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GEOTECHNICAL BEHAVIOR OF THE CATHEDRAL AFTER 10 YEARS OF THE INTERVENTION OF SUBSOIL

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Abstract. *In the year 1989 is advised damage in the vaults of the Cathedral of Mexico city, this alerted on the structural risk having the monument by the large differential settlements accusing; in that year the geotechnical exploration of subsoil began to understand differences in the compressibility of soft clay and establish the unusual geotechnical model of its subsoil allowing to predict the magnitude of future deformations. In addition were carried out topographic and structural measurements, allowing to know the dimensions and inclinations of the structural elements. Based on the results of the Geotechnical study and analyze the evolution of the interstitial water measured groundwater changes, the inclinations of columns and walls was deducted in next 50 years period would increases. This information persuaded the authorities to intervene the subsurface through two actions: a) a corrective that consisted the underexcavation of Cathedral's and El Sagrario foundations, and b) other preventive to generate selective tightening of the subsoil, which was achieved with the establishment of rigid inclusions and injection of mortar by hydraulic fracturing. Underexcavation works began in August 1993 and concluded in June 1998; Hardening subsoil began in 1998 and concluded in 2001. From 2001 to date both temples have continued observing it instrumentally in this article are presented and discussed the most significant results of these topographic measurements taken between 2001 and 2012, which confirm the beneficial effects both the under-cutting and hardening of the subsoil, which constitutes an important example that is being applied to other monuments of the architectural heritage of Mexico city.*

1 PAST HISTORY

Constructing Mexico City's Metropolitan Cathedral on extraordinarily soft soil was a formidable challenge back in 1573, when the building was started. Its creators took advantage of the experience gained by the Aztecs during construction of their Major Temple. In the case of the Aztecs, to the Mesoamerican tradition of superimposing new pyramids over the old ones during the festivities of the New Fire, they incorporated the practical need of adding successive construction stages to their buildings with the implicit purpose of concealing damage produce by differential settlements. Master builder Claudio de Arciniega conceived an outstanding foundation for the Cathedral but even so settlements occurred during the construction of the massive building compelled the succeeding architects to incorporate architectural ingenuity to mask misalignments. In 1630, Juan Gómez de Trasmonte erected the vaults and the transept. Luis Gómez de Trasmonte was appointed in 1656 to build the main dome. He was uncertain about the load bearing capacity of the transept columns and his suggestion of enlarging them was not followed. Lorenzo Rodríguez constructed the Sagrario (parish church) starting in 1749 and he adopted a similar foundation system, but with a lesser quality. Damian Ortiz de Castro decided to repair the San Miguel chapel so it could bear the weight of the western bell tower and also began constructing the campaniles in 1780. Manuel Tolsá completed the Cathedral in 1813 after harmonizing the building and embellishing the dome. The long-lasting construction process took 240 years.

The Cathedral has five naves: the central one bounded by 16 columns and divided by the choir; the two processional aisles running along the length of the church; and the two lateral ones occupied by chapels, that are in turn confined by the peripheral and perpendicular walls. The great central dome, 65m high, is supported by four columns. The two huge and heavy towers are 60 m in height. The church is 60.40 m wide, about 25 m high along the central nave and 126.67 m long with a total weight of 12,700 kN and an average contact pressure of about 166 kPa. The adjacent Sagrario is a church with a Greek cross layout whose walls at the four corners provide support to the vault; its dome rests on four columns. It covers a square area of 47.7 m by side, weighs about 3,000 kN and the average contact pressure is about 132 kPa.

The Cathedral and the Sagrario church have survived up to now thanks to restorations that have taken place over more than 300 years. Interventions have been increasingly complex due to the accumulation of structural damage and inclination, and the exposure to ever higher differential settlement rates. It is more than seven years now since the end of the Project for the Geometrical Correction of the Cathedral and the Sagrario Church and for hardening its subsoil. It is very satisfactory to be able to state that, as verified with field measurements, the behavior of the religious complex improved very favorably after the successive application of underexcavation and selective soil hardening.

