Zeitschrift: IABSE reports = Rapports AIPC = IVBH Berichte

Band: 70 (1993)

Artikel: Leveling and protection at the Metropolitan Cathedral in Mexico City

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DOI: https://doi.org/10.5169/seals-53352

Leveling and Protection at the Metropolitan Cathedral in Mexico City

Compensation des tassements et sauvegarde de la Cathédrale de Mexico

Hebung und Schutzmassnahmen an der Kathedrale von Mexiko-Stadt

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SUMMARY

The Metropolitan Cathedral in Mexico City, one of the most important architectural monuments in the Americas, is built on extremely soft lacustrine clays, over many remains of the ancient City of Tenochtitlan. From the earliest stages of its construction, the cathedral has been affected by ongoing differential settlements due to a heterogenous process of consolidation within the clay deposits. Remedial actions are all intended to counteract the effects of deformations induced in the cathedral as a consequence of this consolidation process.

RÉSUMÉ

La Cathédrale de Mexico, un des plus importants monuments d'architecture dans les Amériques, fut construite sur des argiles lacustres extrêmement tendres, au-dessus des restes de l'ancienne Ville de Tenochtitlan. Dès le début de sa construction, la Cathédrale a été affectée par les problèmes de tassements différentiels, dûs aux processus de consolidation hétérogène des dépôts d'argile.

ZUSAMMENFASSUNG

Die Kathedrale von Mexiko-Stadt, eines der bedeutendsten Baudenkmäler Amerikas, wurde auf extrem weichen, tonigen Seeablagerungen gebaut, auf den Resten der antiken Stadt Tenochtitlan. Seit Baubeginn führte der ungleiche Konsolidierungsprozess im Ton zu Setzungsunterschieden. Die Sanierungsmassnahmen konzentrieren sich auf den Ausgleich der sich an der Kathedrale zeigenden Folgen der Deformationen.

INTRODUCTION

Construction of the Metropolitan Cathedral started during the second third of the XVIth century, from 1573 and was concluded at 1815, over some of the remains of ancient constructions of the prehispanic city of Tenochtitlan. The cathedral, one of the most important architectural monuments in the Americas, was built over a masonry platform about 1.2 m thick which was itself founded on a mass of wood short stakes separated some 60 cm, having a diameter of 20 cm and lengths of 2.5 to 3.5 m. This foundation system was borrowed from existing prehispanic technology. The total weight of the structure is about 127 344 t, and the pressure transmitted to the subsoil is in the order of 12.2 t/m^2. The building is made of volcanic masonry rock; its plan dimensions are 66.36 x 122.26 m it has five naves, a central dome and two bell towers, 60 m high.

The Metropolitan Sagrario parish church, adjacent to the Cathedral, was built between 1749 and 1768. It is also founded on a volcanic rock masonry plataform wich is partly superimposed on the Cathedral's, in its western side. The remainder of the plataform rests on 30 cm thick mortar bed made out of lime and sand wich was placed upon at thin layer of charcoal; on this layer, a mass of wooden stakes, 8 to 12 cm diameter and 2.5 m in length and separated about 1.8 to 2 m each, is set. The weight of this church is 22,500 t and pressure transmitted to the subsoil is about 10 t/m^2. Its footprint is 47.20 m wide and 47.77 m long.

Aztec buildings were also constructed over artificial fills, which consolidated the underlying upper clay strata (fig. 1).

