

Kerisel Lecture

Geotechnical engineering for the preservation of buildings in a sinking city

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ABSTRACT

Mexico City has drawn the attention of geotechnical engineers because of its extremely soft and compressible lacustrine clays. Difficult subsoil conditions prevailing there have posed special challenges to engineers and other specialists concerned with the preservation and conservation of its architectural heritage. This paper presents a cursory look into the general soil conditions in the city and into the factors that combine with them to endanger patrimonial buildings. The dominant factor in this respect is regional subsidence brought about by the exploitation of the deep aquifers that underlie the compressible soils. Effective stress increments caused by it induce damaging differential settlements in the totality of the city's urban infrastructure as well as changes in some of the soils' properties. This paper reviews these factors as well as the solutions that have been devised for correcting, reducing, or arresting differential settlements in its architectural heritage. The effects of regional subsidence are illustrated presenting several cases. Also, the advantages and limitations of traditional solutions are discussed, including the use of surface and compensated footings or deep point bearing piles and other deep foundation systems with devices for regulating the magnitude of loads applied on their heads. Less well-known solutions (underexcavation, mortar injection, and the use of isolation trenches) are also described and assessed critically. Overall, the paper highlights Geotechnical Engineering as being of paramount importance in the preservation and conservation of Mexico City's cultural heritage.

Keywords: *Mexico City Clays, regional subsidence, patrimonial buildings, conservation strategies*

INTRODUCTION

Mexico City lies within a basin surrounded by volcanic ranges whose lower parts, some 2050 km², were once covered by a system of interconnected lakes. The central part of the city is located on the southwestern portion of the basin and a large part of it rests over lacustrine clays. The lake system is practically non-existent nowadays because it has been desiccated progressively over the last 400 years or so. The geological processes that created the conditions for the deposition of the extremely soft and compressible clays that occupy the uppermost strata therein, have been discussed amply elsewhere by Mooser (2000). Investigations into the engineering properties of these matters were initiated several decades ago and are still on-going (Marsal and Mazari, 1959; Zeevaert, 1971; Romo et al, 1988; Girault, 1964; Santoyo et al, 2005; Ovando-Shelley, 2011, 2021).

These clays are notorious for their extremely high water contents, their very low shear strength and their extraordinarily large compressibility. These characteristics can be explained, at least partly, by the large amounts of porous diatomaceous microfossils and ostracods they contain, the quantities of which depend

on the climatic conditions at the time the soil strata were formed and that also influence the degree of chemical affinity among the clay constituents (Peralta, 1973).

It has also been recognized that the huge dynamic amplifications observed during earthquakes in the former lakebed are due to a large degree to the dynamic properties of the soft Mexico Basin Clays. Research into this aspect became of paramount importance after the huge Michoacán Earthquake of 1985 (Rosenblueth & Ovando, 1991). The earthquakes of 7 and 19 September 2017 are cruel reminders of the need for continuing this endeavour.

The Aztecs founded the city of Mexico-Tenochtitlan in 1325 in an islet in the middle of the former lake. The Aztec pyramids, massive earthen structures clad with stone and coloured stucco, underwent extremely large settlements and had to be repaired periodically. Upon the fall of the Aztec empire, the Spaniards demolished the Aztec city and their new city was built literally over the pre-existing one. Spanish masons adapted and used foundation techniques devised by the Aztecs, such as short stakes with flat stone heads and also introduced European construction techniques, not always successfully. In order to limit and mitigate the problems caused by differential settlements induced by the self-weight of structures and in lieu of other technological resources, the height of most structures was generally limited to two stories, with the exception of bell towers in many churches. This limit was recommended in 1550 to avoid their collapse and to avoid earthquake related damage (this is probably the first rule for building earthquake-resistant structures in the Americas). Matters were aggravated because the city flooded periodically.