2 UNDEREXCAVATION AT THE CATHEDRAL AND THE SAGRARIO

The purpose of applying this technique was to reduce differential elevations and tilting induced by differential settlements. It involves lowering the high parts with respect to the low points through the slow and controlled extraction of soil from the bearing strata. Three specific tasks are necessary to apply the method: a) the construction of access shafts; b) the punctual drawdown of the phreatic level; and c) underexcavation or controlled extraction of small portions of soil until removing a pre-established volume. The two first operations are preliminary; the third one constitutes the corrective geotechnical procedure itself.

Underexcavation details. The extracted soil was from the soft clay located at the boundary of the Upper Clay Formation, the morphology of which is illustrated in Figure 1. In each shaft a maximum of 50 radial borings penetrated into the soil in lengths ranging from 6 to 22 m. Figure 2 shows the layout of the shafts, an illustrative cross section of one of them and a profile of the lengths penetrated with underexcavation, as well as a sketch of the closure of the borings to induce the required settlements. Soil was extracted from the bottom of the shafts driving steel thin walled samplers with a hydro-pneumatic cylinder. Boreholes 10 cm in diameter were inclined 20º and a remolding tool was sometimes used to accelerate their closure.

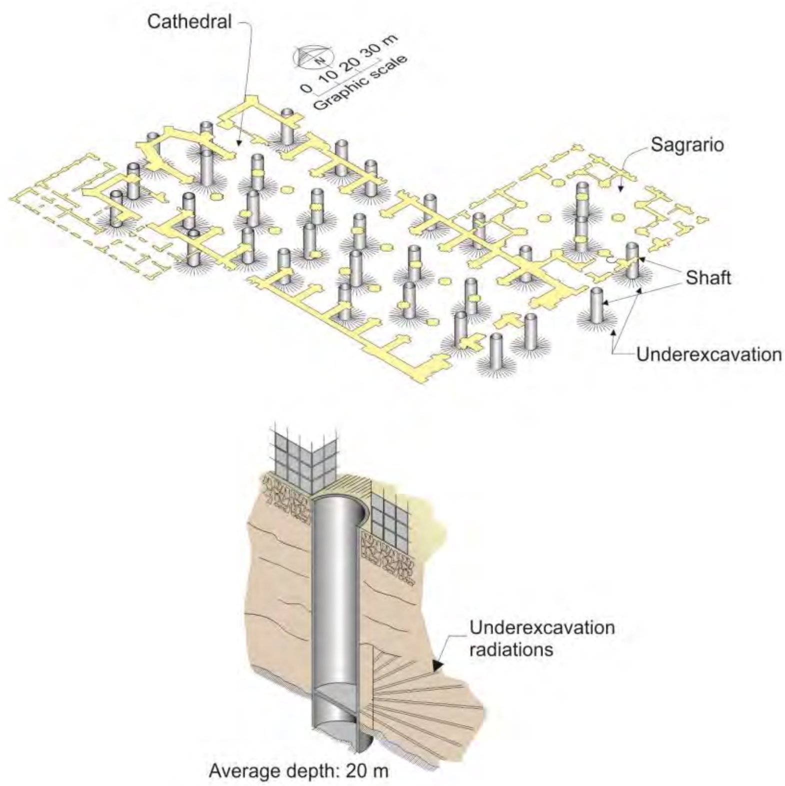

Figure 1 Shafts for the underexcavation process

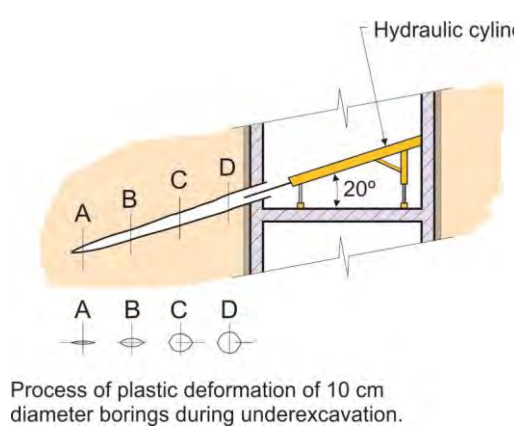

Figure 2 Process of plastic deformation

Correction targets. Figure 3 shows the targets to be achieved by applying the underexcavation method. One of them was proposed by Dr. Fernando López Carmona, and the other one by Dr. Roberto Meli Piralla who performed, respectively, graphic-analytic and numerical structural analyses. The correction targets derived from these analyses are:

a) To close and rotate the lateral walls in order to strengthen the "confining belt" formed by the walls along the perimeter of the temple and along the sides of the chapels.

b) To lower the Cathedral's apse 80 to 95 cm, in a rigid body movement.

c) To lower the Sagrario's north side 30 cm in a rigid body movement.