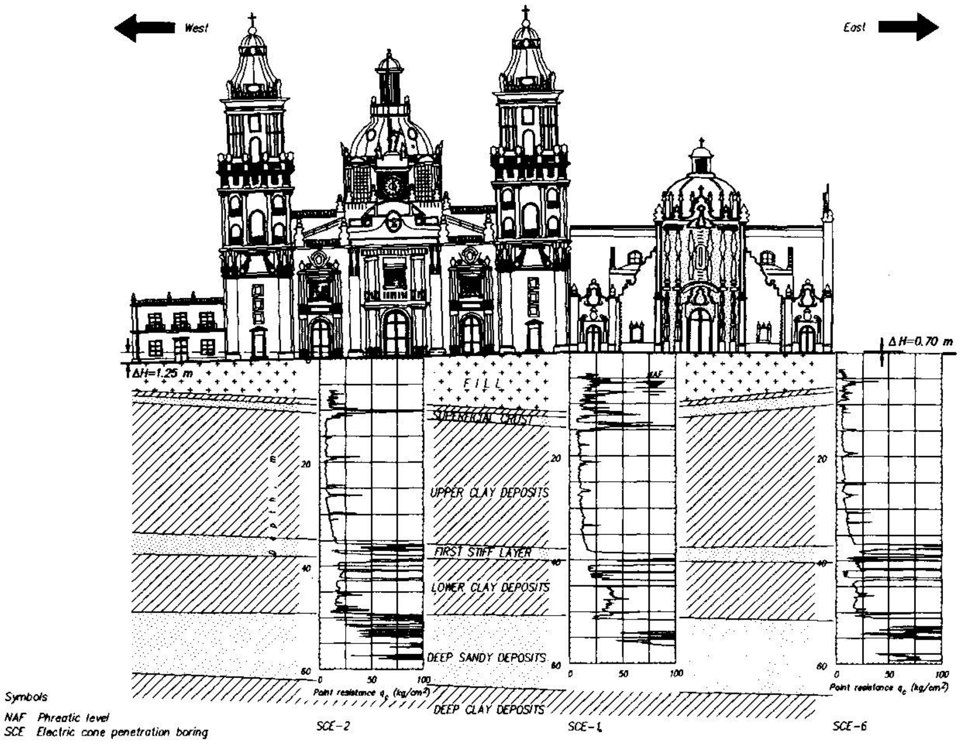


FIG 1 STRATIGRAPHY AT THE SITE AND DIFFERENTIAL SETTLEMENTS AT GROUND LEVEL

Considerable variations appear in the platform thickness, apparently caused by differential settlements that started to occur from the very beginning of the construction. The Cathedral has continued to be affected by ongoing differential settlements. This condition can be verified by architectural adjustments and corrections performed in some of its parts; among these are columns of different higths and wedged masonry layers, such as those found between the first and second windows of the west side tower, which were used to compensate for differential settlements. The continuous differential settlements are well documented since the end of last century.

This paper describes the actual conditions of the Cathedral and the measures adopted to save it, based upon the results of a comprehensive field investigation program. The job is being carried out by a group of the most outstanding mexican profesionals, which I have the honor to lead; they are Messrs. Enrique Taméz, Enrique Santoyo, Fernando López Carmona and Roberto Meli.

THE PROBLEM

In April 1989, severe cracking along the building southeast-northwest direction, revealed that alarmingly large settlements were taking place in the Cathedral. A review of all topographic surveys, as well as of all previous actions taken to mitigate the effects of differential settlements followed; the effects of the construction of a subway and a circular drainage tunnel built in front of the Cathedral were also considered. Surveys performed in 1907 revealed the existence of a differential settlement of more than 1.5 m between the apse and the west tower; in 1972, this settlement reached 2.2 m (fig. 2) and exceeded 2.4 m in 1990. Between the two towers, differential settlements are presently 1.25 m. The Sagrario church has tilted easterly and settled more than 90 cm differentialy with respect to the Cathedral.

