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ASSESSMENT OF THE UNDEREXCAVATION TECHNIQUE FOR LEVELLING STRUCTURES IN MEXICO CITY: THE SAN ANTONIO ABAD CASE

EVALUATION DE LA TECHNIQUE D'EXCAVATION DES COUCHES DE FOND POUR LA MISE A NIVEAU DE STRUCTURES A MEXICO CITY: LE DOSSIER SAN ANTONIO-ABAD

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SYNOPSIS: A large scale experiment was carried out in order to prove the practical feasibility of using the underexcavation technique for levelling historic buildings undergoing large differential settlements in central Mexico City. The paper describes the implementation of techniques for underexcavating the temple of San Antonio Abad, a 9.5 by 34 m, seventeenth century structure. Observations carried out during the experiment showed that settlements and settlement rates can be imposed on the structure under controlled conditions, inducing in it rigid body rotations and torsional movements and that predictive methods can be used to establish preliminary underexcavation programmes. Underexcavating larger, more complex buildings must rely on careful, continuous, observation of the response of the structure by means of extensive instrumentation, i. e. on the application of the observational method.

1. INTRODUCTION

Historic buildings in the centre of Mexico City have been subjected to extremely large differential settlements, especially during the last century. Regional subsidence brought about by extensive exploitation of deep aquifers, vertical and horizontal nonhomogeneities in the distribution of soil compressibilities as well as complex loading histories imposed on the subsoil, on many occasions by a succession of prehispanic, colonial and modern structures, influence the magnitude and rate of differential settlements (Carrillo, 1948; Tamez et al, 1992). The Metropolitan Cathedral in Mexico City, for example, now exhibits a maximum differential settlement of 2.4 m between its apse and the base of its western tower. It has been estimated that the Cathedral and the adjoining Sagrario Church will collapse within the next sixty years if the present rate of differential settlements is maintained.

After analyzing several alternatives for correcting the behaviour of the Cathedral --underpinning with piles or shafts, reducing regional subsidence by restoring locally piezometric levels, etc-- it was decided that, technically and economically, the most adequate means of bringing it back to a stable condition was to lower the higher areas by underexcavation. Previous experiences using this technique are very few, at least in Mexico City. Hence, it was decided to carry out a large scale experiment in order to prove the practical feasibility of the procedure by applying it on a masonry structure built on a similar geotechnical environment and having similar materials and structural layout as the Cathedral. The temple of San Antonio Abad was chosen for this purpose. This paper focuses on an analysis of the information gathered during the experiment, on the lessons learned from it and on the assessment and calibration of two methods for predicting the magnitude and distribution of surficial settlements induced by underexcavation.

2. CONDITIONS IN SAN ANTONIO ABAD

A plan of San Antonio Abad shows that it is a single nave church having a cylindrical vault supported by masonry walls stiffened with counterforts. The church, built in the late seventeenth century, is 34 m long and 9.5 wide and was founded on surficial masonry footings which transmit an average pressure of 60 kPa. The foundation was reinforced in 1986 by adding two reinforced concrete footings running under the masonry walls. Plan and elevation views are provided in fig 1. The largest differential settlements induced by regional subsidence that were observed before the experiment, mainly towards the southwest, were 1.8 and 0.8 m, along the longitudinal and transversal directions respectively.

Four CPT tests were carried out at the site down to a depth of 35 m; results of two of these are given in fig 1. Stratigraphical conditions are typical of the lake zone in central Mexico City. Namely, a sequence of highly compressible silty clays overlain by a hard surficial crust and by artificial fills and underlain, below 35 m where a firm sandy stratum is found, by other very compressible strata, down to about 40 m. It is clear that point penetration resitance in the western CPT boring is smaller, along the whole of the explored depth; a similar picture is obtained when comparing CPT results along the north-south direction where the southern portions were weaker. The development of differential settlements towards the southwest is thus explained.