A geometrical control model, with a one millimeter precision, was devised to program these fundamental goals. The model was compared step by step with routine topographical measurements at the parishioners' level and with convergence measurements and conventional and electronic plumbs.

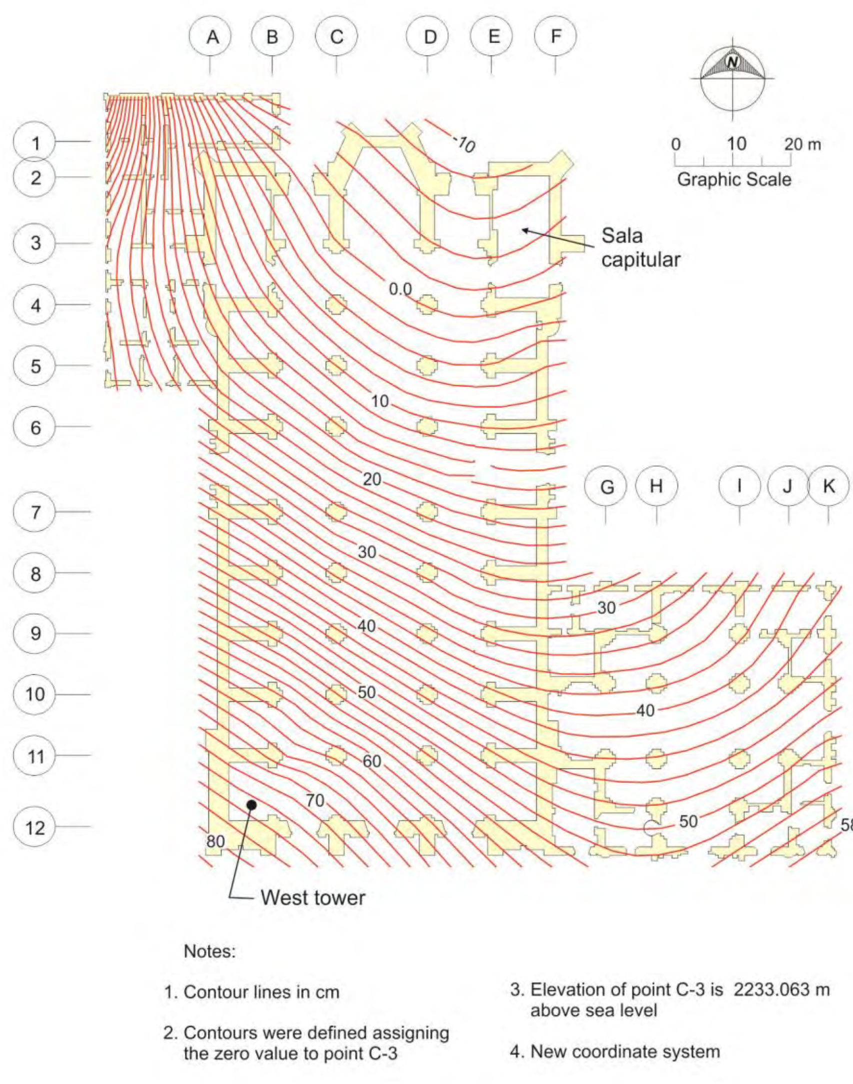

Figure 3. Differential correction between levelings 1 and 203 performed by TGC (25/oct/91 – 20/sept/99)

Structural bracing. Underexcavation was executed with the assistance of a complex preventive bracing system to control any unexpected deformations and to prevent any structural damages. This system operated during the whole process to adjust it to the gradual changes induced and without ever supporting the totality of its design load.

Underexcavation control. In the process of underexcavation, the weight and the moisture content of the material extracted were accurately and rigorously monitored; unaltered soil samples were also retrieved for laboratory testing to obtain their mechanical properties. Soil extraction began in 3 August, 1993, and finished in June, 1998; 4,220 m were removed in about 1,451,000 extraction operations. Underexcavation stopped once the structural targets of the project were achieved and, thus, the religious complex was once again exposed to the action of differential settlements of the subsoil.