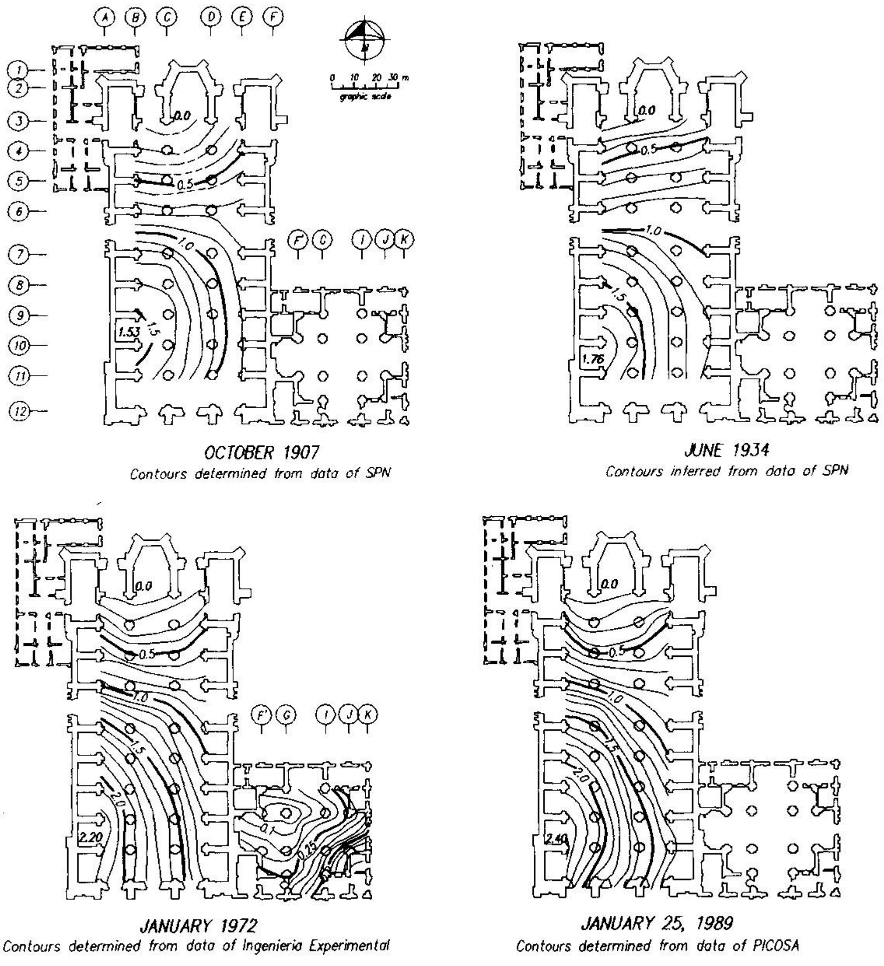


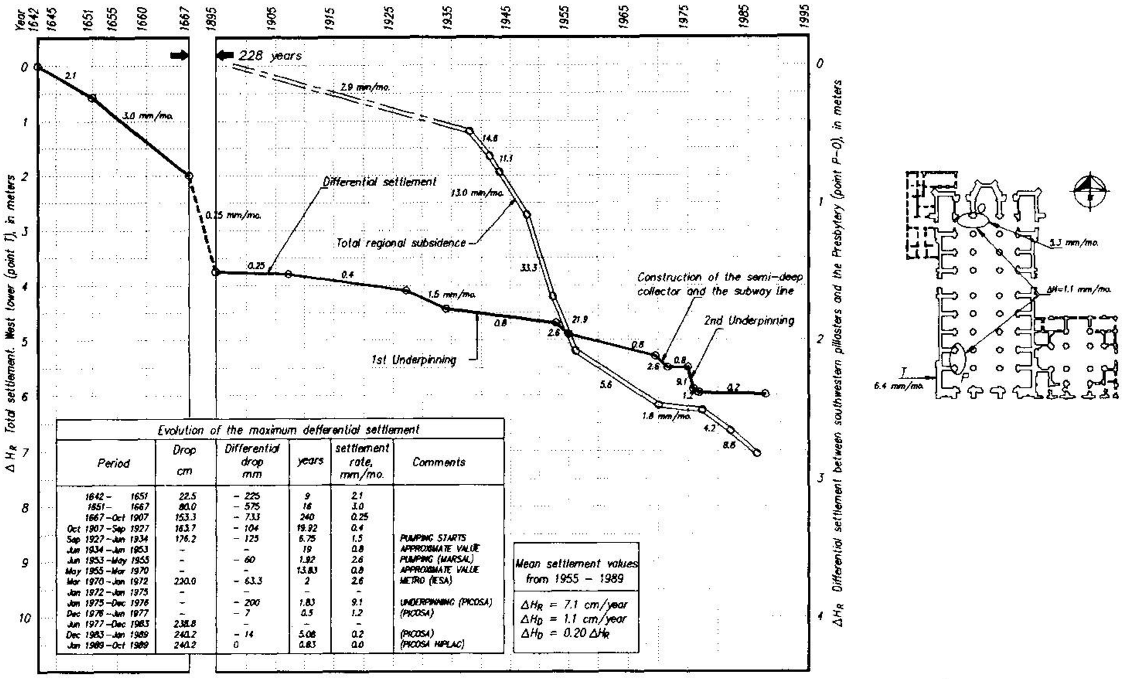
FIG 2 EVOLUTION OF THE DIFFERENTIAL SETTLEMENTS

