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Testing and monitoring for the restoration of the metropolitan Cathedral in Mexico City

TESTING AND MONITORING FOR THE RESTORATION OF THE METROPOLITAN CATHEDRAL IN MEXICO CITY

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SUMMARY

The Mexico City Metropolitan Cathedral is undergoing rehabilitation work based on the subexcavation technique in order to correct the significant differential settlements now reaching up to 2.4 m. During this work, the monitoring systems play a very important role. The paper illustrates the automatic monitoring systems installed by ISMES and ENEL to monitor in real time the movements of the supporting structure of the Basilica. The most interesting data recorded by the monitoring systems are presented, as well as the results of the flat-jack tests performed to measure the existing state of stress of the major supporting structures.

1. INTRODUCTION

The Metropolitan Cathedral was built on the remains of ancient Tecnochtitlan, just after it was conquered and destroyed by the Spanish crown. Demolition of the Aztec capital was systematically accomplished in order to clear the land for the construction of a European-like metropolis.
Tecnochtitlan had been built upon a lacustrine soil over a period of several hundreds of years, so that successive backfills and other adaptations had to be implemented in order to support the huge, heavy buildings. The lacustrian region was formed in recent geological times, as a result of different events which laid a sedimentary layer over very soft clay deposits several hundred meters thick, subjected to periods of isolation, hydration, volcanic ashes, sand layers , etc.
More than once, the Cathedral leaned during the first stages of its construction, requiring periodical corrections to its verticality and adjusting the final height of the walls and towers in order to have a horizontal plane for the vaults.
As the years passed, the problem of soil dewatering has resulted in a progressive increase in consolidation that, during this century, have provoked a 7,5 m settlement in the Cathedral zone. In critical seasons the rate of the phenomenon has exceeded 30 mm/month. The stratigraphic profile of the foundation soil of the Cathedral is shown in Fig. 1 along with the results of static cone penetrometric tests.

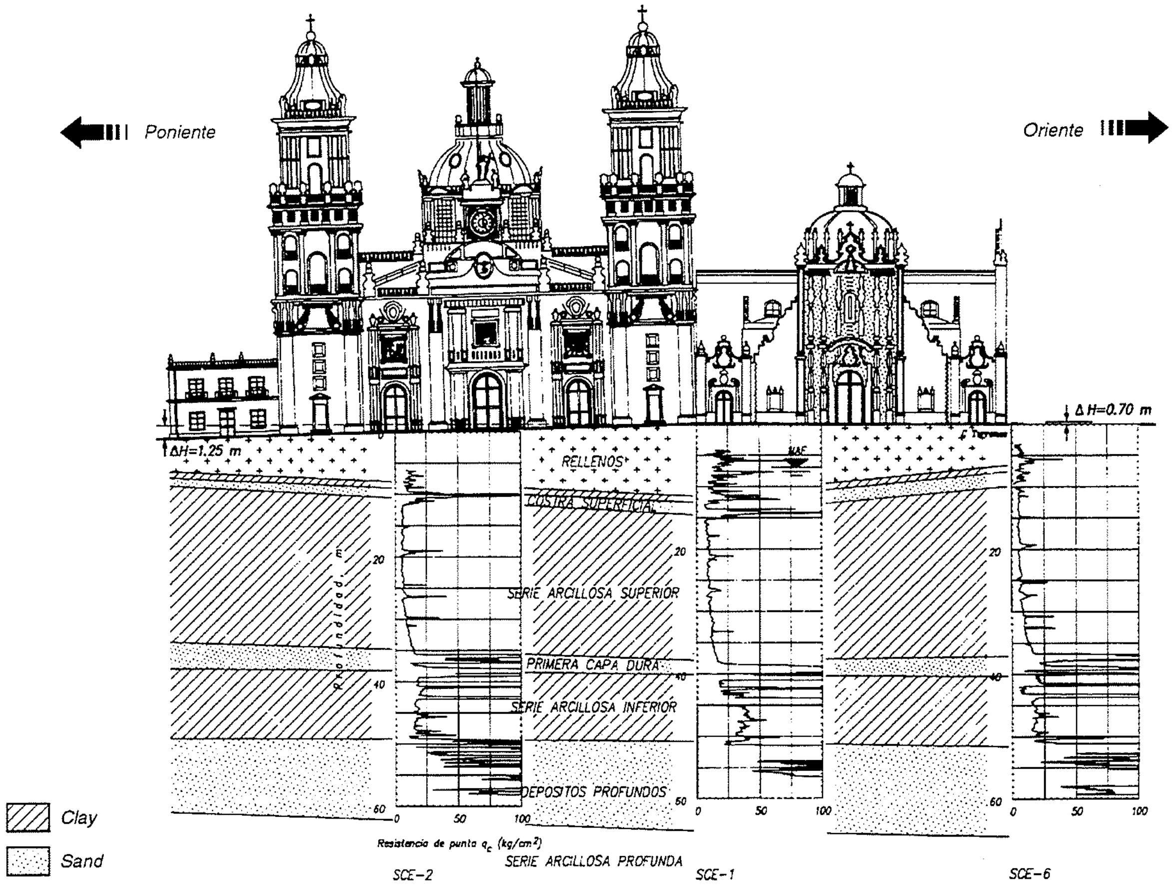

Fig. 1 - Stratigraphic profile of soil foundation of the Cathedral with the results of static cone penetrometric tests.