3. TECHNIQUES IMPLEMENTED FOR UNDEREXCAVATION

Three shafts (diameter = 3.0 m) were excavated along the north wall down to about 10.0 m. Underexcavation was carried out by driving horizontal tubes into the soft clay at a depth of 9.0 m. Extraction of soil was performed using a 3" diameter tube provided with a 4" sleeve. The extractor penetrated as much as 7.0 m into the clay and was driven with an hydraulic jack powered by an electric motor that reacted against the shaft lining. The location of the shafts as well as details of the extractor are shown in fig 2.

Underexcavation was carried out from 19 November, 1990, to 18 June, 1991. Two objectives were established. First, to induce a rigid body rotation along the church's longitudinal axis in order to

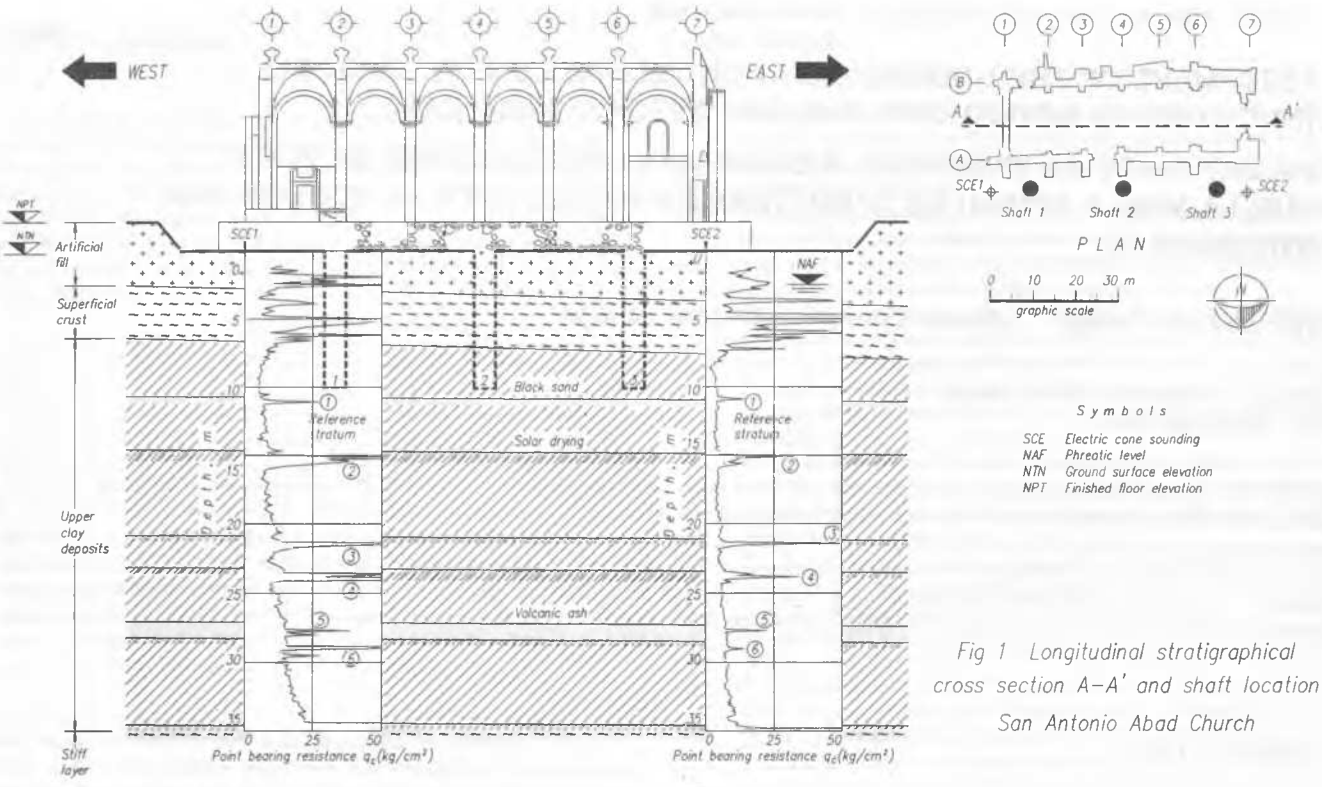

Fig 1 Longitudinal stratigraphical cross section A–A' and shaft location San Antonio Abad Church

correct the southward settlements by underexcavating from the three shafts. Second, to induce torsional movements and eventually the breakage of the vault by underexcavating only from the northwest corner. The rigid body phase of the experiment was terminated towards the end of February, 1991; on 17 March, the second phase of the experiment commenced.

