GEOMETRICAL CORRECTION AND SUBSOIL HARDENING FOR HERITAGE SITES IN MEXICO CITY. LESSONS LEARNED

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ABSTRACT

Mexico City is affected by regional subsidence caused by groundwater extraction, a process that began in the late 19th century. Its effects are manifested through differential settlement, structural distortion, cracking, and failure in colonial-era buildings within the Historic Center. Numerous monuments exhibit structural distress due to cumulative differential subsidence—a phenomenon that, unfortunately, will continue to evolve. Given that a drastic cessation of groundwater extraction is currently unfeasible, regional subsidence is expected to persist indefinitely.

To address this challenge, a mitigation strategy has been implemented to differentially harden the subsoil beneath these structures. This is achieved through the use of vertical mortar inclusions and grout curtains, or via structural underpinning with micropiles.
Key words: Settlement, Subsidence, Collapse, Subsoil, Underpinning, Inclusions, Micropiles.

INTRODUCTION

The settlements originally recorded in the colonial structures of the Historic Center stabilized by the mid-19th century. Consequently, it is certain that both current and future subsidence is driven by the reduction in pore water pressure resulting from deep-well pumping.

The magnitude of these differential movements justifies the decision to implement differential subsoil reinforcement, aimed at equalizing subsidence rates and enhancing structural performance.

This technique has been successfully applied to major architectural monuments and a significant number of residential buildings. Its implementation and technical rationale are rooted in the Experimental Method described herein, as well as its specific adaptation to ground hardening projects.

THE OBSERVATIONAL METHOD

Subsoil improvement, like any engineering process, must be rigorously monitored to ensure it meets project goals and objectives. The technical rationale for its implementation is based on the Observational Method, which continues to exert a decisive influence on solving complex engineering challenges worldwide. This approach is particularly prevalent in Europe, where it is common practice to construct tunnels and subway stations in close proximity to ancient structures and historical monuments (Powderham, 2003).

HISTORICAL PRECEDENTS OF THE METHOD

Between December 1938 and June 1941, Karl Terzaghi served as a consultant for the construction of the Chicago subway, supported by Ralph Peck and in collaboration with Hardy Cross, as noted by Cross (1998). This project provided an extraordinary opportunity to assess safety factors and settlements induced by tunnel construction, groundwater extraction, clay consolidation, and lateral earth pressures on sheet piles and retaining walls—all monitored through reliable instrumentation (Goodman, 1999).

The next significant case Terzaghi addressed using this approach was the ore storage yard at Republic Steel in Cleveland.

Years later, when Ralph Peck delivered the Ninth Rankine Lecture in 1969, titled "Advantages and Limitations of the Observational Method Applied to Soil Mechanics," his core message was to formalize the working methodology pioneered by Terzaghi.

To implement this method, several simple, low-cost monitoring systems are commonly used in conventional leveling projects, including *Hydrostatic leveling, Topographic leveling, Tilt and Settlement Monitoring, and Crack and Fissure Monitoring*

SUBSOIL HARDENING

The design method for subsoil hardening is based on successive approximation and relies on the following premises:

a) Mortar injections reduce clay deformability as a function of the volume and geometry of the injected mortar, as well as the initial deformability of the soil itself.

b) Laboratory tests on both natural and treated specimens serve as a guide for determining the mortar volume required to achieve a specific reduction in the soil mass's deformability. Test results indicate a minimum injection ratio of 1% relative to the treated soil volume. Changes in deformability become significant at 4% and substantial beyond 6%, while ratios exceeding 10% are rarely necessary.

c) The required reduction in deformability is estimated from the differential deformation rates derived from future settlement analysis, applying Terzaghi's Consolidation Theory.

d) The increase in effective stress driving soil consolidation stems from a reduction in pore water pressure, which is triggered by regional groundwater extraction.