2. DESCRIPTION OF THE CATHEDRAL

The Metropolitan Cathedral is a basilical building of five naves and eleven tranverse modules. It is 115 m long and 66 m wide, has two 62 m-tall towers and a 17 m-diameter dome in the transept. This dome represents the heaviest and most critical part of the roof. The structure is supported by a grid of foundation beams (3.5 m deep) and by a foundation mat with a thickness of about 2 m. Timber piles (with a diameter of 0.2 m and a length of 2 - 3 m) are spaced every 0.6 m underneath the foundation mat. The primary construction material is a kind of poor concrete composed of volcanic aggregates and a lime-sand-mortar. The arches and columns are made of andesitic stone sills.

Settlement of the structure started during the early stages of construction, as evidenced by the many significant adjustments made to the dimensions and shape of the construction members. For instance, the length of the columns varies according to the settlements experienced by their bases at the time when the arches and vaults were built. The maximum difference in length is about 0.85 m.

The span and rise of the arches and vaults were adjusted in order to achieve an almost flat roof. After the completion of the roof, the structure acquired a greater stiffness thus the differential settling proceeded at a lower rate. Nevertheless the large cracks and the inclination of the upper parts of the columns reflect the very large distortions suffered by the structure following its completion.

Fig. 2 shows the pattern of differential settlements measured in the floor of the Cathedral some time prior to the beginning of the rehabilitation work (late 1989). The maximum value of the differential settlements at this point in time was about 2.40 m.

By examining the differential settlement pattern, two major mechanisms of deformation can be appreciated. One is the settlement toward the south-west corner, another is the "emergence" of the central nave in the northern part. The first mechanism has produced a pattern of transverse cracks in the roof and walls, especially near the central dome, and some separation of the southern facade, with its very heavy towers, from the rest of the church. The second mechanism produced the outward rotation of the columns and lateral walls and the opening of the vaults and arches in the roof, causing a pattern of longitudinal cracks in the roof, floor and foundation.

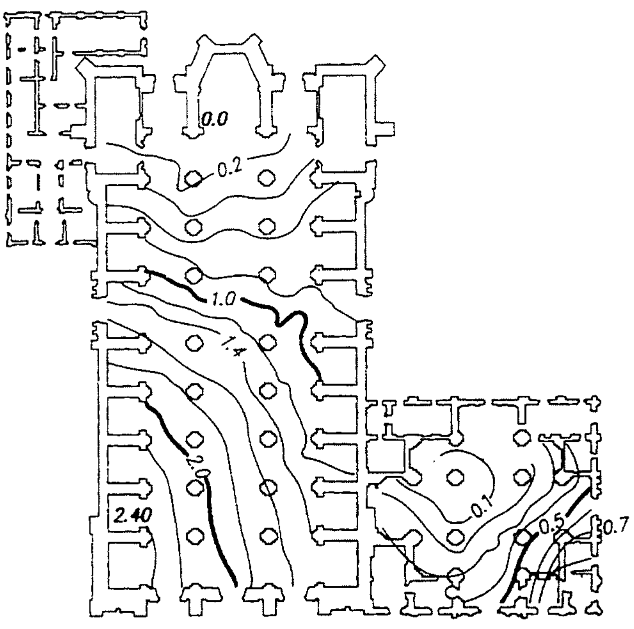

Fig. 2 - Pattern of differential settlements measured in the floor of the Cathedral.

This second mechanism is the most critical from a structural point of view because of the inclination of the columns receiving the greatest vertical loads, especially those supporting the central dome. The total eccentricity between the upper and lower part of the columns is, for this case, 0.6 m representing 25% of the size of the column. Some vertical cracks at the upper part of the columns are attributed to the compressive stresses generated by the eccentric compression.

3. REHABILITATION WORK

To reduce the rate of differential settlement it was decided to use the underexcavation method in the clay layer, below the backfills. In this manner settlement would be increased at those points where sinking is now slower because of the greater degree of consolidation in those zones. Thus, the vaults would be closed by means of a twist of the outward naves to an inward direction, simultaneous with another twist of the whole framework to the northeast.

This methodology is quite complex and is highly risky, given the particular characteristics of the framework, the wounds in the system and the huge size of the monuments.