Differential settlements accumulated over the previous 65 years as a result of regional subsidence were basically eliminated through underexcavation by the end of June 1998. When the treatment was completed, the maximum correction induced was 92 cm, between the apse and the southwestern corner.

Structural damages . Underexcavation initially induced movements to recover the confinement provided to the vault by the walls, which can be proved because measurements showed that the vault rose a few centimeters. The underexcavation sequence was adjusted later to produce a second type of movement, rigid body displacements towards the northeast. Corrective settlements contributed to the closing of the cracks and to reducing tilts in columns. However, new cracks developed and others that already existed widened. Also, an ashlars stone fell off a window and plastering dropped from some points as well.

Nonetheless, damages were considerably smaller than those expected at the beginning of the project.

3 MORTAR INJECTION UNDER THE CATHEDRAL AND THE SAGRARIO CHURCH

However, as seen in Figure 3, towards September 1999 the maximum corrective settlement reduced to 88 cm and to 30 cm at the Sagrario. This difference from 92 to 88 cm is due, as discussed previously, to the fact that upon the end of underexcavation and the stoppage of the pumping operations, the effects of regional subsidence returned and, as a result, part of the corrective settlements that had been achieved was lost. Historical differential settlement between points C-3 and B-11 changed from 243 cm in 1989 to 174 cm in June 1998. The angular correction between these two points was 26.3'.

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 rock fill, 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, Figure 4.

Drilling techniques. In view of the complexity of the structures and their foundations, it was necessary to use several drilling equipments. Pneumatic and electric drilling rigs were adapted to be used within the narrow aisles of the crypts. Some of them were mounted on mobile bases to facilitate their transportation. Referring to the drilling tools, pneumatic bottom hammers, tri-cone bits, simple drag bits, and reamers were used at the depths where the holes would be grouted. In drilling from the atrium, heavy rigs mounted on vehicles were used; only at certain stretches was ski-mounted equipment utilized. Perforations were dug with a procedure similar to that used at the crypts, but with a somewhat larger diameter.

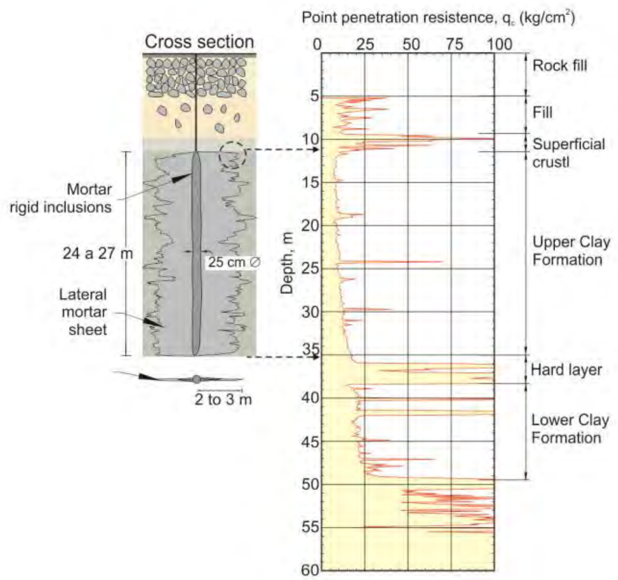

Figure 4. CPT sounding to define the injection depth

First soil hardening stage. It was performed between September 1998 and September 1999. It can be observed in Figure 5 that grout percentages vary from 2 to 7%at the Cathedral and from 1 to 5%at the Sagrario. The inclusions were introduced in the Upper Clay Formation as follows: 419 at the Cathedral, 111 at the Sagrario, and 55 at the Curia Building. The Cathedral's southwest corner and the northeast south east corners of the Sagrario were grouted form 8 September 1998 to 4 June 1999. The Cathedral's southwest corner was injected in two stages, applying about 50 % of the total amount in each. Later, from 7 June 1999 to 9 September 1999, the south zone received an injection of 2 %. Distribution of mortars was decided taking into account the compressibility based zoning of the subsoil.

Second soil hardening stage. It took place from May to June 2000 and was complemented with injections that were carried out between 9 November and 22 December that year and with those made in the museum from 2 November 2001 to 20 January 2002. A total of 585 inclusions were cast in the soft clays, together with their respective assemblages of lateral sheets. The total volume of injected mortar was 5,189 m^3.