e) Current pore water pressure data shows a loss of up to 180 *kPa*. Unfortunately, this drawdown is projected to increase; future predictions must be modeled in consistency with the site's stratigraphy.

f) The zoning in plan and depth of the current deformability of the subsoil is done by correlating this variable with the tip resistance of the electric cone or with numerous conventional consolidation tests.

g) The lateral stiffness of the clays can be determined using Marchetti's dilatometer (DMT).

h) The injection percentage is determined through an iterative process of successive approximation. Mortar selection is based on stiffness, workability (pumpability and injectability), and cost-effectiveness. Volumetric percentages are then proposed and distributed according to observed settlement patterns. By establishing the soil's modulus of compressibility, settlements are calculated across a spatial study matrix. The optimal injection percentages are those that result in uniform settlement. This procedure provides a valid solution, although other solutions can be obtained with different quantities of mortar, depending on its stiffness (Km).

i) The shear strength of mortars is defined based on the required km stiffness, according to the numerical model of the soil mass.

j) The theoretically obtained injection percentage should be treated as an estimate; the final field values must be refined using the Observational Method. This requires a phased injection approach to gradually adjust mortar volumes based on the real-time structural response.

k) In the long term, complementary adjustments may be implemented, providing targeted injections in sectors where monitoring data justifies further intervention.

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CASE STUDIES

a) Metropolitan Cathedral and Tabernacle, Mexico City

The Metropolitan Cathedral and Tabernacle in Mexico City represent an emblematic case of monumental construction on geologically complex terrain. Situated on what was once an island in the ancient Lake Texcoco, these monuments face challenging geotechnical conditions due to subsoil composed of highly compressible clays and anthropogenic fill. Construction of the Cathedral began in 1573 and concluded in 1813, while the Tabernacle (Sagrario Metropolitano) was built between 1749 and 1768. Since then, chronic differential settlement has compromised the structural stability of the complex.

To mitigate differential subsidence, the technique of underexcavation was implemented. This method involves the controlled removal of soil from beneath the foundations of the building's elevated sections, thereby equalizing settlements by inducing a managed lowering of the highest areas. This procedure was inspired by a method proposed in 1962 for the Leaning Tower of Pisa and was specifically adapted to the soil conditions of the Valley of Mexico.

By the completion of the underexcavation phase in June 1998, a maximum induced correction of 92 cm was achieved between the apse and the southwest corner. The differential settlement between points C-3 and B-10, which stood at 243 cm in 1989, was reduced to 156 cm by June 1998.

These subsidence values justify the decision to apply differential subsoil reinforcement to both the Cathedral and the Tabernacle. The objective was to standardize settlement rates and improve the overall structural response.

Initial pilot tests were conducted in the west atrium within a 16 x 4.5 m area, involving 18 boreholes injected between November 1997 and January 1998. Subsequently, between September 18, 1998, and January 4, 2002, a total of 5,189 m^3 of mortar were injected into 585 strategic points, hardening the subsoil in critical zones as illustrated in Fig. 1.

The same figure shows the areas where it was necessary to harden the Upper Clay Formation of the subsoil, in order to reduce the large differences in the subsidence that afflict these structures and to implement a better performance.

It was also observed that the injection percentages varied from 1 to 7% in the Cathedral and from 1 to 5% in the Tabernacle. The injection was carried out using 585 deformable mortar cores with their respective sets of lateral plates.

Zones and percentages of grouting. The mortar grout recommended to reduce the compressibility of the subsoil under the Cathedral is made with controlled amounts of cement, bentonite, pumice sand and additives. Reductions of deformability depend on the stiffness of the mortar and on the percentage of grout injected. This last concept is the ratio between the volume of mortar and the volume of soil to be improved. The borings to carry out the injection need to cross the thickness of the rockfill, of the archaeological fills and of the superficial crust and should then go through the clays of the Upper Clay Formation that were grouted down to their contact with the First Hard Layer. The unconfined compressive strength at 28 days is 4,400 kPa.