History of the Settlements

Regional subsidence is a consequence of the consolidation of the soft clay layers brought about by the over-exploitation of deep aquifers. Between 1900 and 1930 the regional subsidence rate averaged 2.9 mm/month; it ranged 11 to 14 mm/month during the fourties and reached 33 mm/month in the mid-fifties.

Strict measures banning the exploitation of existing wells and the construction of new ones were rigidly enforced, after city authorities were prompted to do so by geotechnical engineers. These measures paid off: by the end of the sixties, the subsidence rate was 5.8 mm/month and 1.8 towards 1975. These favorable tendencies were unfortunately reversed by 1978, when the subsidence rate started increasing again, from 4.2 mm/month in that year, to 8.8 in 1983. Presently, it is 5.9 mm/month.

Differential settlements in the Cathedral due to non-homogeneous distribution of compressibilities within the underlying soft clay deposits, accounts for 20 percent of the total differential settlements between the apse and the west tower (fig. 3).



Evolution of the maximum defferential settlement

Period	Drop cm	Differential drop mm	years	settlement rate, mm/mo.	Comments
1642 – 1651	22.5	– 225	9	2.1	
1651 – 1667	80.0	– 575	16	3.0	
1667 – Oct 1907	153.3	– 733	240	0.25	
Oct 1907 – Sep 1927	163.7	– 104	19.92	0.4	
Sep 1927 – Jun 1934	176.2	– 125	6.75	1.5	PUMPING STARTS
Jun 1934 – Jun 1953	–	–	19	0.8	APPROXIMATE VALUE
Jun 1953 – May 1955	–	– 60	1.92	2.6	PUMPING (MARSAL)
May 1955 – Mar 1970	–	–	13.83	0.8	APPROXIMATE VALUE
Mar 1970 – Jan 1972	220.0	– 63.3	2	2.6	METRO (IESA)
Jan 1972 – Jan 1975	–	–	–	–	
Jan 1975 – Dec 1976	–	– 200	1.83	9.1	UNDERPINNING (PICOSA)
Dec 1976 – Jun 1977	–	– 7	0.5	1.2	(PICOSA)
Jun 1977 – Dec 1983	238.8	–	–	–	
Dec 1983 – Jan 1989	240.2	– 14	5.06	0.2	(PICOSA)
Jan 1989 – Oct 1989	240.2	0	0.83	0.0	(PICOSA HIPLAC)

FIG 3 MAXIMUM REGIONAL AND DIFFERENTIAL SETTLEMENTS

As the subsoil under the Cathedral undergoes different subsidence rates, the resulting pattern of differential settlements is quite complex. These facts had not been properly understood during previous attempts to underpin the Cathedral.

PREVIOUS UNDERPINNING ATTEMPTS

Between 1930 and 1940, fill materials were removed from the foundation cells, defined by the grid of masonry beams, and these beams were latteraly confined with reinforced concrete also a concrete raft was incorporated into the foundation of each cell. As a consequence of these modifications, pressures transmitted to the soil were reduced by roughly 3 t/m^2; the behavior of the Cathedral improved over a short period. A new attempt to reduce or eliminate differential settlements began in 1972; this time the Cathedral was underpinned with control piles which not behave completely as expected. Pile driving was very problematic and was carried out with great difficulty.