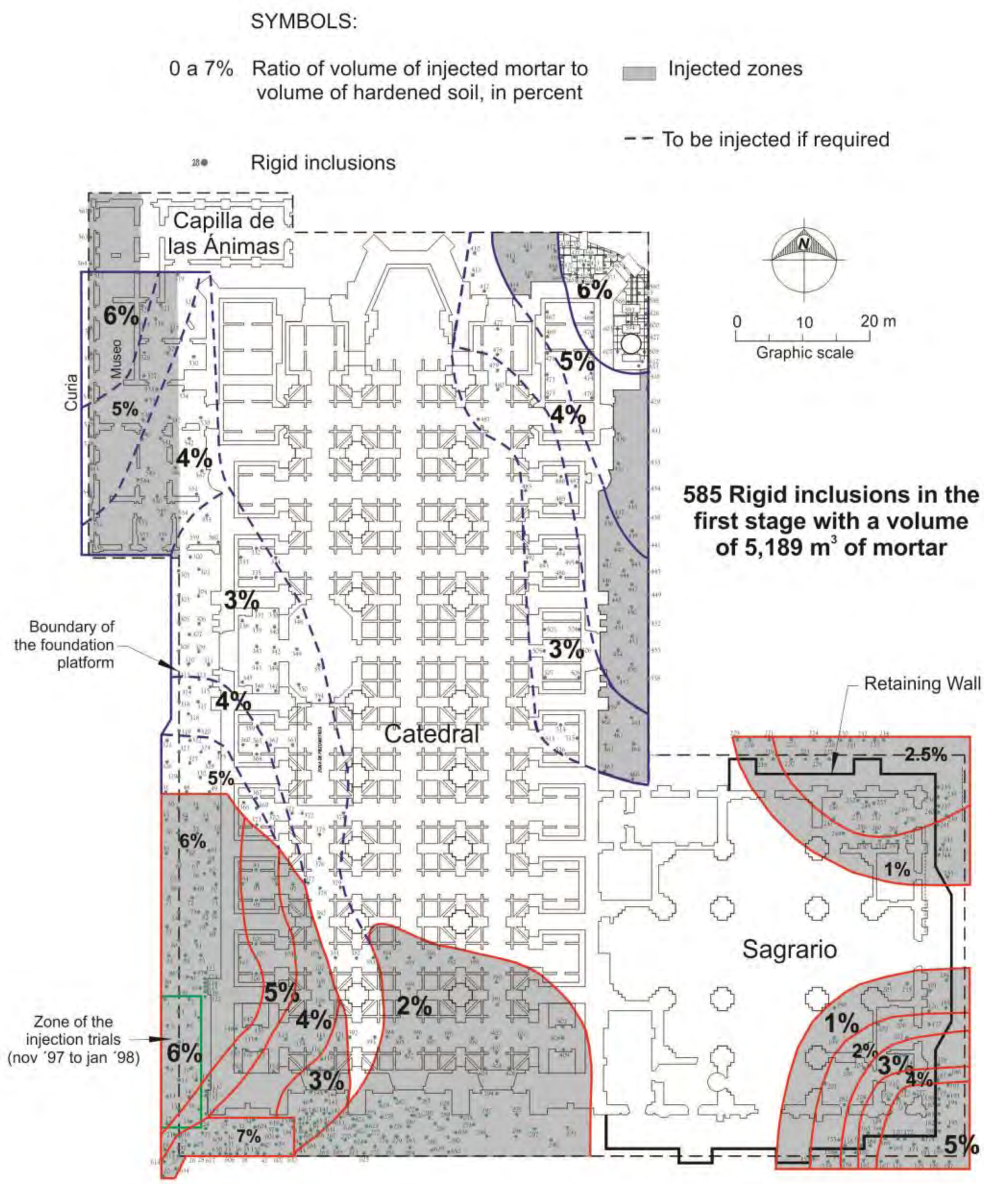

Figure 5. Subsoil grouting under the Cathedral. First stage: Sep 98 to Sep 99; second stage: May to July 2000

4 OBSERVED BEHAVIOR

In applying the Observational Method, the structural behavior of both the Cathedral and the Sagrario church was monitored rigorously using a large number of measuring instruments. Soil response was evaluated mainly from high precision topographic surveys.