Mortar manufacturing. The mortar used for core inflation and horizontal injection is manufactured with material mixing and dosing equipment, controlling the volumes of the aggregates.

To obtain quality control over the manufacture of the mortars, their viscosity and volumetric weight properties were determined in the field, and specimens were taken to perform resistance tests in the laboratory.

The fluidity of the mortars was controlled to ensure they were pumpable. Viscosities were measured using the Marsh cone, and optimal viscosities were found to be between 60 and 80 seconds. Regarding mixtures containing bentonite, a maximum content of 6% was established as the rule for obtaining workable mixtures in the field.

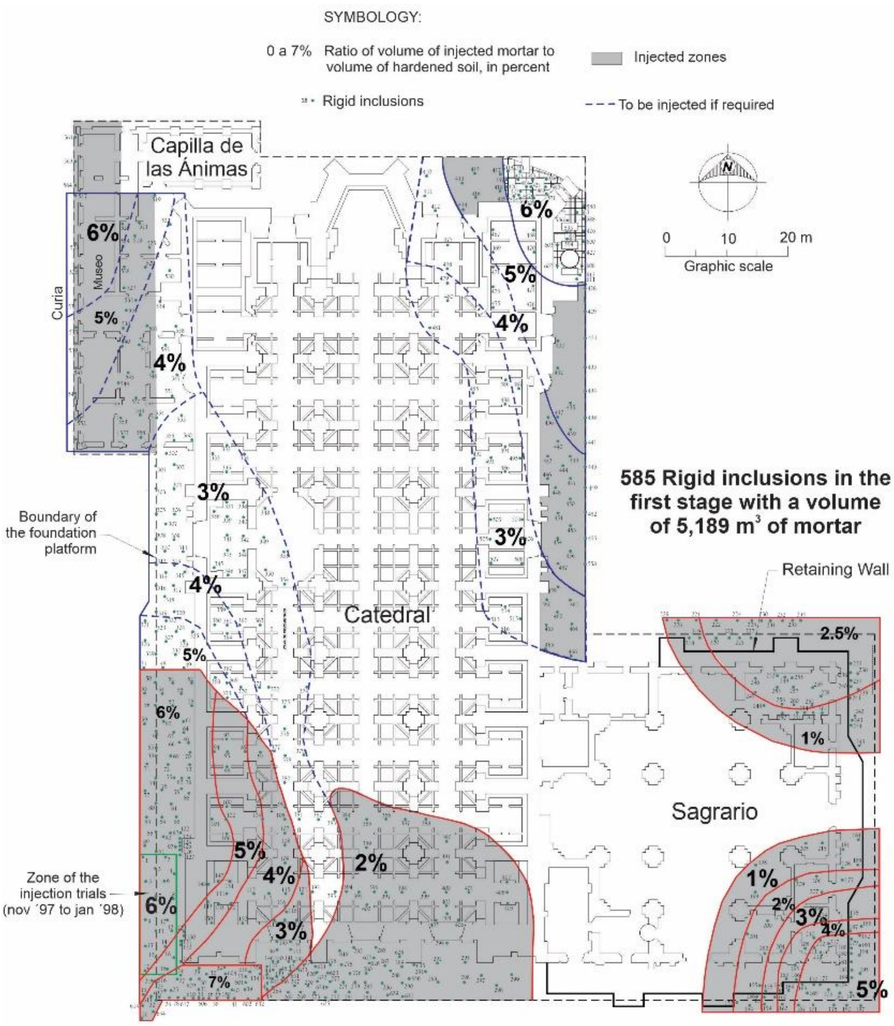

Figure 1. Injection of the subsoil of the Cathedral and the Tabernacle (September 18, 1998 – January 4, 2002)

Figure 2a illustrates the initial behavior, represented by the annualized subsidence rates observed between January 7 and September 2, 1991. The data shows that the central section of the Cathedral experienced a relative heave of 17 mm/year with respect to the northeast corner, and 15 mm/year relative to the West Tower. In the Tabernacle (Sagrario), the maximum vertical movement occurred at the southeast corner, reaching 16 mm/year relative to benchmark C-3 located near the Cathedral's apse.