The effects of the underexcavation works on the structure were monitored by precision levelling of fixed points on the outside of the church and by the measurement of plumbs installed in the columns in the church; convergence measurements at several transverse sections were also taken. Additionally, the volume of soil extracted from each of the tubes was carefully logged.

4. OBSERVATIONS DURING UNDEREXCAVATION

A plot of the volume of soil underexcavated versus time is provided in fig 3, for each of the three shafts. Between 3 December 1990 and 28 February 1991, the rate of volume extraction from each of the three shafts was the same. Over this period of time which corresponds to the rigid body rotation phase, surficial settlements along the outer perimeter of the church are clearly correlated with the volume of underexcavated soil, as may be concluded from anlyzing the data presented in fig 4. Also, uniform settlement rates were induced around the church over this period. Overall, analoguous conclusions can be extracted from the analysis of figs 5 and 6, evolution of transversal rotations and tilts with time, respectively. Also, convergence measurements taken during this period indicated negligible movements at cross sections i. e., rigid body rotations were indeed achieved.

Before undertaking the second phase of the experiment, a rest period was allowed during the first fortnight of March, 1991. At this time a bentonite slurry was injected into the horizontal borings at a pressure equal to the original pore pressure, as determined from open tube piezometers installed previously. Settlements did stop during the rest period (fig 4). Transversal rotations and tilts showed a somewhat erratic behaviour (figs 5 and 6), possibly due to the fact that readings were close to the resolution threshold of the measuring system.

The effects of the second phase, the inducement of torsional movements, can be also assessed by means of figs 4 to 6. Between 17 March and 10 June, soil was only extracted from shaft 3. Clearly, this induced different settlement rates on the control points (fig 4); those closest to this shaft exhibited the highest rates, as expected. Transversal rotations and tilts progressed at roughly the same rate (figs 5 and 6), also as expected. From 10 June to 18 June, soil was extracted from all three shafts and the same tendencies continued.

After the end of underexcavation, movements diminished gradually over a few days and in just about one week, they stopped for all practical purposes. Continuous observation of the structure was carried on until the end of September. No measurements were taken thereafter except for precision levelling which resumed towards the end of March 1992.

As may judged from the the measurements taken, the structure responded fairly rapidly, about one week after underexcavation continued, at the beginning of the second phase, it started moving again. It is also evident that the rate of movements imposed on the structure was adequate in that it did not damage the structure and it allowed for taking sufficiently precise measurements with unsophisticated equipment; also, the vertical settlements induced by underexcavation more than compensated the settlements brought about by regional subsidence (13 mm/month against 1.4 mm/month). Other larger and more complicated structures such as the Cathedral may require additional instrumentation and continuous data recording that can only be achieved logging data automatically.