These piles are provided with a device to control the magnitude of loads at their heads can be applied. This feature, according to suppositions made on the project, could have allowed the effective correction of the whole building and eventually suppressed differential settlements.

A number of factors prevented the success of this system. For instance, some piles were defectively driven and others were not properly socketed into the hard layer, others turned out to be short and became floating piles. Positive frictional forces in excess of 120 t would allow the transmission of projected loads to the pile heads by assuming that this would be added to the point bearing capacity. However, compression of the clay strata due to regional subsidence generated downward drag forces on the piles, i.e. negative skin friction, rather than the expected positive frictional forces. Thus, the overal capacity of the piles was drastically reduced; assuming no defective piles, the individual capacity is only 100 t. If the working suppositions for control piles had been verified, the system could have suppresed sudden settlements, but it would not have avoided differential settlements because the foundation raft unavoidably follows surficial movements; otherwise, an apparent emergence of the building would ensue. In that case the totality of loads, about 130,000 t, would have to be borne by the piles, that have an overall capacity some four times smaller.

By adding about 1,500 control piles, the weight of the Cathedral could be completely transferred to deeper strata. This alternative was carefully examined and set aside when it was realized that there is virtually no space for driving more piles under the Cathedral as it stands; new piles could be accommodated but only if substantial and exceedingly costly structural modifications were made at the basement level.

The influence of the subway and the deep drainage tunnel were studied along with a survey of piezometric conditions. The subway became a drain because of the procedure with which it was built; nowadays, the volume of water flowing into it is no longer large and its influence on the behavior of the Cathedral has consequently diminished. Water flowing into the drainage tunnel seems to be significant, but neither of these two factors is as important as the pumping of water from deep wells, which is extensively and massively occurring throughout the Valley of Mexico. Piezometric levels are frankly worrying; the loss of hydraulic heads at depths ranging between 25 and 50 m is about 18 t/m^2. It means that the phreatic level which is actually located at a depth of 7.4 m and at 3.5 m in 1972 will slowly descend to a depth of 25 m, assuming no changes in the present pumping conditions. It may be possible by installing a slurry trench 65 m deep and a system of infiltration wells, to reduce the consolidation process only 18 to 25 percent.

Natural water content in Mexico City clay can be as high as 500 percent. Once extracted by pumping, restituting water by injection as it has been several times suggested is extremely difficult, only partially effective and very expensive. The expansion of the urban zone has reduced the area of infiltration for the replenishment of the aquifers in the Valley of Mexico, and many problems have risen as a result.

Average total regional settlement in the lake zone is 7.50 m since the turn of this century, which will roughly double in the next 75 years, according to analyses made on the basis of compressibilities determined from undisturbed samples. Future regional subsidence will give rise to more differential settlements in the Cathedral. Predictions of settlement over the periods of 1990 to 2010 and 1990 to 2065 have been clearly plotted (fig. 4).