As shown in Fig. 3 small diameter radial boreholes have been drilled at the base of 30 shafts at a depth of about 20 m. The closing of the boreholes due to the weight of the overlying soil and structure produces a settlement at the surface.

Careful programming of the volume and location of the excavated soil, the desired distribution of settlements can be achieved with great precision.

The induced movements must be monitored by surveying in order to confirm that the effects of the underexcavation met the expectations of the project; it was important to avoid any kind of dispersion or differential motion among parts of the building, and the stress systems that enable the balance of the framework had to remain unchanged during this delicate response to the monument's historical deformations, which have accumulated over centuries.

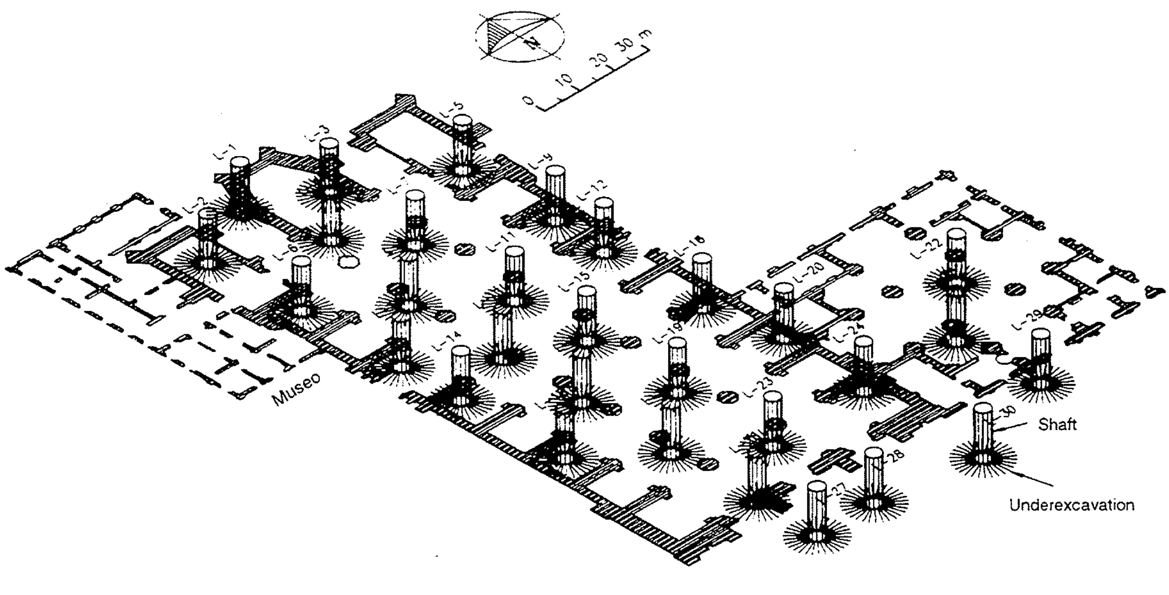

Fig. 3 - Scheme of the underexcavation method adopted for the rehabilitation of the Cathedral. 30 vertical shafts 20 m deep have been excavated and radial boreholes have been drilled at the base of each shaft.

A manual system was firstly designed for the aforementioned purpose. It consisted in surveying operations by traditional direct pendulum, convergence measurements with optical instruments, measurement of the opening of the cracks by removable extensometers, levelling in ground floor and vaults. Although these operations were essential to keep strict control of the building's geometry and to confirm the movement caused by the underexcavation, the project risked some difficulties in control, since manual records were only obtained with a delay of fifteen or twenty days.

In light of the complexity of the soil-structure interaction and the continual need to adjust the motion of the two buildings (the Cathedral and El Sagrario) to cause them to settle harmoniously, avoiding any kind of damage from one to the other, it was necessary to get immediate information about induced movements.

At a certain point, it became dangerous to proceed with the project unless the whole framework was monitored in real time with an automatic monitoring system.

A first automatic monitoring system was installed by ISMES in 1994 with the financial support of ENEL. The system was completed at the beginning of 1996 with the contribution of the General Direction of SEP. During the two phases of installation of the monitoring system, a detailed analysis of the state of stress of the supporting structure of the Cathedral was also carried out by ISMES.

4. EXPERIMENTAL STRESS ANALYSIS

By using the flat-jack testing technique, the state of stress on the main supporting structures of the Cathedral was determined with special attention to the static conditions of the columns which present significant deviation from verticality.

The flat-jack testing technique is based on the stress release caused by a plane cut normal to the surface of the wall. Two reference points are installed on the wall surface and the initial distance (d_i) between the two points is measured. A cut perpendicular to the wall surface is then made and the stress release is determined by a partial closing of the cutting, the distance (d) after the cut being $d < d_i$. A thin flat-jack is placed inside the cut, and the pressure is gradually increased to cancel the previously measured convergency.