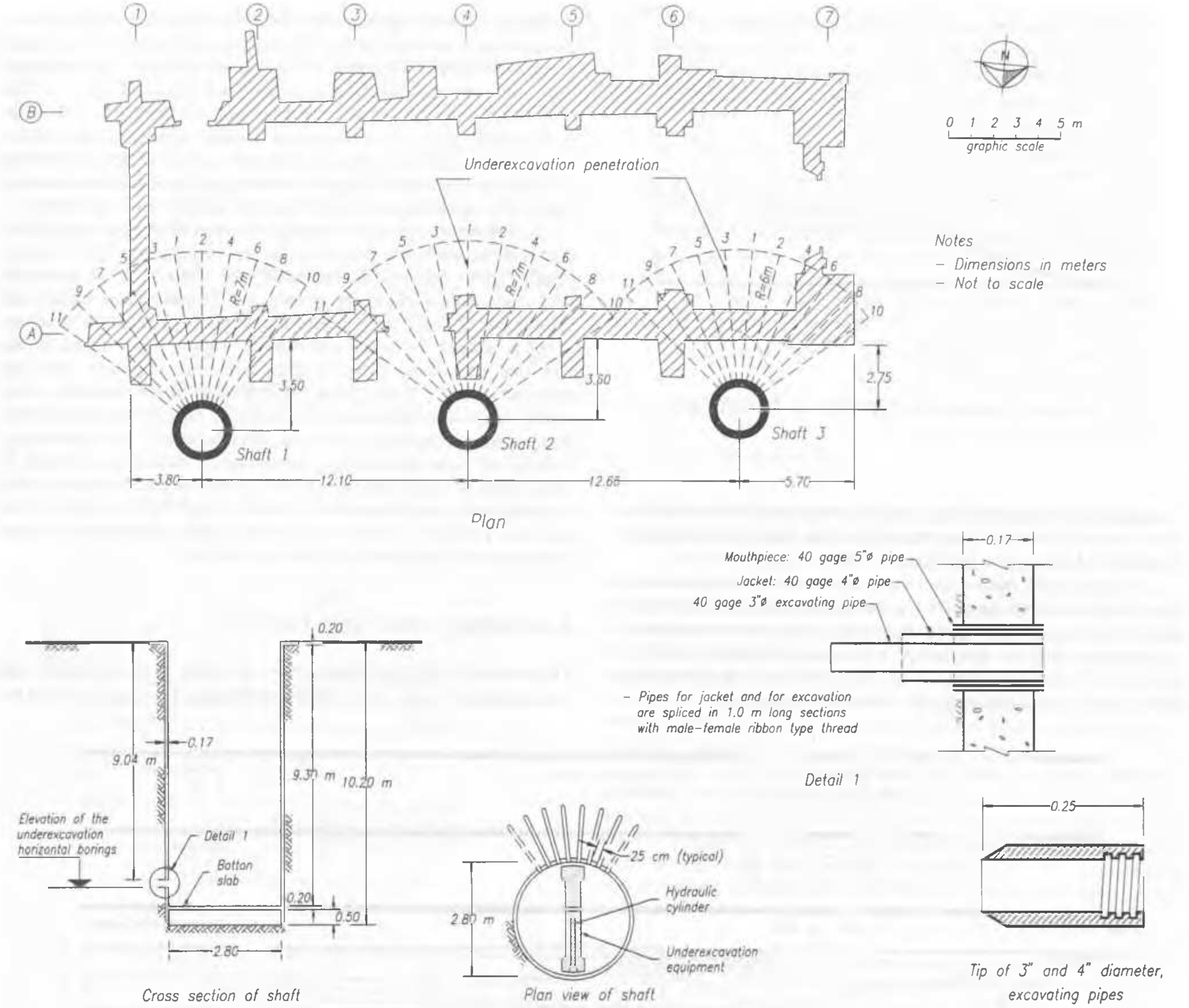

Fig 2 Location of shafts and distribution of underexcavation borings, San Antonio Abad Church

5. PREDICTION OF MOVEMENTS

Surficial settlements produced by underexcavation were calculated using two methods derived originally for calculating the displacements produced within a soil mass due to the excavation of circular tunnels. One of the methods is analytical and applies Carrillo's (1949) theory of tension centres to the case of a cylindrical cavity bored inside an elasto-plastic medium (Alberro and Hernández, 1988). The other one is empirical and was derived from the observation of actual settlements induced by tunnelling in Mexico City Clay (Tamez and Santoyo, 1988).

The analytical method uses continuum mechanics to obtain the displacement fields within a semi-infinite mass due to the presence of a cylindrical cavity; two corrective functions account for the boundary conditions at the surface. The displacements along three orthogonal directions associated to the x, y and z directions at any point within the soil mass are given by:

$$u = (D/h)[\, A\,(x',y',z') + (1 - 2\mu)\, B\,(x',y',z')]$$

$$v = (D/h)[\, A'(x',y',z') + (1 - 2\mu)\, B'(x',y',z')]$$

$$w = (D/h)[\, A''(x',y',z') + (1 - 2\mu)\, B''(x',y',z')]$$

where x', y' and z' are normalized coordinates with respect to the depth of the boring, h. The origin of the coordinate system coincides with the end of the cavity and the y' axis with its longitudinal axis. A, A'' and B, B', B'' define the shape and size of the displacement field and are given by integral functions. The quotient D/h depends on the displacements along the tunnel lining, the stress state and the