Behavior between August 2, 2018, and June 3, 2020. The annualized rates of cumulative differential subsidence for this period are presented in Fig. 2b. The results indicate that, in general, the Cathedral's perimeter is now subsiding at a slower rate than the primary reference point (C-3).

A similar trend is observed in the southern section of the Tabernacle, where subsidence rates have slowed significantly. A zero differential was recorded in this area, representing a 100% reduction compared to the 20 mm/year differential observed at the southeast corner in 1991.

At the Museum, the settlement rate decreased by 80%, dropping from 26 mm/year in 1991 to just 5 mm/year during the most recent monitoring period.

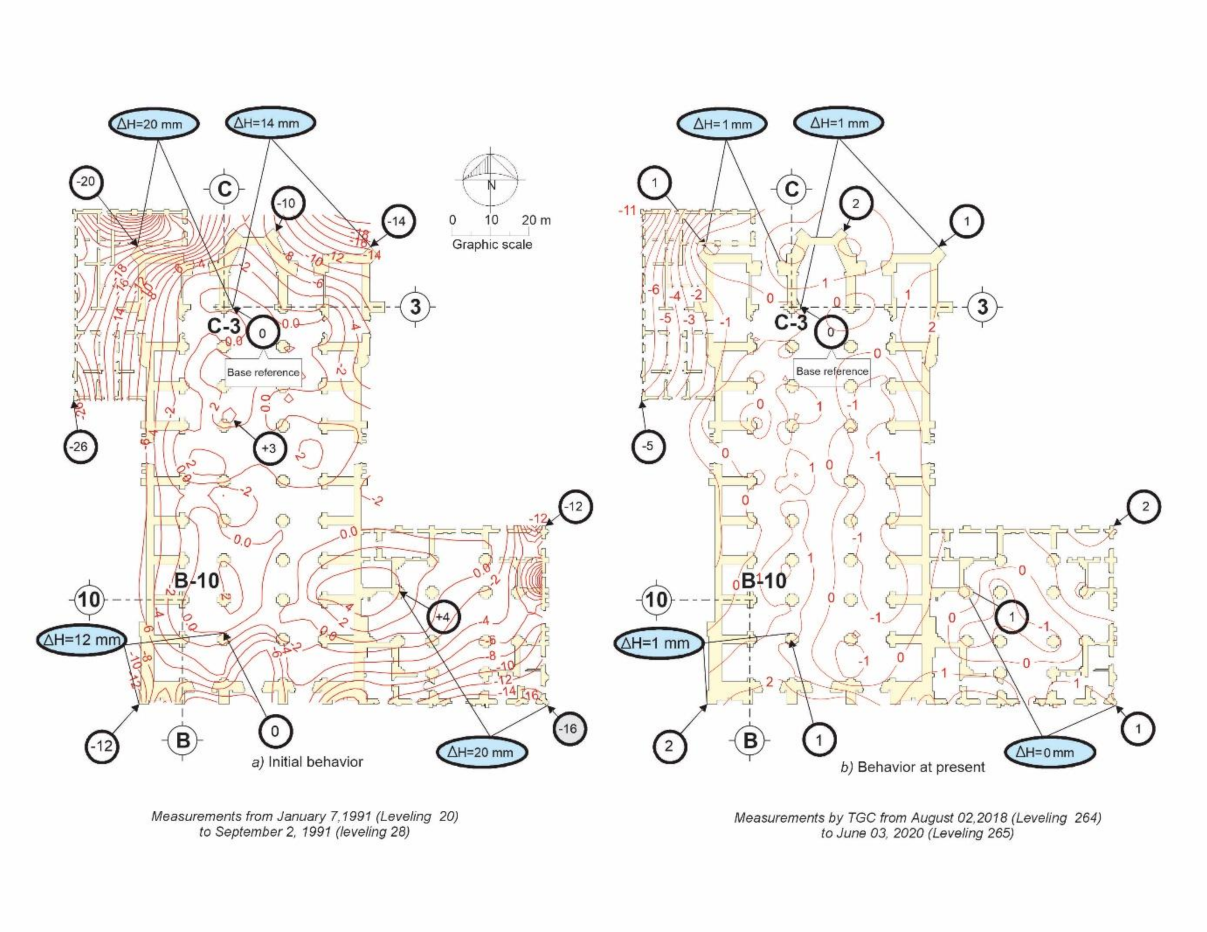

Figure 2. Comparison of annual subsidence rates in mm

b) Temple of Saint Augustine and Chapel of the Third Order

To mitigate the effects of regional subsidence on the Temple of San Agustín and the Chapel of the Third Order—and thereby reduce the magnitude of future settlements and structural failures—various geotechnical solutions were evaluated. Based on these analyses, and considering both technical and economic constraints, the optimal solution identified was ground improvement via mortar injection. This technique follows the precedent set in 1910 to correct the subsoil behavior of the National Theater (now the Palace of Fine Arts).

The application of this methodology at San Agustín began by mapping the subsoil zoning based on clay deformability. The volume of injected mortar was proportional to the deformability distribution within the subsoil; generally, zones of higher deformability required a higher volume of injection.