The value of the state of stress (σ) in the testing point is given by:

$$\sigma = P \cdot Km \cdot Ka$$

where:

P = oil pressure;

Km = jack constant which must be determined in the laboratory;

Ka = Aj/Ac (ratio between the surface of the jack and the surface of the cut).

A phase of a flat-jack test on a pillar is shown in Fig. 4. Owing to the special shape of the surface of the columns, the presence of the decorative vertical channelling has been neglected.

Fig. 4 - View of a flat-jack test for measuring the state of stress of a column.

As an example, Fig. 5 shows the stress values measured on the main columns which are supporting the control dome. In the same figure, the deviation from verticality of the four columns is also indicated. It can be observed that the measured values of the states of stress are in good agreement with the deviation from verticality of the columns. The greatest value of the state of stress (8.75 MPa) has been measured on the columns which present the greatest value of deviation from verticality (0.66 m). In some points the measured values of the state of stress are very low, which means that some portions of the supporting structures have been unloaded by the crack pattern.

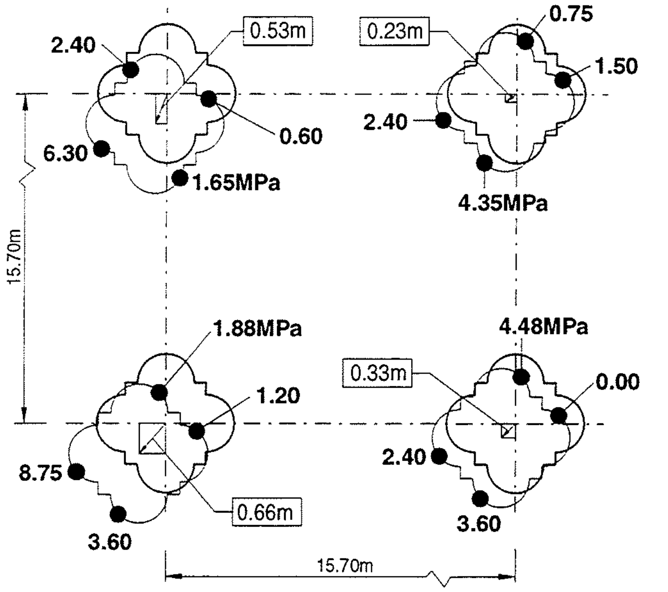

Fig. 5 - Stress state measured by flat-jack testing technique on the four columns supporting the central dome. The deviation from verticality of the columns is shown.

The general lay-out of the testing points is shown in Fig. 6 with the indication of the stress values measured by flat - jack testing technique.

5. MONITORING SYSTEM

The automatic monitoring system, installed on the main supporting structures of the Basilica was designed in order to five exhaustive information regarding the following:

- measurements of the absolute horizontal displacements of the vertical structures by using direct pendulums with telecoordinometers;
- measurements of the relative displacements between the vertical structures, by using long-base extensometers;
- measurements of temperature changes and radiation characteristics by using temperature sensors and radiometers.

