists of comparing the soil's bearing capacity with the design loads, applying a resistance factor to the net bearing capacity, and a load factor to the design loads. It is important to note that negative skin friction that may develop on the walls of foundation elements must be accounted for in the total vertical load.

Analysis Results

The results indicate that the assumed embedment length in the frictional stratum governs whether the end-bearing control piles meet the criteria under each proposed load. By contrast, the friction piles satisfy the NTC (2017) criterion only for loads ≤ 25 t, provided a minimum pile length is achieved.

The behavior of end-bearing and friction control piles, 0.40 m and 0.45 m in diameter, installed in the southern area of the Cathedral, was reviewed. To review the behavior of the control piles, it was verified that these elements did not exceed the failure limit state, as defined in the Complementary Technical Standards for the Design and Construction of Foundations (NTC, 2017), under the loads established in the test program proposed by the Institute of Engineering (II-UNAM).

Additionally, the criteria of Tamez (2001) and Zeevaert (1983) were considered to review the behavior of the end-bearing piles. In determining the end bearing capacity of the foundation elements supported on the Hard Layer, three internal friction angles (30°, 40°, 45°) were considered for this stratum to compare results across cases. However, it is important to highlight that the expected friction angle is a minimum of 40°, so taking this into account, the following can be concluded:

- The control piles, both 0.40 m and 0.45 m, supported on the Hard Layer have sufficient end bearing capacity to prevent the tip from penetrating the resistant stratum according to Tamez's criterion.

- The safety factors obtained according to the Zeevaert criterion range between 1.97 and 2.46, and between 2.33 and 2.84, for end-bearing piles of 0.40 m and 0.45 m in diameter, respectively, for the loads proposed in the test program.

Upon reviewing the failure limit state according to the NTC (2017), it was found that if a zero-embedment length in the frictional stratum is considered, the 0.40 m diameter piles would not comply with the inequality $\Sigma Q F_c < R$ for loads of 50 t, 75 t, and 95 t. However, if these foundation elements are assumed to have a minimum embedment length of 0.70 m, they would not exceed the failure limit under any of the proposed loads. Here, $\Sigma Q \cdot F_c$ denotes the sum of factored vertical actions (Q) multiplied by the corresponding NTC load factors (F_c), and R is the design axial resistance of the pile/foundation system.

On the other hand, for piles with a diameter of 0.45 m, assuming a zero-embedment length, they would not satisfy the inequality for loads of 75 t and 95 t. However, if these foundation elements are considered to have a minimum embedment length of 0.45 m, they would not exceed the failure limit under any of the proposed loads and satisfy the NTC (2017) provisions.

CONCLUSIONS

It is important to emphasize that the piles placed in the Cathedral and the *Sagrario* do not correct or govern the behavior of these structures. They are mechanisms that contribute to the stability of the foundation and the structure.

The review, which employs three methods for existing piles, is intended to provide a framework for predicting the short- and medium-term behavior of the structures.

Therefore, it is essential and urgent to continue monitoring the piles and all installed instrumentation, to carry out periodic leveling of the Cathedral complex, and to allocate an annual budget for the maintenance and repair of the structures.

The scope of the current research is limited, and a broader, more ambitious program is required to maintain the complex in optimal condition.

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