To address this challenge, a differential subsoil reinforcement strategy was proposed for the Temple and Chapel using vertical mortar inclusions and grout curtains (sheets). Influenced by the specific stress conditions at each site, these form a composite arrangement of soft clay strips and mortar sheets.

A general summary of the subsoil treatment for the Temple of San Agustín and the Chapel of the Third Order is provided in Table 1. The process involved installing injection points to form columns (pillars), followed by the creation of mortar sheets facilitated by sleeve tubes located on the sides of the pillars. The injection rate is defined as the volumetric ratio of mortar to the treated soil mass. This ratio, expressed as a percentage, is calculated as a function of the soil's initial deformability.

Table 1. Injection volume and number of inclusions in each stage

Stage	Injection dates	Num. of inclusions	Volume of mortar injected (m^3)
First	February – April 1999	86	846
Second	October 2001 – February 2002	27	496
Third	February 2002 – March 2002	----	130
Fourth	January 2012 – May 2012	158	335
	Total	***271***	***1807***

The four stages of the phased treatment are illustrated in Figure 3. For simplicity, the Temple and the Chapel were divided into several sectors; the primary injection focus was concentrated on the west side of the Chapel, gradually decreasing toward the east side of the Temple.

During the first stage, a maximum injection ratio of 4% mortar by volume was applied, which was subsequently increased to 6% during the third stage.