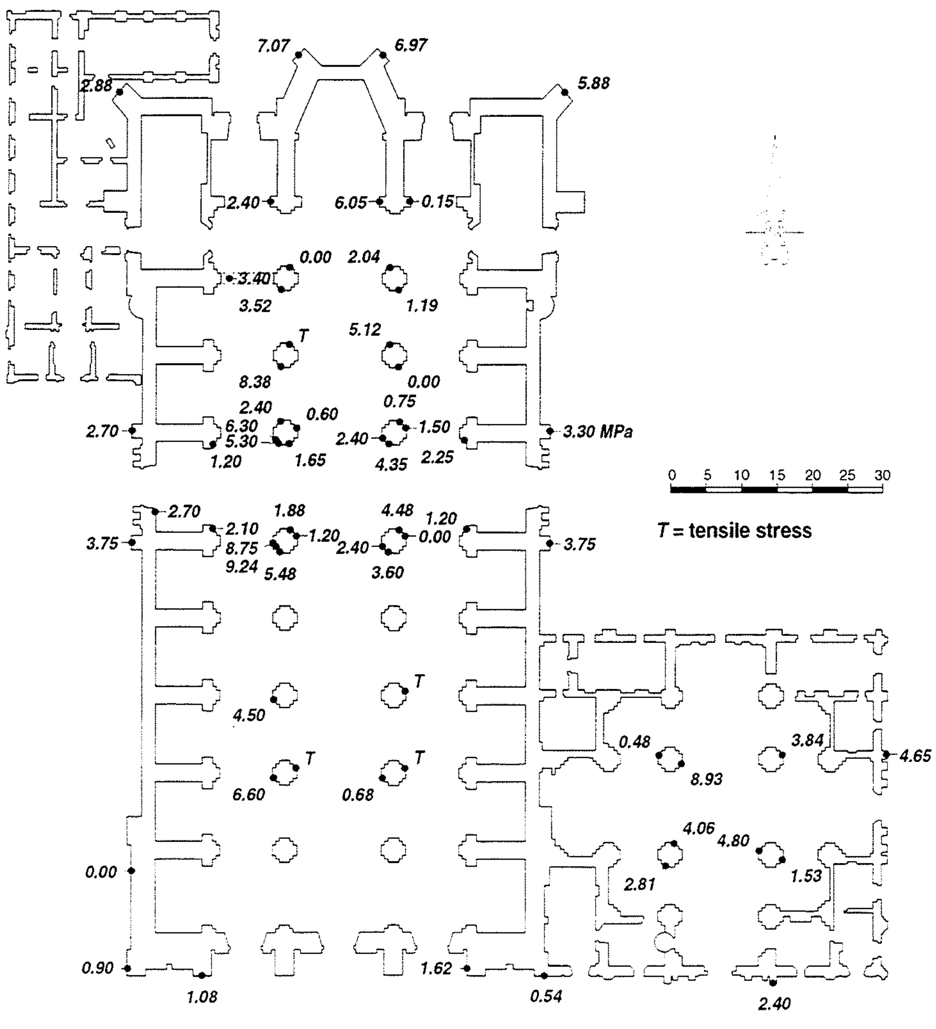

Fig. 6 - General lay-out of the stress-state values measured on the supporting structures of the Cathedral.

The first phase of the monitoring system, installed by ISMES in June '94, consisted in:

- 4 direct pendulums on the supporting columns of the central dome
- 8 long-base extensometer in the arches of the central nave of the cathedral at the level of the chapitels;
- 3 long-base extensometers on the central columns of the "Sacrario"
- 4 temperature sensors
- 1 radiometer.

On February '96 the monitoring system was completed by adding 6 direct pendulums (2 in each of the towers of the facade, two in the central columns of the "Sacrario" and 2 in the zone of abse) and 11 long-base extensometers (on the naves of the cathedral and on the "Sacrario").

The general lay-out of the instruments is shown in Fig. 7 while in Fig. 8 the installation of a long-base extensometer at the top of a column, is shown.

Fig. 8 - Installation of a long-base extensometer at the top of a column.

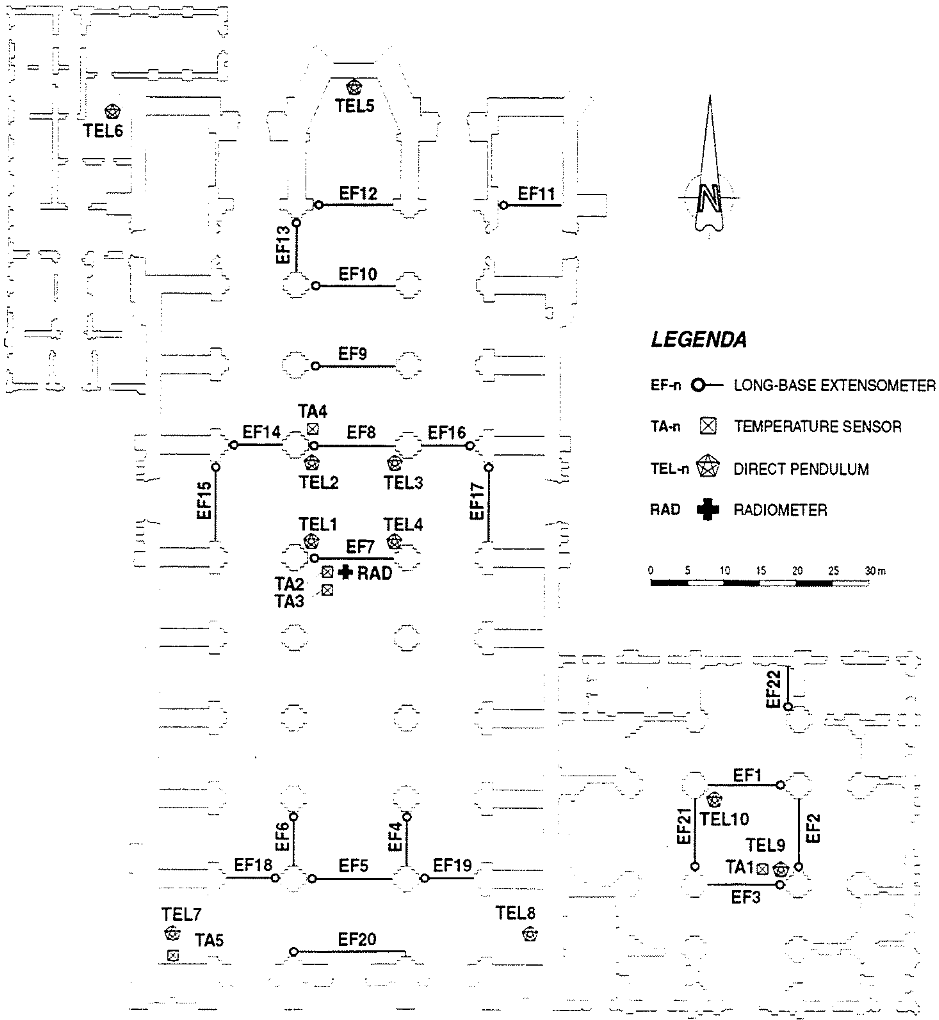

Fig. 7 - General lay-out of the instruments connected to the automatic monitoring system.