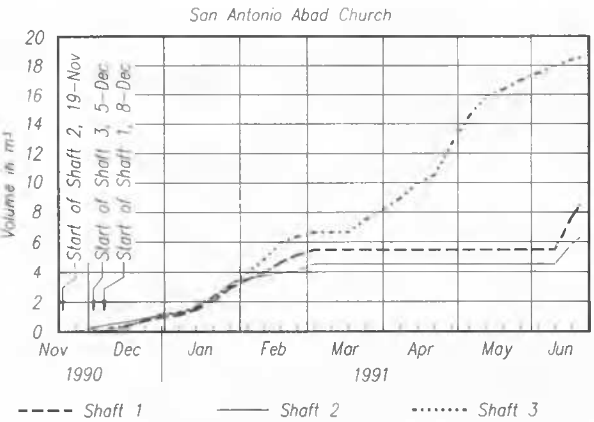

Fig 3 Volume of underexcavated material in each shaft

soil properties in its surroundings, and the magnitude of the cavity's internal pressure, should it be pressurized. The method is described *in extenso* by Alberro and Hernández (1988).

The empirical method assumes that the vertical displacement field encloses a volume limited by plane surfaces along the boring's longitudinal axis and by triangular ones along its transverse direction. The magnitude and the distribution of vertical settlements can be found if the volume enclosed by the dispacement field equals the volume of soil displaced during the closure of the boring.

Computer programmes were written for applying the two methods to estimate the settlements induced by underexcavation. Both methods were calibrated using the data gathered during the first stage of the experiment. In the case of the anlytical method, soil properties were adjusted and excellent matches were obtained between the observed and the calculated settlements up to 28 February, 1991. The displacement field of the empirical method was also modified to obtain good agreement between observed and calculated settlements over the same period of time. Afterwards, both methods were used to predict the settlements during the second phase of the experiment.

Predictions using the empirical method turned out to be better than with the analytical procedure, as can be judged in fig 7. Axis A in this figure identifies the northside wall and axis B the southside wall. Both methods, however, overestimate displacements towards the eastern side of the church, surely because the stiffness of the structure is not accounted for in the calculations. This is also evinced by the fact that the actual displacements were far smoother than the calculated ones. Clearly, given the crudeness of the methods, better quality predictions ought not to be expected. Despite their limitations, these two procedures can be used advantageously for establishing preliminary underexcavation programmes in future applications. It should also be noted that more refined anlytical procedures can only be expected to yield approximate results, given the complexity of the problem. Presently, further analyses of the underexcavation procedure are under way using the finite element method.

6. SUMMARY AND CONCLUSIONS

The techniques developed during the experiment in San Antonio Abad --excavation of shafts, development of horizontal borings-- showed the