In general, the smaller early Spanish structures, dwellings, and private houses, only lasted for a few decades. In the erection of large manor houses, palaces, civic buildings, or the larger religious buildings such as convents and churches, engineers used ingenuity, patience, and large amounts of money. Innovative foundation solutions were tried and tested in many cases. In this respect, the building of the Metropolitan Cathedral is seminal since a huge masonry platform — actually a foundation raft of large proportions, 60 by 120 m approximately — was used for the first time in the city in 1573. These more massive structures were subjected to recurrent interventions to correct structural damage caused by differential settlements induced by the consolidation of the underlying clays produced by the overburdens imposed on the soil by the structures themselves. On many occasions, foundations were altered, and underpinning of the larger convent churches and cloisters was not rare. Overall, the approach for building foundations and foundation systems was empirical, and it was late in the nineteenth century when attempts to rationalize these techniques were first introduced.

Problems in buildings caused by differential settlements have been aggravated due to the exploitation of the aquifer that underlies the clays of the former lake area. Pumping of water from the aquifer began in the second half of the nineteenth century and induced a consolidation process in the clay strata, which in turn produced regional subsidence that continues to the present day, as initially explained by Carrillo (1948). Resulting settlements are far from being uniform. Structures built on these grounds accumulate differential settlements and irreversible structural damage gradually builds up. This, in turn, increases their vulnerability to other detrimental agents such as the recurrent earthquakes that affect the city.

Old buildings erected after the fall of the Aztec Empire were first subjected to the effects of differential settlements induced by self-weight and, much later, to those originated by regional subsidence. Today, the latter produces the most detrimental effects. Settlement rates in the central part of the city can be correlated to water extraction rates; presently central Mexico City is subsiding between 8 and 12 cm/year, but there are zones in the outskirts, towards the edges of the former lake bed, where the ground settles 40 to 60 cm/year (Santoyo et al, 2005).

The consolidation process triggered by the depletion of pore pressures inside the clay masses can be mitigated significantly if pumping of water from the aquifer were to be banned or stopped altogether, a situation which is not likely to occur given the urban and demographic trends observed over the past decades in the city. Even if that were to happen, the effects of that stoppage would only be noticeable in the midterm. It should also be appreciated that more than two-thirds of the water consumed in the city is pumped from the underlying aquifer.

Differential settlements will continue to occur in the foreseeable future and most of the architectural heritage of the city will be increasingly endangered. In dealing with this problem, geotechnical engineers face an enormous challenge for which it is necessary, among other things, to review critically some of the solutions put forward previously to mitigate the effects of differential settlements on structures.

GEOTECHNICAL CONDITIONS

As indicated previously, geotechnical conditions in Mexico City have been studied systematically since the 1950's and are reasonably well established. The geological processes present in the Basin of Mexico resulted in an ordered sequence of soft clay strata interspersed with lenses and layers of harder clayey silts with sands, which is present in the larger part of the area occupied by the lakes. This in turn, allows for the formulation of a rather simple stratigraphical model which is well known by local engineers. A summary of the main stratigraphical characteristics is presented next.

Stratigraphy in the city area

A west-east profile passing through the centre of the city, Figure 1, can be used to illustrate the main soil strata present in the subsoil of Mexico City. The main part of the city is located on the western portion of the lake and spreads up the hills on that side of the valley. The stratigraphical model can be derived from that figure, as follows:

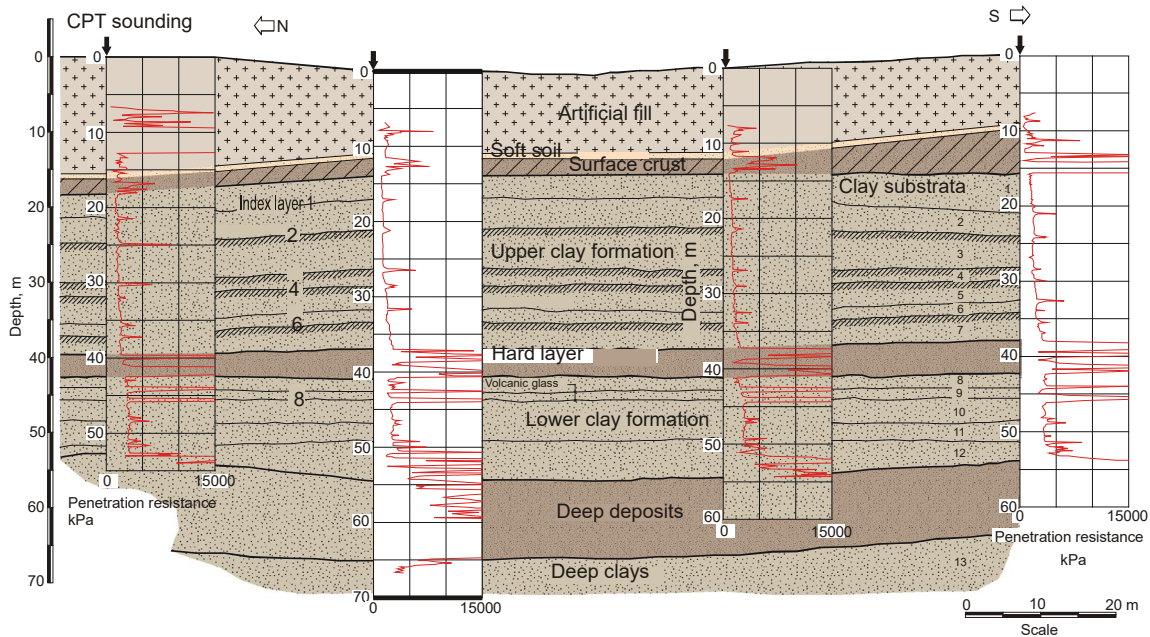


Figure 1 Stratigraphy along an East-West axis in central Mexico City (after Santoyo et al, 2005)

Surficial soils. A large portion of Central Mexico City rests on artificial fills, on many occasions the ruins of old pre-Hispanic buildings. The thickness of these fills, rubble, or masonry fragments within a remoulded clay matrix, can vary sharply over short distances in the older part of the city where they sometimes reach depths of more than 15 m. In sites with no artificial fills, a hard desiccated natural crust formed by low plasticity silts and silty or clayey fine sand, MH-ML, constitutes the upper stratum and gets thinner or may even be absent towards the east.

Upper clay formation. These are extremely compressible, highly plastic, volcanic clays interspersed with relatively thin lenses of volcanic ashes or sandy silts. Water contents in sites not subjected to surficial loads, mainly in the east, can sometimes be as high as 500% whilst in the clays found in the central part of the city, i.e., in sites subjected to large, permanent surface loads, it may vary between 150 to 250%. These clays can be as thick as 40 m in the centre of the lake and only about 25 m in the old city core.

First hard layer. This is a sequence of seams and lenses of sands and sandy silts with clayey silts; softer silty clays are usually found between these seams. Coarser materials, even gravels, may be found towards the west, near the edge of old lakebed, where its thickness can exceed 3 m and it gets thinner as one runs towards the centre of the valley, where it may be absent or only be a few decimetres thick.

Lower clay formation. These are also highly compressible clays that have been subjected to much larger overburdens and, consequently, are less compressible and display larger shear strengths than the upper clay formation. Its thickness varies from about 5 to 10 m and is also interspersed with three or four layers of sands and sandy silts. Its base is found at depths of about 55 m in the centre of the city and at more than 70 m in the east side.

Deep deposits. These are alluvial deposits which include sands, coarse sand and gravel as well as older, more consolidated, lacustrine clays that overlie the basalts, in the east, and volcanic tuffs, in the west, that constitute the base rocks.

For almost all practical purposes foundation engineering or problems related to regional subsidence and seismic response! the relevant strata reach down to the second clay formation. This stratigraphical model is applicable in the larger part of the Lake Zone.

Evolution of soil properties

As a result of the on-going consolidation process that brings about regional subsidence, strength and stiffness of the relevant soil strata change. The graph in Figure 2 shows the evolution of CPT strength over a 14 year period at a site in the former lake area.