The results obtained by this measuring equipment during the first period of observation are completely satisfactory. The instruments followed, with great precision, all phases of underexcavation now in progress and they were able to give prompt information in order to correct local anomalies in the structural behaviour induced by the underexcavation process.
Fig. 9 shows the absolute displacements measured by the telecoordinometers at the top of the four central columns of the cathedral in the period July '94 - Sept. '95. It can be observed that all the columns are moving in the desired direction and they are progressively decreasing the deviation from verticality that they exhibited at the beginning of the underexcavation.

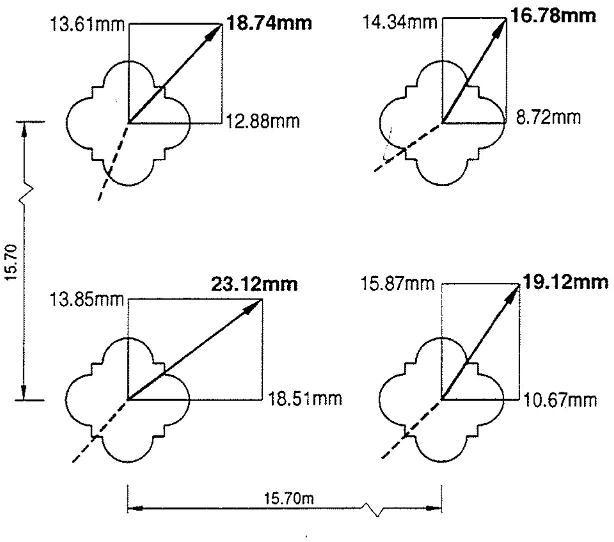

Fig. 9 - Absolute displacements measured at the top of the four columns, which are supporting the central dome, in the period July '94 - Sep. '95.

The analysis of plots of displacements versus time recorded by the telecoordinometers is also very interesting. Fig. 10 shows the two displacement components (x, y) measured by the direct pendulum TEL 1. An initial phase can be observed, characterised by progressive movement (with a constant rate of deformation) in the desired direction. On 31.03.1995 the underexcavation was stopped. Starting from this date an inversion of the movements of the four columns was observed which started again to move in the same direction they followed prior to underexcavation. When the underexcavation resumed (24.07.95), the movement of the columns was again in the desired direction.
A similar effect can be observed by examining the long-base extensometer results. Fig. 11 shows plots of the movements recorded by the extensometer EF 8 which is installed on the central nave of the Cathedral. The diagram shows a progressive closure of the cracks in the first phase, then a reopening after the cessation of underexcavation and finally, when the works started again, a new closure of the cracks at a rate similar to that of the first phase.
These two examples clearly show the great sensitivity of the measuring instruments which permit to following and guiding very carefully, in real time, the rehabilitation works.
The behaviour of the second group of instruments installed on February '96 is also very interesting and initial results indicate that the supporting structures are moving as foreseen by the designers. Fig.12 shows the displacements recorded by the new direct pendulums in the period March '96 - June '96. The displacements of the four central columns, measured in the same period, are also indicated.