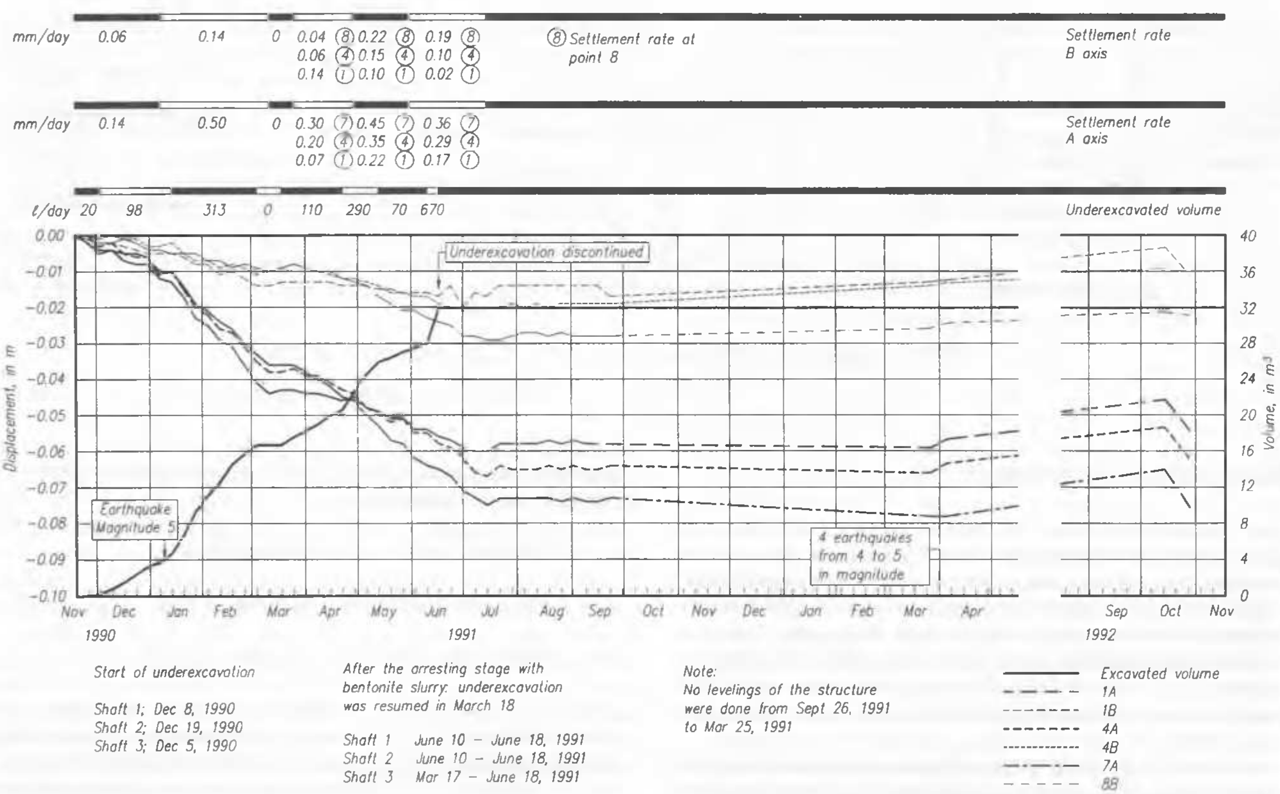

Fig 4 Underexcavated volume vs vertical displacement
San Antonio Abad Church

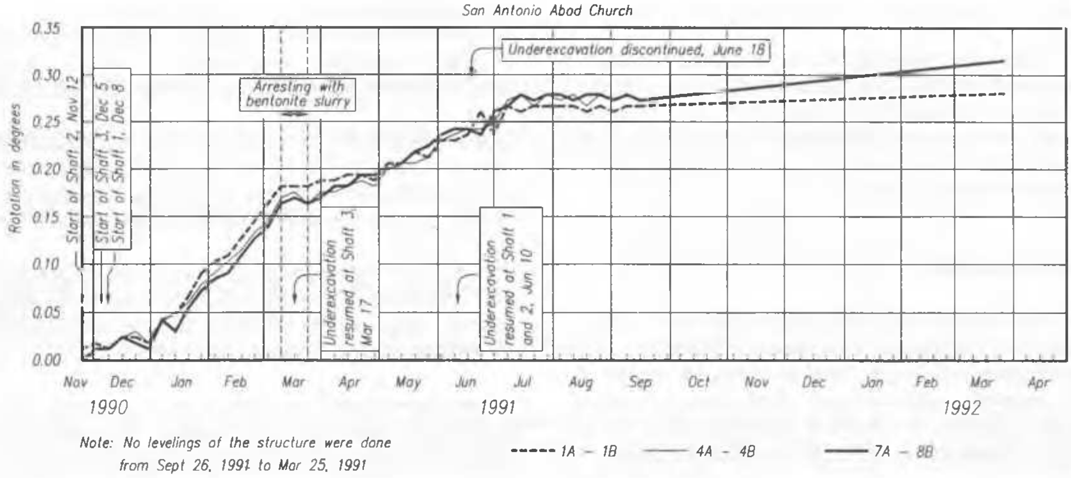

Fig 5 Transversal rotation during underexcavation

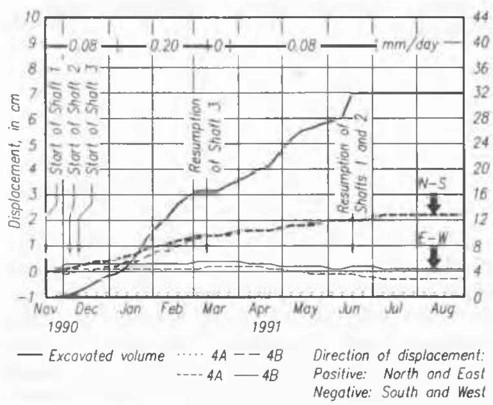

Fig 6 Underexcavated volume vs tilting

feasibility of applying the underexcavation procedure for levelling structures undergoing large differential settlements.

The first objective of the experiment, to induce rigid body rotations in the structure, was fully attained. Furthermore, displacement rates were imposed under controlled conditions to the structure and were large enough so as to compensate settlements induced by regional subsidence. As for the second phase of the experiment, the objectives were only partially fulfilled. Torsional movements were induced but the cracking of the vault could not be brought about. Had the experiment continued over a larger period of time, this objective would have been surely attained.