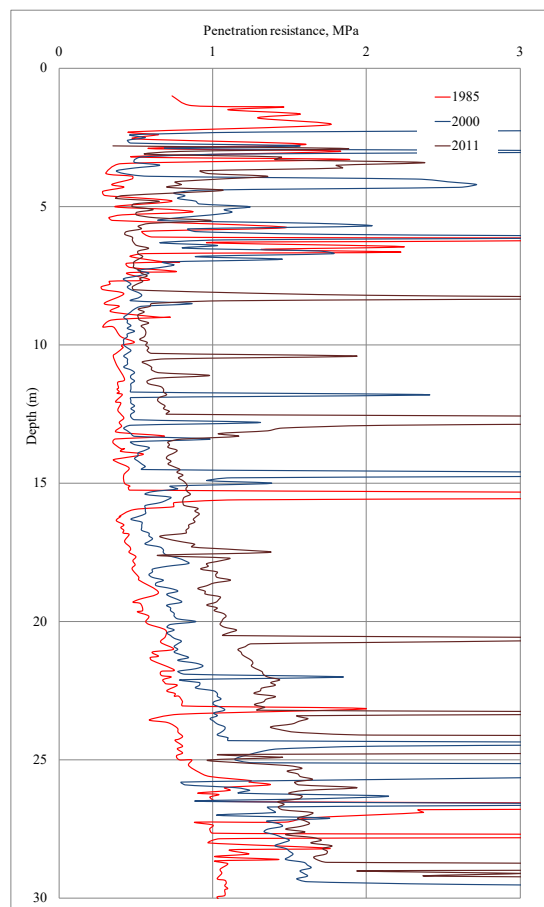


Figure 2 Evolution of CPT strength at the SCT site in the former lake bed.

Note that the CPT profiles can also be used to assess the compression of the deformable strata. Shear wave velocities also change with time as shown in Figure 3 with the results of suspension logging data (Kitsunesaki, 1980) for soundings at the same site and over the same period. As the depletion of pore pressures continues, effective stress increments gradually occur. Overconsolidated soil elements in e vs σ' space will get closer to their virgin consolidation line and will eventually yield, if exploitation of deep wells persists. Results of oedometer tests given in Figure 4 and performed on soils, sampled at the same site and retrieved from the same stratum show changes of void ratio over time as well as the changes of yield stresses. The graph also shows that the virgin consolidation line of the three samples is essentially the same. The tests performed in 1986 and 2001 were carried out following exactly the same procedures as those followed in 1959 by Marsal & Mazari (1957).

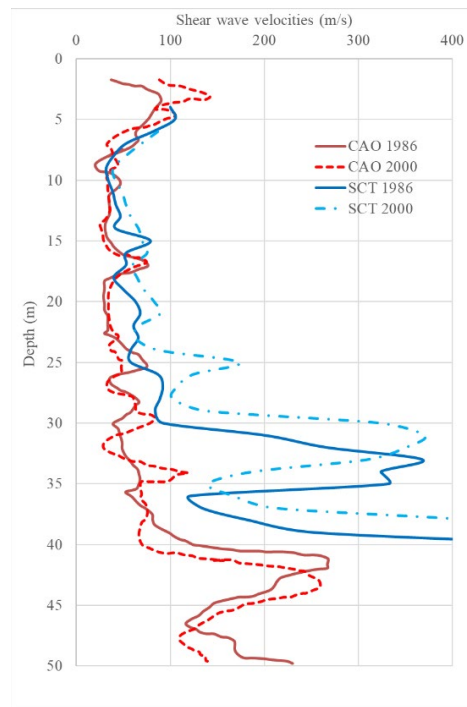


Figure 3 Evolution of shear wave velocities at the SCT and the CAO sites in the former lake bed.