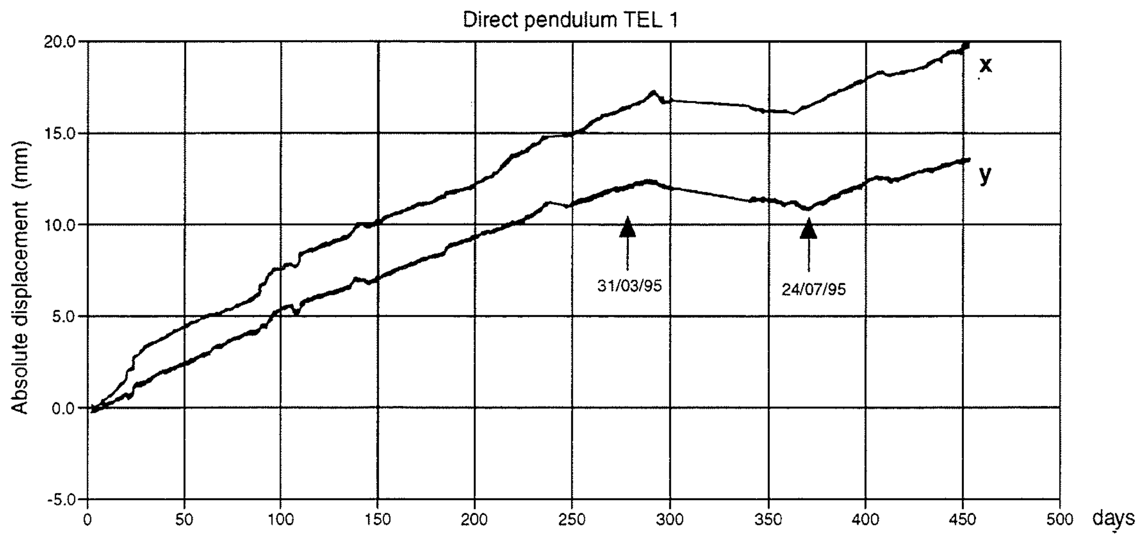

Fig. 10 - Plots of the two components of the absolute horizontal movement of one of the central columns of the Cathedral measured by direct pendulum TEL 1. On 31.03.95 underexcavation was stopped and on 24.07. 95 was recommenced.

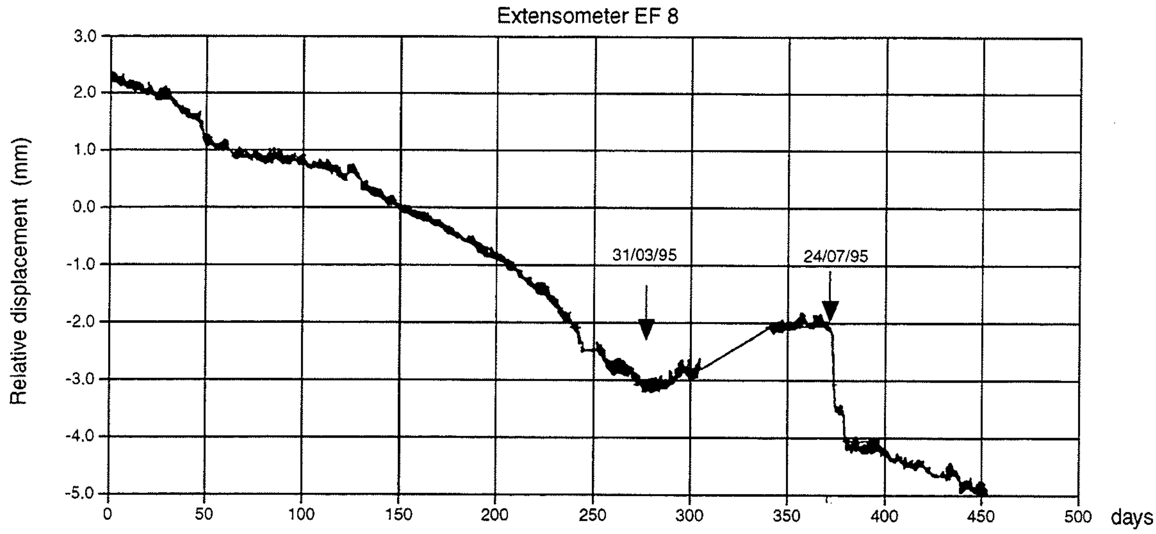

Fig. 11 - Plot of the relative movements between two central columns of the Cathedral measured by long-base extensometer EF 8. On 31.03.95 the underexcavation was stopped and on 24.07.95 was recommenced.