The experiment also showed that the observation of the structural behaviour is perhaps the single most important factor in applying the underexcavation technique. Predictive methods can be used to estimate the order of magnitude of the expected settlements and, hence, used as a first approximation for establishing underexcavation programmes. Nevertheless, the actual control of the

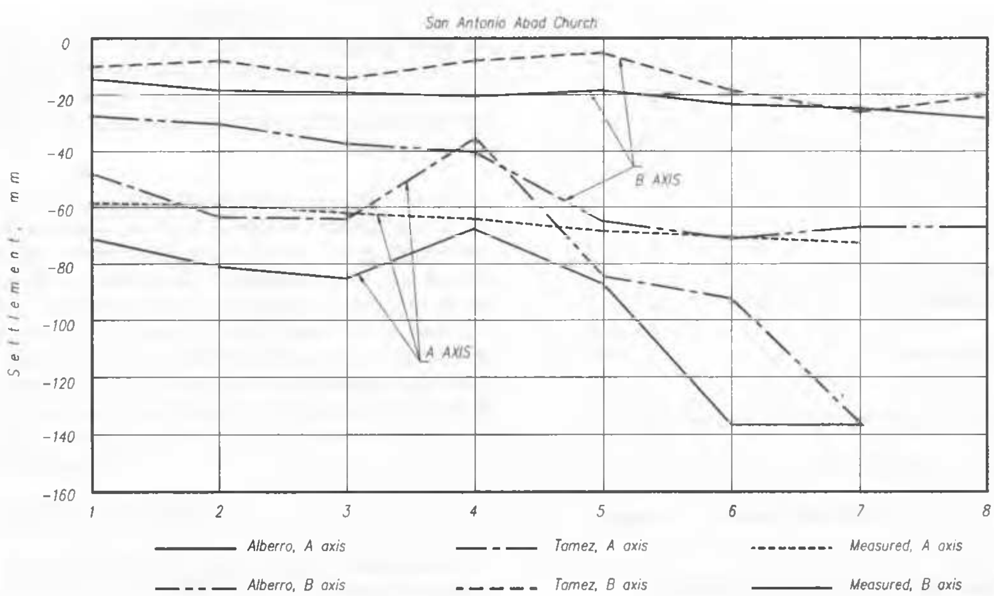

Fig 7 Measured and calculated vertical displacements along axes A and B of the San Antonio Abad Church

method must rely on observations taken during the course of underexcavation.

The use of rather unsphisticated equipment in the church of San Antonio Abad for monitoring its response proved to be adequate for the purposes of this experiment. However, this may not be the case in larger and more complex structures, in which extensive automatic continuous monitoring systems should be installed in order to control the underexcation sequence.

7. ACKNOWLEDGEMENTS

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