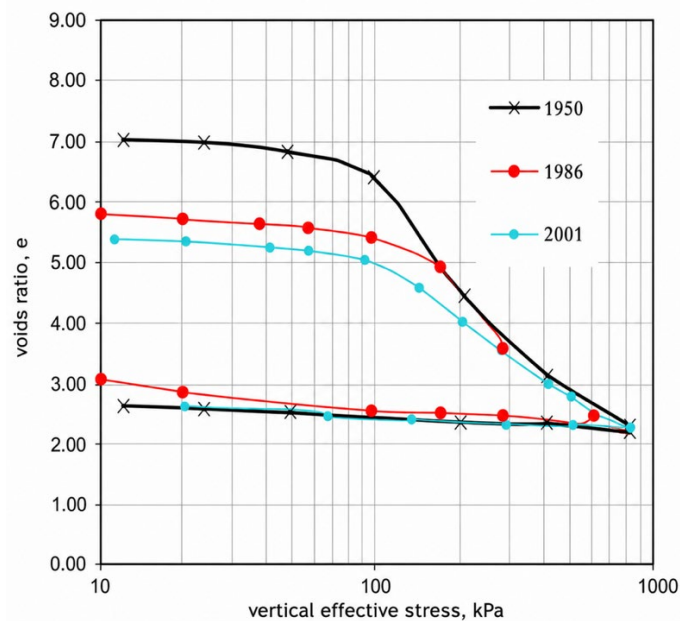


Figure 4 Results of oedometer tests performed on samples retrieved from the same stratum at the same site in the former lake bed (After Ovando-Shelley, 2021)

Theoretical models have been developed to study the evolution of pore pressures due to deep well pumping. The first such proposal was due to Carrillo (1948) who applied Terzaghi's consolidation theory to explain rationally the regional subsidence in the city. Other models that overcome some of the limitations of Terzaghi's have also been used to estimate the evolution of pore pressures within the compressible strata as well as the resulting effective stress increments. These models assume the compressible clay strata are elasto-plastic-viscous materials (Ovando-Shelley et al, 2007; González et al, 2020, 2024; Manica et al, 2020).

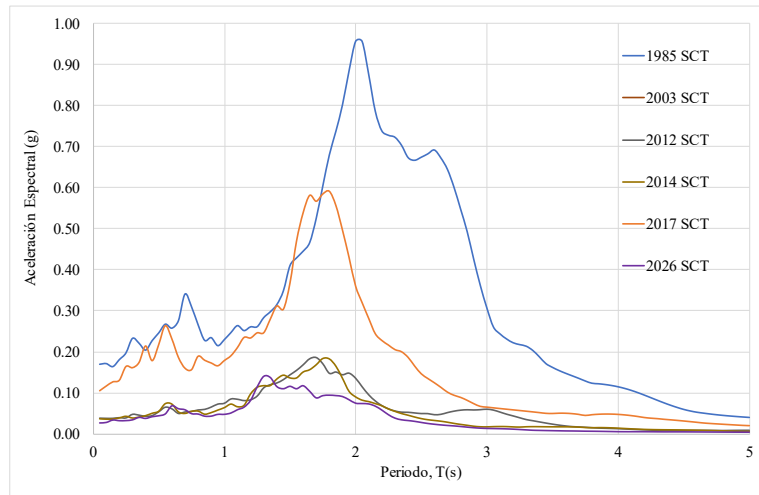


Figure 5 Response spectra calculated from acceleration records obtained during several earthquakes at the SCT in the former lake bed.

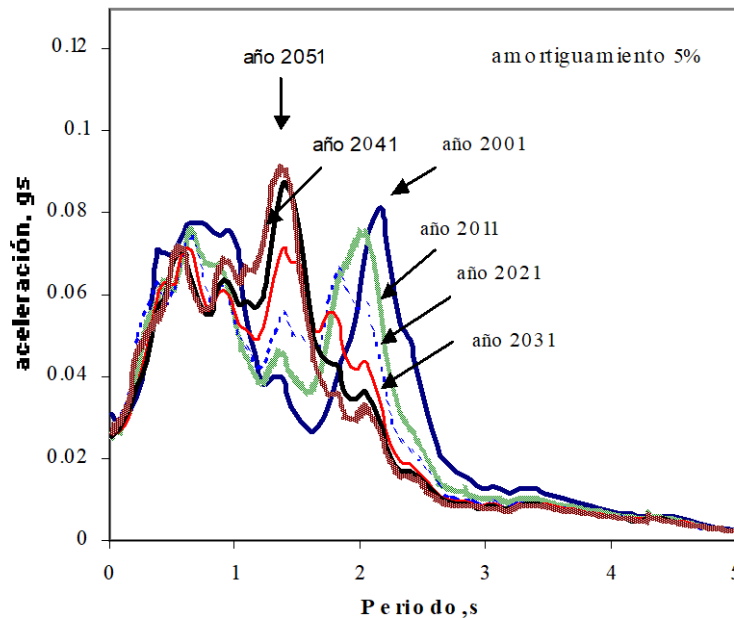


Figure 6 Evolution of response spectra at a site near the Metropolitan Cathedral in central Mexico City.