Precision topographic surveys . These measurements were made at 246 control points distributed over the whole area covered by the monument. Column and pilaster plinths as well as chapel walls were leveled, including reference steel bolts embedded in the outer walls. Points were located at the walls of the Capilla de las Animas and of the Curia, at the atrium fence bars, and at the top of the deep benchmarks. These levelings were carried out every two weeks from October 1991 to the end of 1999; it was subsequently decided to schedule them monthly. A total of 215 levelings were made as of August 2000. Three levelings per year were done afterwards, until 2004. Two levelings were made in 2005 and none in 2006; one leveling was made since 2007 to 2009; and the last survey was made in October 2012 which added up to a total of 262.

Settlements accumulated since the beginning of the project in October 1991 and since the start of underexcavation in August 1993 were reported graphically by means of contours lines. Differential settlements produced every 28 days were also presented graphically. During the leveling, the zero curve corresponds to the historical reference: a point located at the apse, at the intersection of axes C and 3, in the west side of the Altar de los Reyes. It was therefore possible to obtain the differential movements with respect to this point. All leveling are referred to a deep benchmark installed at a depth of 100.4 m below the surface (BNP-100) and are correlated to the Atzacoalco Benchmark. The movements recorded are the combination of those induced by regional subsidence and those produced by the effects of the corrective and preventive actions discussed and described before.

Effectiveness of soil grouting for hardening purposes. The effectiveness of subsoil grouting can be evaluated by comparing settlement rates at the Cathedral and the Sagrario before and after injecting mortars. Figure 6 shows a picture of the initial behavior expressed graphically by plotting settlement rates observed between January 7 and September 2 of 1991. It can be observed that the central part of the Cathedral emerged with respect to its northeast corner, at a rate of 16 mm/year, and with respect to the western bell Tower at 14 mm/year. The Sagrario shows a maximum settlement rate at its southeast corner of 16 mm/year with respect to point C-3, located close to the apse of the Cathedral, and 20 mm between the southeast corner and the northwest columns.

The behavior in October 2012 is presented in Figure 6. From the analysis of this graph it can be inferred that the Cathedral is still sinking but that it is settling almost uniformly, as expected. From the direct comparison of the graphs in that figure, two conclusions can be derived: a) injection of mortar grouts into the subsoil modified positively the pattern of settlement rates; and b) this modification was beneficial for the structures because it achieved a substantial decrease of differential settlement rates.

For example, relative differential settlement between point C-3 and the southwest corner passed from 12 mm/year in 1989 to 1 mm/year in 2012. Overall, differential settlements in this last year were, on average, only 12 % of those existing in 1989, at the onset of the project.

Settlement distribution within the soil. Deep bench marks, 40, 60, 80 and 100 m deep, were installed in the Cathedral's atrium with a twofold purpose: a) to measure total settlements, and b) to determine the distribution of settlements within the subsoil. These benchmarks are constructed with twin concentric pipes. The internal one act as a reference mark and therefore it is continuous and rests at the selected depth. The external pipe is compressible and, hence, it absorbs axially the vertical deformations undergone by the soil between the surface and the depth of the benchmark. The inner tube remains free, i.e. it is not affected by buckling as are conventional bench marks built with rigid outer pipes. Friction forces acting against the inner pipe are in fact eliminated.