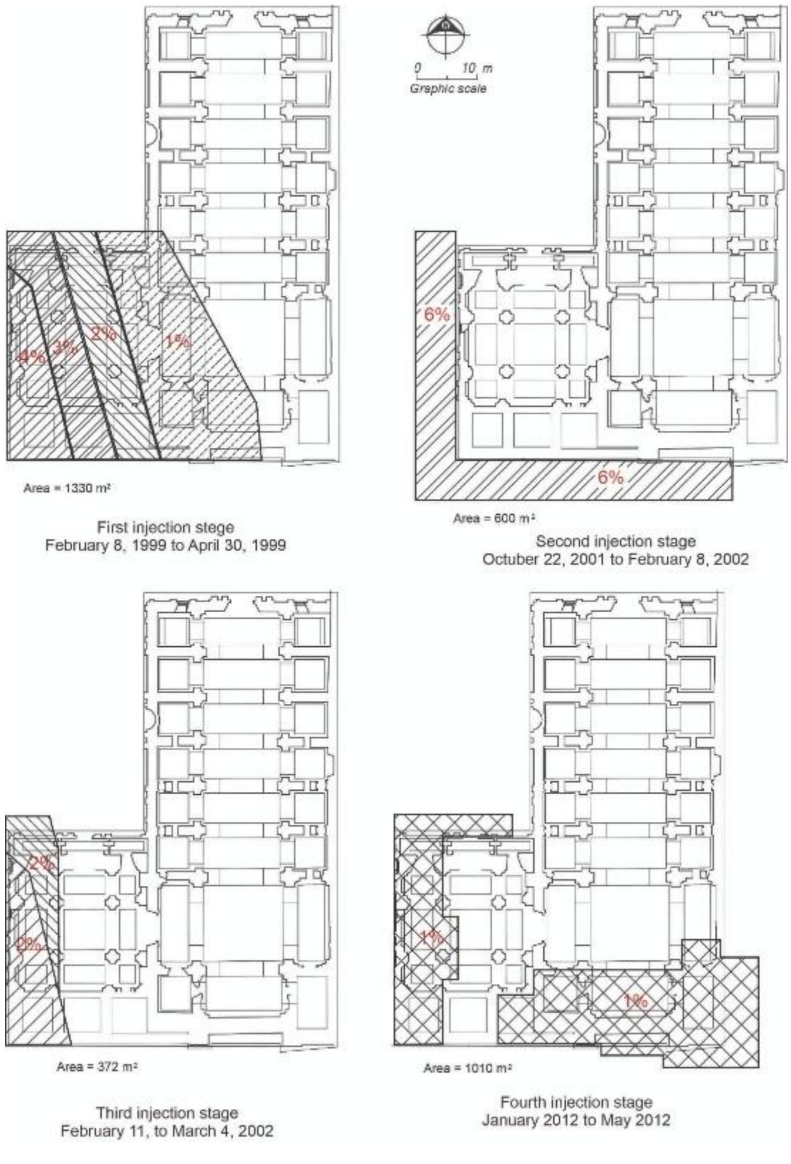

Figure 3. Injection areas carried out during the four stages.

The results of the latest leveling survey, conducted in April 2015, are presented below. To illustrate the subsoil's response to the interventions, the deep leveling benchmark (BNP-100)—installed in the northwest corner of the former temple's garden—was used as the primary reference Point.

Initial Configuration. Figure 4a graphically displays the isovelocity curves. Between September 9, 1978, and September 20, 1995, the maximum differential settlement velocity reached 14.7 mm/year, trending toward the southwest corner of Chapel of the Third Order.

Current Configuration (April 2015 – December 2017). Analysis of Figure 4b shows that the maximum differential subsidence rate in the old temple has decreased to 1 mm/year, occurring at the center of the structure. The joint between the two structures subsides at a rate of 3 mm/year relative to point P-9 (intersection of axes B-5). In relation to this same point, the southwest corner of the Chapel (I-15) exhibits a differential rate of 4 mm/year.

Comparative Analysis. Comparing these figures, it is evident that as of December 2017 (Figure 4b), both temples continue to subside, but at a significantly slower and more controlled rate, as anticipated. These results confirm that the installation of rigid inclusions in the subsoil has positively modified the subsidence patterns for both the Temple and the Chapel.

Specifically, the rate of differential settlement has been drastically reduced. For example, the relative subsidence between axis A-5 and the southwest corner of the Chapel (I-15) dropped from 14.7 mm/year in 1995 to 4 mm/year in 2017—a 70% reduction in settlement velocity.