These changes of effective stress also modify seismic soil response. Response spectra obtained from several acceleration histories recorded during at the SCT site within the former lake zone show in Figure 5 the shortening of dominant period, as the soil stiffens due to effective stress increments caused by deep well pumping.

Estimates of the evolution of seismic site response have also been provided elsewhere (Ovando-Shelley et al, 2013) for site at central Mexico City, next to the Metropolitan Cathedral, as illustrated in Figure 6. Response spectra shown there were calculated applying the viscous-elasto-plastic model mentioned previously from which evolution of pore pressures and effective stress increments were obtained. Soil properties, static and dynamic, were modified accordingly. One dimensional site response analyses were then performed in the modified strata to obtain the estimated response spectra shown in Figure 6 that have been described in full detail previously (Ovando et al, 2007). Input motions at the base of the compressible strata were derived from acceleration records obtained during the Tehuacan Earthquake of 1999.

Summarizing, regional subsidence does not occur uniformly in the former lake area on account of the heterogeneous distribution of compressibilities at specific sites caused by local evolution of stress histories and by stratigraphical variations induced by differential compressions in the relevant strata. Self-weight consolidation induced by most of the structures erected during the Spanish rule has already finished. Presently, regional subsidence has been the major factor inducing the apparition and evolution of differential settlements in those buildings for the last 150 years, at least. Earthquakes have also produced damage and are increasingly hazardous for the architectural heritage of the city since the progressive accumulation of differential settlements increases their seismic vulnerability.

EFFECTS OF REGIONAL SUBSIDENCE ON CULTURAL HERITAGE

Settlements induced by deep well pumping have been recorded since the middle of the XIXth century by means of conventional topographic levellings. A reference point located near the base of the west tower of the Metropolitan Cathedral in has subsided nearly 15 m over nearly 120 years (Santoyo & Ovando, 2004; Tamez et al, 2007). Deep bench marks installed nearby display the compression of deformable strata down to a depth of 100 m, as seen in Figure 7. The overall settlement has varied between 2.0 and 9.0 cm/year from 1992 to 2025. Note that the contribution of soils below 100 m is rather important since the compression of those strata represents 69 to 58 % of the total overall settlement from 2012 to 2025 These deeper soils have only been studied marginally in the past and are practically unknown nowadays, a situation that must certainly be reversed.

Figure 7 *Records of deep bench marks installed at the Metropolitan Cathedral.*

Lately Interferometric Synthetic Aperture Radar (InSAR) has been applied in the city as a means for monitoring and measuring ground movements. InSAR has allowed for the detection of both widespread subsidence patterns and localized deformations with high precision. Furthermore, buildings and infrastructure at significant risk due to ongoing subsidence have also been identified, as exemplified by Poreh et al (2021).



Figure 8 Left: Remains of the Main Aztec Temple in 1924. Right: The remains as seen in 2022

After the fall of the Aztec City in 1521, the Spaniards destroyed the pyramids, the temples and the palaces that once formed part of the pre-hispanic religious precinct were razed and were literally buried to enable the construction of the new city. Spanish buildings were then built on top of the Aztec ruins and remained covered for more than three centuries, until 1978 when important archaeological findings prompted the execution of excavations to explore the remains of the main Aztec temple. The photograph in the left-hand side of Figure 8 shows a view of the site in 1924 when the remains of the Main Temple were partially covered by the colonial buildings. As seen there, the ruins were still seen below the street level. The picture in right hand side of Figure 8 shows the site in 2022, a few years after the beginning of the excavations that uncovered most of the former Main Temple. Its ruins are now above the street level. The removal of the colonial structures in 1978 overconsolidated the underlying clays and, when subjected to the on-going regional consolidation process, they are sinking at a smaller rate than the surroundings. Hence, they are emerging with respect to adjacent sites. Also note that the relative emergence is not taking place uniformly due to the different stress histories induced at the centre and the periphery of the ancient pyramidal temple.