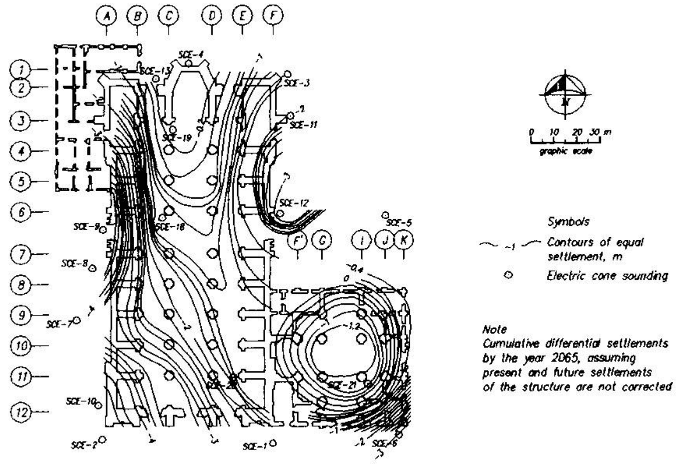


FIG 4 ESTIMATED CUMULATIVE DIFFERENTIAL SETTLEMENTS BY THE YEAR 2065

Towards 2010, differential settlements between the apse and the west tower will be 3 m; between the apse and the east tower, 1.6 m and between the central line and the corners of El Sagrario, 0.7 m. In 2065, settlements in the same points will increase to 4.4 m, 2.0 m and 4.2 m respectively. Clearly, these buildings would collapse between 2010 and 2030, if remedial actions are not taken to improve the behavior of their foundations. These structures have satisfactorily resisted many earthquakes through the centuries, but this situation might change as progressive settlements and distortions will implacably increase their seismic vulnerability.

PROPOSAL FOR SOLUTION

Four procedures for facing the problem have been analyzed. The first one is the addition of 1,500 piles, each with a minimum individual capacity of 100 t. The construction reasons for rejecting this procedure were carefully considered.

The second one involves the use of 240 large diameter (2.4 m) piers supported by resistant strata located at 60 m depth. This method would require the construction of very a grid of sturdy beams, in order to transfer the total weight of the structure to the piers heads, which would be provided with sophisticated control devices. Economic considerations, as well as the forseeable construction difficulties have led to the rejection of this method.

The construction of an impervious slurry trench along with water injection wells, in order to reestablish piezometric levels and reduce the rate of regional subsidence has been analyzed. Adopting this solution would imply the continuous operation and maintenance of the injection points. However, stoppages in operation of injection pumps would reactivate subsidence ipso facto. Rather than an integral solution, this method is a palliative, or a complementary measure to be used in conjunction with other methods. The volume of water required for the injections without the slurry trench is roughly equal to the daily needs of 15,000 people and certainly an unaffordable luxury in Mexico City where water is so scarce.

The fourth proposed procedure is a method of underexcavation which was deemed to be the most feasible solution, technically and economically. In this method, the magnitude of differential settlements is reduced by excavating soil from the more deformable strata, in order to achieve a uniform subsidence rate over the structure. The following considerations were taken into account:

a. The basic geometry of the Cathedral gives it the capacity to resist strong seismic demands, as the differential subsidence has reduced this basic capacity. If conditions existing before 1935, when regional subsidence began increasing at an alarming rate, can be restored the earthquake-resistant capacity of the Cathedral would also be restored.

b. The method allows for geometrical adjustments in the suprestructure, which can reverse the effects of deformations developed over the last few decades. For instance, inclinations of some of the pillars and columns already amount to more than 3 percent of their height; tilting of the lateral naves has increased the chord in the arches of the main nave by more than 40 cm, cracking and fissuring support points as well as the vaults.

Briefly stated, the underexcavation method consists of removing soil by means of horizontal borings drilled from a large diameter vertical shaft; excavation is carried out below the foundation level, preferably within the plastic clays. The volume of soil excavated gives rise to controlled settlements whose velocity can be adjusted at will. Selective excavation allows the correction of distortions in the platform and the superstructure. Analytical tools for predicting the effects of underexcavation derive from plasticity based methods, commonly used in tunneling. Perforation of a hole within the soil mass produces displacements; if the hole collapses and a new one is drilled, surface settlements will increase. Successive drilling and underexcavation will eventually cause the required amount of corrective settlement.

A hydraulic machine for drilling horizontal borings is placed at the bottom of the access shafts; the borings, 7.5 cm in diameter and 6 m long, are horizontally drilled; upon their removal a small inute tunnel is left, which gradually closes and eventually collapses in about 20 hours; successive radial perforations performed at predetermined time intervals are used to precisely control the magnitude and rate of the ensuing settlements.