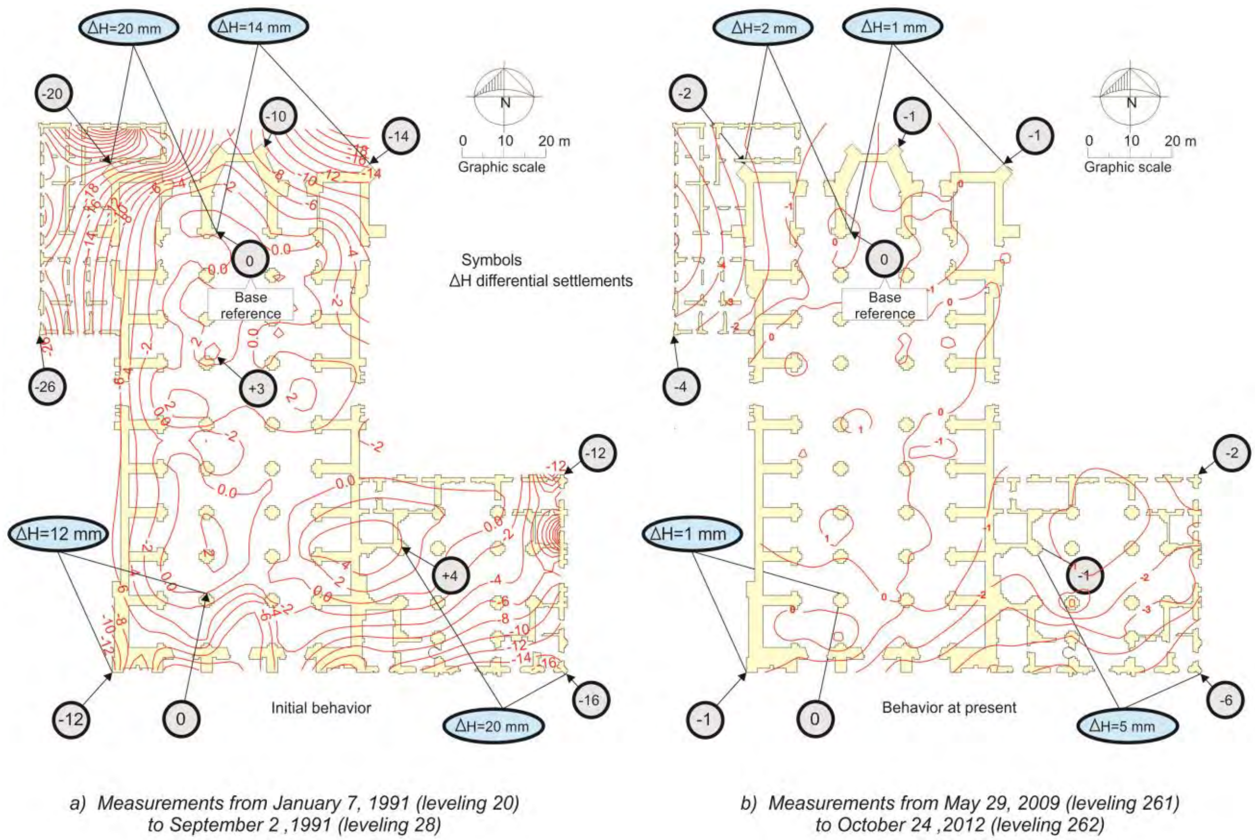

Figure 6. Comparison of annual subsidence rates in mm

Settlements measured at the deep benchmarks are shown Figure 7 as well as the contribution in percentage of the major compressible strata to total settlements. In 1991 before geotechnical work in the Cathedral began, the Upper Clay Formation contributed with 54 %, the Lower Clay Formation and the deep silty clays of the former third lake, with 46 %; settlements below 80 m were nil. At the time those data were disquieting because they proved wrong the ancient hypothesis that considered that the compression of the uppermost clays was the sole contributor to regional subsidence. The measurements of October 2012 are even more alarming because they show that the Upper Clay Formation contributed with 7 %; 93 % took place below those clays and 69% is occurring below 100 m.

5 CONCLUSIONS

Underexcavation at the Cathedral and the Sagrario started in August 1993. The preliminary goal was defined by Dr. Fernando López Carmona; subsequently, this goal was modified in 1994 by Dr. Roberto Meli. The geometrical correction achieved satisfies both proposals. Once the underexcavation complied with the correction objectives established by the structural advisors of the project, the Advisory Technical Committee decided to conclude it in May 1998. Vertical corrective settlements after almost five years stabilized at a maximum of 88 cm.

The need to prevent the long-term effects of regional subsidence justified the application of mortar injections. The implementation of this method of subsoil hardening under the Cathedral was based on theoretical and experimental studies in the field and in the laboratory.

Recent evolution of differential settlements sustained by the Cathedral and the Sagrario has demonstrated that mortar injection of the subsoil had beneficial effects on the behavior of both churches. Settlement contours at the level of the plane of plinths confirm that historic settlement patterns were most favorably modified.