Other examples of the effects of regional subsidence are given Figures 9 and 10 which show, respectively, the emergence of deep well casings installed originally in the early XXth century at a site in central Mexico City. As seen there, the magnitude of settlements that occurred in the city over nearly one hundred years exceeded 7 m. Differential settlements on a XVIIIth century building, century School for Girls (Colegio de las Vizcaínas) are evinced by Figure 10 in 1950. Not surprisingly, cracks and fissures result as a consequence, affecting the structural integrity of the building.

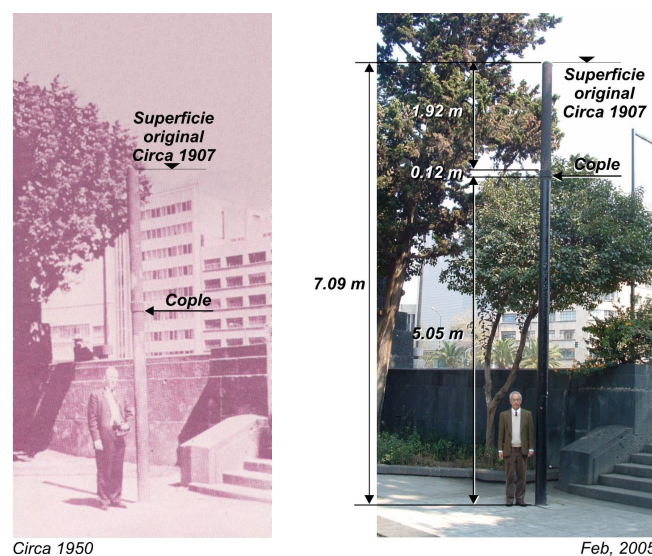


Figure 9 Relative emergence of deep well casings in central Mexico City



Figure 10 A XVIIIth century building as seen in the 1920s (left) and the 1970s (right)

REMEDIAL MEASURES

A necessary first step towards restoring and preserving a monument is to identify the factor or factors that bring about damage. Structural damage can be usually related to either stress or strain concentrations which are the result of the accumulation of unwanted deformations. Before acting on a monument it is useful to have a conceptual framework with which geotechnical engineers will gain insight into the nature of the problem and within which the applicability and efficacy of plausible intervention techniques to solve the problem under consideration can be assessed qualitatively. The basic principles of Geotechnical Engineering provide the necessary framework subject to the constraints resulting from regulations imposed by conservationists or others (historians, politicians, urban planners, social organizations, etc). The study of soil conditions must aim at the reconstruction of the effective-stress-history at the site. In this context historical research must not be limited to the building, it must also include the soil. Geologists, historians and archaeologists can provide useful data and information. Documentary research is also useful.

Notwithstanding that differential settlements affecting buildings and urban infrastructure in Mexico City are brought about by regional subsidence, other factors may also need to be accounted for in the assessment of feasible remedial measures. Congenital factors like design or construction errors may prompt the apparition of unwanted settlements as well as changes in building use or in environmental factors. Another well-known factor is the increase of water content in the soil mass by floodings; leaks in sewage or water supply pipes have enhanced the apparition settlements. Reduction of humidity in the subsoil has also been identified as a factor that can potentially induce unwanted soil displacements. Removal of trees or removal of humidity, existence or construction of underground structures and also by geotechnical peculiarities at the site (hard spots, soft spots), or by nearby excavations nearby, construction of buildings nearby, slope instability, earthquakes.