This procedure has been implemented in the church of San Antonio Abad, located about 1 km south of the Cathedral. The geometry of the vault of San Antonio Abad is similar to the main vault of the Cathedral; soil and subsoil characteristics are roughly the same in both locations.

The work at San Antonio Abad served as an experimental model for the thechnique. Tools and mechanical instruments were perfected and times needed for closure of horizontal drillings were established. This experimental model allowed for the development of a good control and monitoring system for the procedure.

Results of the experiment developed in San Antonio Abad were highly encouraging and the decision to implement this method in the Metropolitan Cathedral was, to a large extent, based upon that success.

The general deformation pattern in the Cathedral shows a hump towards the northern part of the central nave and generalized subsidences towards the south and southwest. Hence, the purpose of underexcavation would be to level off this hump and by so doing, restore in part the verticality of the columns. The periphery of the superstructure has been propped in order to make the lateral naves rigid, while the central one was left free. Induced tilts will tend to close the central arch, maybe causing some fracturing in the vault, which will have to be repaired afterwards.

If conditions existing in the year 1934 can be reestablished, a comprehensive refurbishment of the Cathedral will follow. It is likely that a new phase of underexcavations will be necessary in about 20 to 25 years. Over this period, the Cathedral will undergo settlements caused by regional subsidence that will induce small distortions in its superstructure.

This procedure started to be implemented in 1991 and some of its results can now be seen, as the construction of shafts (fig. 5) and the effect of continuously pumping water have modified deformation trends by reducing the magnitude of differential settlements and stopping the tilting of lateral naves and their external walls. Future work will result in reversing the movements of naves and walls; columns and walls will also rotate until conditions existing in 1934 can be restored. The project does not intend to straighten the building completely.

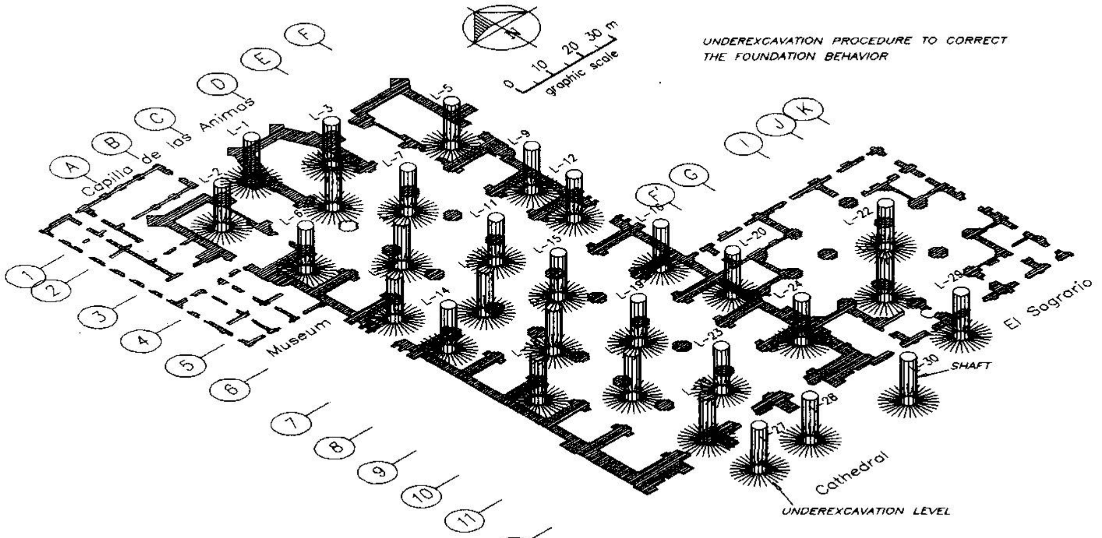


FIG 5 SHAFT AND RADIAL UNDEREXCAVATION BORINGS LOCATION

A complex monitoring system, including leveling surveys and convergence measurements inside the Cathedral, is being used to control this method. Likewise, careful records of the volumes of the excavated soil will be continuously carried out during the underexcavation process. The first stage of underexcavation work will start in 1993 and is expected to span over six to eight years.