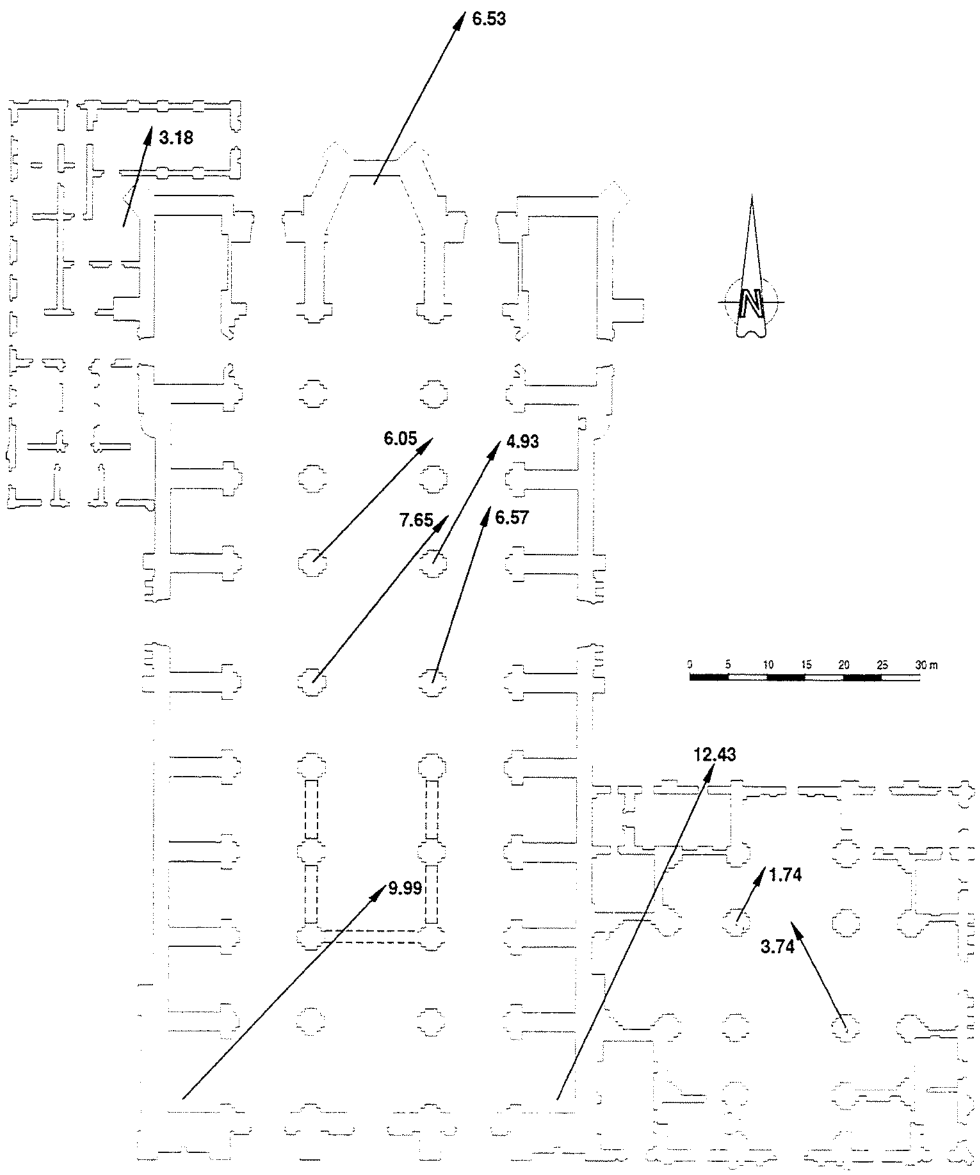

Fig. 12 - Absolute displacements measured by all the pendulums in the period March 96 - June 96.

6. CONCLUSIONS

The underexcavation technique used for the rehabilitation of the Cathedral of Mexico City has never been used before for a building of this size and complexity. To date the results have been completely satisfactory.

The global effect of underexcavation at Feb. '96 can be seen in Fig. 13 wherein the positions of the plumb-line at the centre of the dome indicate the history of the movement of the Cathedral from the time of its construction and the recovery (about 15 cm) obtained with the underexcavation works.

The rehabilitation work of the Cathedral is now reaching a very delicate phase. When a 50 cm rectification of differential settlement had been achieved, the efficiency of the underexcavation tended to decrease owing to the boundary conditions of the structure.

In particular there are critical points which must be examined with special attention: the behaviour of the columns whose movements are conditioned by the presence of the vaults, the double space of the vault in the sacresty, the distance between the towers and the central nave, the opening in the transept and the behaviour of the perimetral walls which support a considerable horizontal compressive stress and could be affected by bulging effect.

All these problems now can be kept under continuous observation by using the automatic monitoring system, the only reliable tool to understand if the behaviour of the structure is following correctly the prediction of the designers.

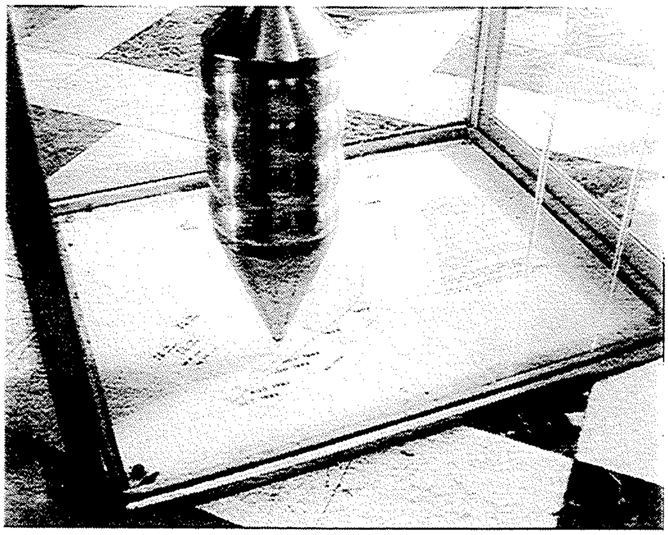

Fig. 13 - Plumb-line installed at the central dome of the Cathedral. The history of movement is shown as well as the recovery due to underexcavation.

7. REFERENCES

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