History approach to geotechnical design on heritage structures: mexico city´a met...

[Religion](), [Christianity]()

Abstract

This paper talks about the Mexico City´s Metropolitan Cathedral which was mitigated from deformations self weight consolidation and regional subsidence and further accumulation was prevented and it also puts forth suggestions for planning a post graduate course on Geotechnical Design focused on heritage structures, based on the study of case histories.

Introduction

In this paper we describe how geotechinal techniques were applied to the case of Mexico City’s Metropolitan Cathedral. The Metropolitan Cathedral in Mexico City was affected with fissures and cracks caused by differential settlements that became alarming in 1989 when the authorities decided to undergo yet another intervention, the fourth in the XXth century, to salvage the monument. Detailed discussions and descriptions of the relevant geotechnical aspects of the case have been published elsewhere (Tamez, et al, 1997; Ovando-Shelley and Santoyo, 2001; Santoyo and Ovando Shelley, 2004).

Geotechnichal Environment

Analysis of the 21 CPT tests and 2 borings and previous knowledge accumulated over the years in and around central Mexico City led to establishing the stratigraphical characteristics at the site. The soil at the boundary between both churches is stronger because it corresponds to the zone that has received the heaviest load transmitted by the Aztec temples, by an archaeological fill, and by the two heavy Colonial structures. Towards both ends of the profile penetration resistance reduces almost by a half. This condition induced the tilting of the southern part of the Cathedral towards the west whereas the Sagrario is inclined to the east. The depth of the contact plane between the natural shallow crust and the soft clays was defined from information derived from the CPT tests. The surface was originally flat but as a result of the consolidation induced by the Aztec pyramids it underwent depressions as deep as 10 m. This is why the site was leveled with artificial fills to shape a new initial plane before the construction of the Colonial churches. Estimations show that pore water may eventually define a hung aquifer formed by the infiltration of rainwater and by seepage from potable water and sewage mains.

Historic Survey

The area of metropolitan cathedral was originally covered by the main Aztec Ceremonial Precinct. The subsoil was initially reinforced by driving about 22, 500 wooden stakes, 3 to 4 m in length. On top of them a masonry platform was built over an area of 140×70 m. This area is larger than the one actually occupied by the Cathedral because it was originally conceived as a seven nave temple with four towers, one in each corner. Other religious buildings were built around the Cathedral. Consolidation of the subsoil induced by Aztec temples and structures pre-existing at the site produced differentials in the compressibility of the clay strata which in turn, caused differential settlements in the Cathedral since the beginning of its construction. Structural misalignments caused by these deformations were compensated as construction progressed by modifying the heights of columns and walls in order to level the springing of the vaults.

Diagnosis

The maximum differential settlement in the Cathedral over 419 years, until the end of 1989, was 2. 42 m, It is due consolidation induced by the weight of the pre-existing Aztec temples and of the subsequent Colonial structure; and regional subsidence of the city. The effect of regional subsidence on differential settlements at the structures was followed with precision topographic leveling surveys carried out at the Cathedral and the Sagrario during the stage of preliminary studies. The levelings were performed at the plane of the plinth of the columns supporting the Cathedral therefore allowing continuity in the leveling of this surface that have been carried out since 1907. A forecast of long-term settlements was carried out using traditional soil mechanics methods assuming that the churches would be left as they were in 1989. As mentioned before, future settlements at the Cathedral and the Sagrario depend on the evolution of the pore-water pressures in the clay deposits. These estimations showed that future differential settlements brought about by water pumping would endanger seriously the cathedral should no actions were to be taken to correct accumulated damage or to prevent it in the future. It was also concluded that a large magnitude earthquake such as the one that occurred in 1985 could induce a stress condition that could seriously compromise the stability of the churches, particularly that of the western tower. Hence it was necessary to reduce the magnitude of both accumulated and future differential settlements.