El Sagrario will be subjected to a similar process, which will first stop and then invert present trends, rotating the structure towards the Cathedral and correcting differential settlements as required. The procedure may be repeated in twenty to thirty years.

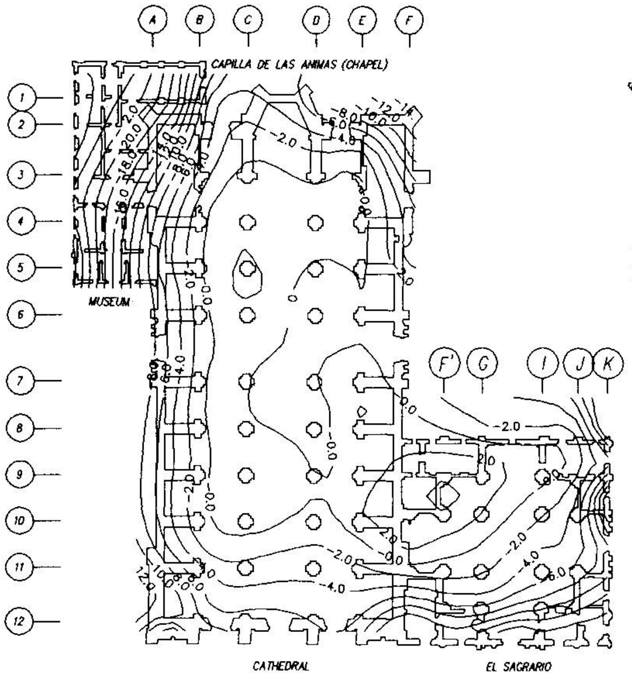


FIG 6A CONTOURS OF EQUAL SETTLEMENT RATE, IN mm/year; MEASUREMENTS FROM JAN 7, 1991 (N20) TO SEPT 2, 1991 (N28)

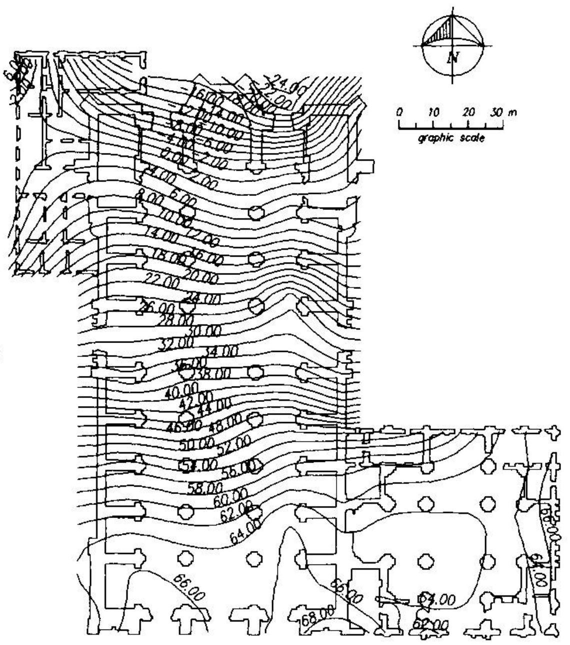


FIG 6B CONTOURS OF EQUAL SETTLEMENT RATE, IN mm/year; MEASUREMENTS FROM OCT 25, 1991 (N-1a) TO OCT 26, 1992 (N-25a)

CONCLUSIONS

Figures 6A and B shows annual rate of settlement contours for the Cathedral and the Sagrario before and after the construction of the shafts. Clearly, the effect has been definitely beneficial for the condition of both structures in terms of the floor level configuration. Also, no significative damage to the structures ensured as a curequence of these movements. Up today the main driving factor for achieveng this is, the selective operation of dewatering system for the excavations of the shafts.

Much finer and precise control of settlements can definitely be achieved by means of the underexcavation technique already developed. Hence, the results shown in fig 6 are both encouraging and they also demostrate the structure ability to withstand the induced settlements.