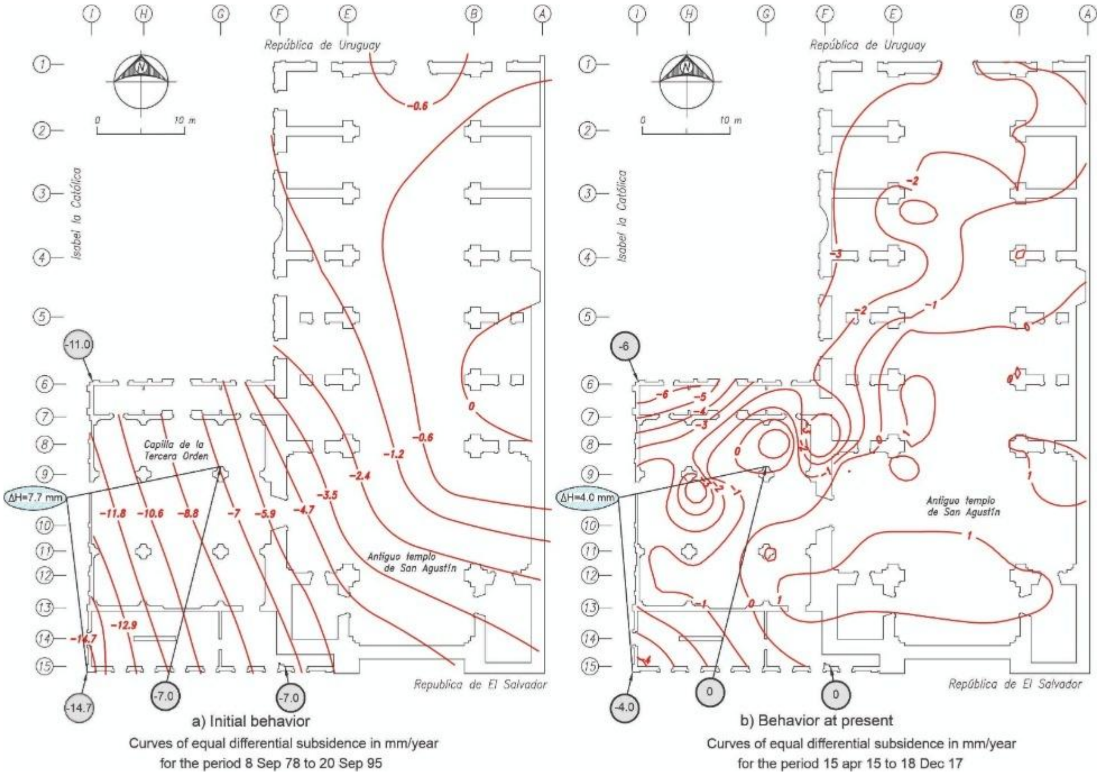

Figure 4. Comparison of annual subsidence rates

Based on the data presented, it can be concluded that the installation of rigid inclusions in the subsoil has positively modified the subsidence patterns of both the Temple and the Chapel, significantly reducing differential subsidence rates. A clear example of this effectiveness is the relative movement between axis A-5 and the southwest corner of the Chapel (I-15), which decreased from 14.7 mm/year in 1995 to 4 mm/year in 2017, representing a 70% reduction in settlement velocity.

CONCLUSIONS

Recent developments in the differential subsidence of the Cathedral and the Tabernacle (Sagrario) demonstrate that mortar injection into the subsoil has yielded significant beneficial effects on the structural condition of these temples. The current plinth level configurations clearly indicate that historical subsidence patterns have been favorably modified.

When comparing the annualized differential settlement contours, the impact of the four subsoil improvement stages at the Temple of San Agustín is evident. From September 1978 to September 1995, the maximum differential settlement rate was recorded at the Chapel of the Third Order, reaching 14.7 mm/year; however, between April 2015 and December 2017, the Chapel exhibited significantly reduced differential movement. In the case of the former temple, the differential subsidence was successfully redistributed toward its four corners.

The data and analyses presented in this paper demonstrate that subsoil hardening is the most effective alternative for ensuring the preservation of these monuments. Recent monitoring data supports the conclusion that ground hardening represents the definitive long-term solution to the geotechnical challenges afflicting these historic structures.

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