Solution Proposals

The following five possible solutions for correcting historic differential settlements and to reduce future differentials were studied: Piles supported on the Hard Layer: Aim was to uniform settlements by driving 1500 point-bearing piles to the First Hard Layer. Shafts supported by the Deep Deposits. Sinking of the two clay formation does not depend on the settlement of the structure for this type of solution. Underexcavation in soft clays. It would require excavating small diameter micro-tunnels that would close due to plastic deformation of the soft clays; successive opening and closure of the tunnels would gradually induce corrective settlements until reaching the deformation targets fixed according to structural considerations. Pore water recharge. They studied by recharging water artificially into the permeable subsoil strata. And found that this would control 70% of the settlement until the injected water remains permanently else it starts to settle again. Underpinning with micropiles. “ Pali radice” or inclined and vertical small-diameter micro-piles were also studied. Intertwined inside the clays, these elements create hard blocks that transfer loads to the deeper strata. This solution would require an enormous amount of such elements. After considering various factors like time, money, effective in all aspects it was concluded that the best solution was the Underexcavation Method.

Underexcavation At The Cathedral And The Sagrario

The main reason for introducing this technique is to reduce the tilting and differential elevation occurred due to differential settlements. This process also involved in bringing the higher parts to the lower level by extraction of bearing soil stratum. Three specific tasks were necessary to apply the method in our case: a) The construction of access shafts b) The punctual drawdown of the phreatic level and c) Under excavation or controlled extraction of small portions of soil until removing a pre established volume. Preparatory work began by excavating 32 access shafts whose number and distribution were determined applying analytical and numerical methods. Their bottom was taken down to top of the Upper Clay Formation, between 14 and 25 m. A pumping system was applied during the excavation to gradually drawdown the phreatic level and to prevent bottom failure; it operated throughout the whole soil extraction process. Precision topographic surveys were made by measuring 246 control points distributed over the whole area covered by the monument. These levellings were carried out every two weeks from October 1991 to the end of 1999; it was subsequently decided to schedule them monthly. 2000. Three levellings per year were done afterwards from 200 to 2004. Two levellings were made in 2005 and none in 2006; the last two levellings we made in December 2007 and December 2008.

Geometrical Correction Achieved

The maximum correction induced was 92 cm then, between the apse and the southwestern corner. However, in September 1999 it reduced to 88 cm and to 30 cm at the Sagrario. The difference from 92 to 88 cm is due, as discussed previously, to the return of the effects of regional subsidence upon the end of under excavation and the stoppage of the pumping operations. Under excavation initially induced movements to recover the confinement provided to the vault by the walls. Corrective settlements contributed to the closing of the cracks and to reducing tilts in columns. Analyses showed that the safety conditions of the churches were at no time at all in the course of the project in a situation of risk. The most critical aspect regarding the safety of both churches concentrated on the columns, and it was therefore decided to grout them to achieve long-lasting improvements in their safety factors.

Mortar Injections

To hardening selectively the underlying clays to attain a uniform or fairly uniform distribution of compressibility. This prompted the injection of grouts into the soft underlying clays, from 1910 to 1925. Those injections were aimed to arrest radically the settlements, although to no avail. Although this doesn't reduce the settlement but this made to settle uniform. Field tests showed that fluid mortar injected into the clay produces fissures and cracks along planes whose orientation depends on the initial in situ stress state. In this case mortar penetrates in the fissures forming vertical or nearly vertical sheets since Mexico City Clay is normally consolidated (the major principal stress is vertical). The test was followed with: a) Settlement measurements at different time intervals, within a grid of control points; b) Monitoring the hydraulic conditions within the clay mass before, during and after the test; c) Measurements of wave propagation velocities with a seismic cone and lateral stresses with a Marchetti dilatometer. The grout was made with a mixture of cement, bentonite, pumitic sand and admixtures. 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 total volume of mortar injected was 6934 m3.

Behavior After Grouting

Comparing settlement rates at the Cathedral and the Sagrario before and after injecting mortars proves that subsoil grouting was indeed successful. The maximum differential rate of 18 mm/year developed between the center and the northeast corner. Two conclusions can be derived: 1) injection of mortar grouts into the subsoil modified positively the pattern of settlement rates; and 2) This modification was beneficial for the structures because it achieved a substantial decrease of differential settlement rates.

Final Comments

The participation of engineers in patrimonial conservation projects complements the task of architects, historians, archaeologists and conservationists. Underexcavation was successfully applied at the Metropolitan Cathedral in Mexico City.