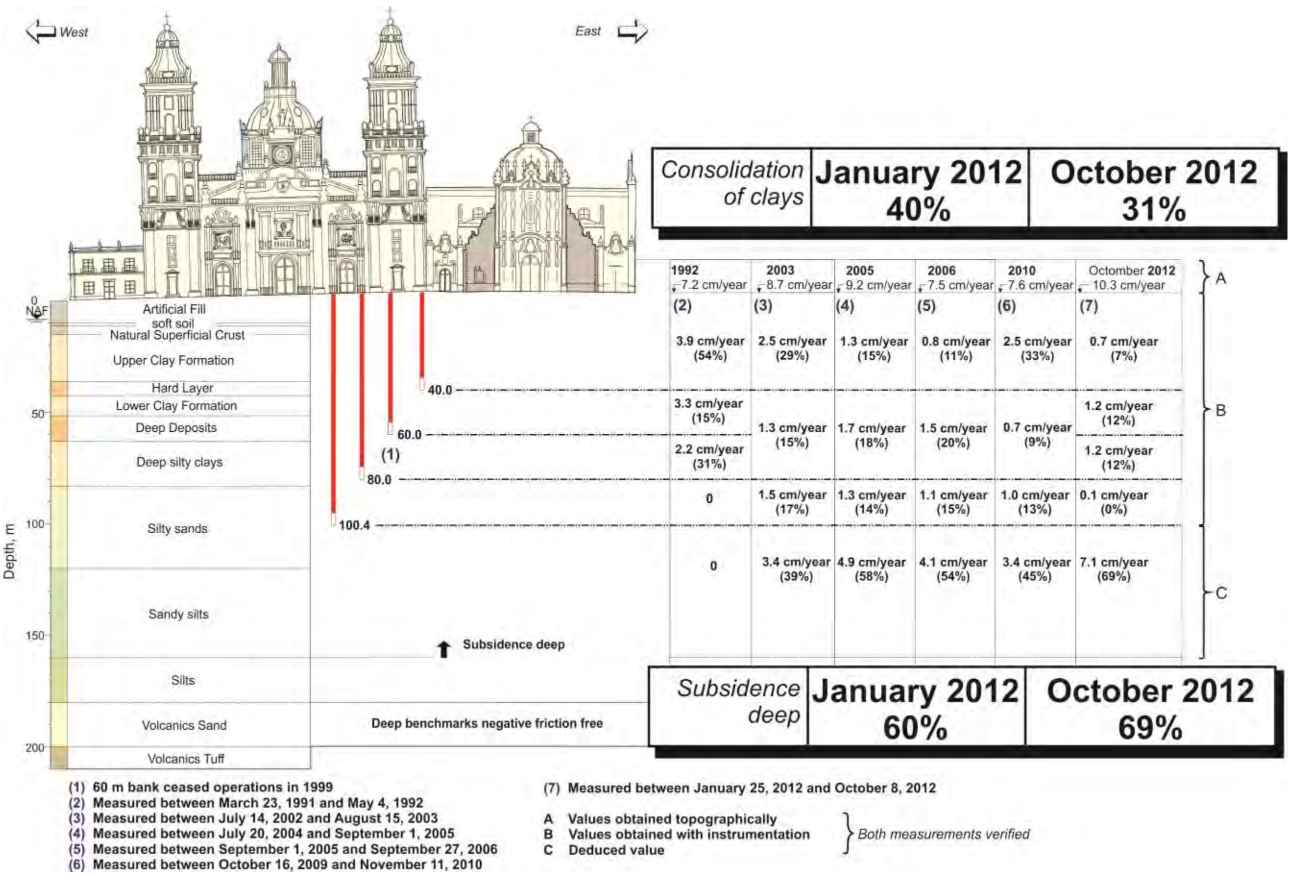

Figure 7. Annual settlement distribution between 1991 and 2012 in the Cathedral

6 ACKNOWLEDGEMENTS

Sergio Zaldívar, architect, headed the project since it began in 1989 until 2000; Dr. Xavier Cortés Rocha took over the direction of the project afterwards. Member of the Technical Committee that overlooked the development of the project are duly acknowledged: Dr. Fernando López Carmona, Dr. Roberto Meli, Dr. Enrique Tamez, Ing. Enrique Santoyo Villa, Ing. Hilario Prieto. Dr. Jorge Díaz Padilla acted as secretary for the committee and as consultants, Dr. Efraín Ovando Shelley and Ing. Roberto Sánchez.

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