As to the nature of the measures that can be taken, some are preventive and others, corrective. Most solutions to correct or prevent the apparition of differential settlements can be drawn from existing or accepted Foundation Engineering practice. Regarding engineering practice in Mexico City, some of these measures were mainly based on empirism and it wasn't until late in XIXth that engineers tried to limit overburden stresses transmitted to the underlying soil in new constructions. The rule of thumb consisted on limiting contact stresses in foundation element to not more than 50 kPa. In old buildings bearing capacity problems are by far the less frequent, they occur mainly in the short term. They usually arise if a disrupting agent introduces changes in the prevailing geotechnical conditions. Natural agents like torrential rains, flooding or earthquakes, even tsunamis in coastal areas, may reduce shear strength or increase applied stress leading to bearing capacity failures. Anthropic agents can be equally disrupting and in the case of bearing capacity problems, are

mainly related to man-induced changes in water content within soil masses like leakage from cisterns, sewage or water supply lines, construction of dams or channels, or, among others, excavations in neighbouring sites, construction of buildings in the vicinity or tunnelling under the monument.

Underpinning

In Mexico City, broadening of surficial footings or the restoration of original foundation elements have been used in some cases. These are measures that apart from reducing stresses in the subsoil may also be complemented with elements to stiffen the foundation system. These measures do not necessarily avoid the exposure of the foundation system to the effects of regional subsidence but may improve its structural capacity for undergoing stresses induced by differential settlements. Broadened footings have also been combined in a few cases with the addition of micropiles forming arrays similar to *pali radice*.

Compensated foundations

The well-known basic idea of this foundation type is to balance the weight of a new structure with the weight of soil excavated for its construction, often incorporating deep basements to reduce net settlement on soft ground. This technique was first used in the late XIXth but no records exist to document its usage. A better-known case is the building of the National Lottery near the city centre. It was built between 1945 and 1946. Its foundation was conceived by José Antonio Cuevas and was reported in the 1936 International Conference of Soil Mechanics (González C., 1936). The photograph in Figure 11 shows the building as it looked in 1946 and the sketch also shown there illustrates the foundation slab with individual cells that could be filled with water selectively to correct differential settlements, if required.

Many modern buildings in the city have compensated foundations, some of them having friction piles as settlement reducing devices. The local building code includes design guidelines that, when applied judiciously, lead to reliable solutions.

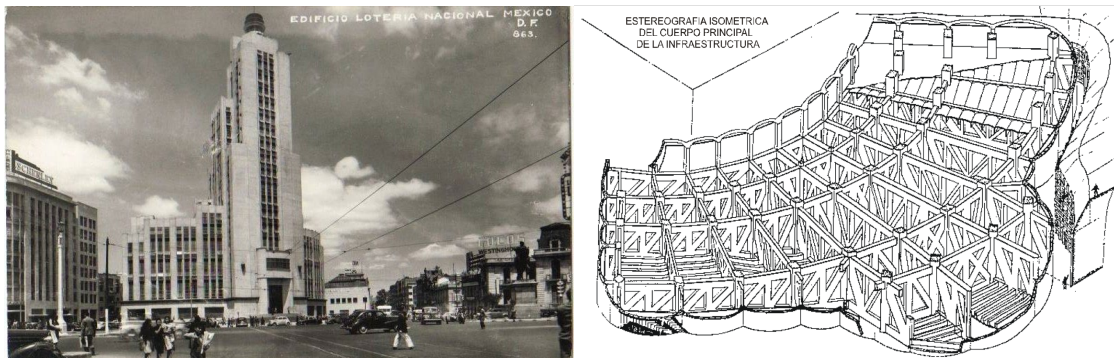


Figure 11 Left: the building of the National Lottery in central Mexico City. Right: Conceptual sketch of its compensated foundation.

Point bearing piles

Differential settlements can be eliminated altogether if deep foundation elements, point bearing piles driven down to either the First Hard Layer or to the Deep Deposits. There are many tall buildings that have foundations of this kind and in all of them provisions must be taken to deal with relative emergence, a situation that can have a very detrimental effect on light weight neighbouring structures.

The monument to the Independence, built in the early XXth century and inaugurated in 1910, provides an iconic example of the use of point bearing piles in the city. The monument is a 36 m tall tower that was initially conceived having a large and very rigid surficial foundation slab. As the tower was being



Figure 12 The monument to the Independence of Mexico. Left: View as it stood in 1910. Right: View as it stood recently

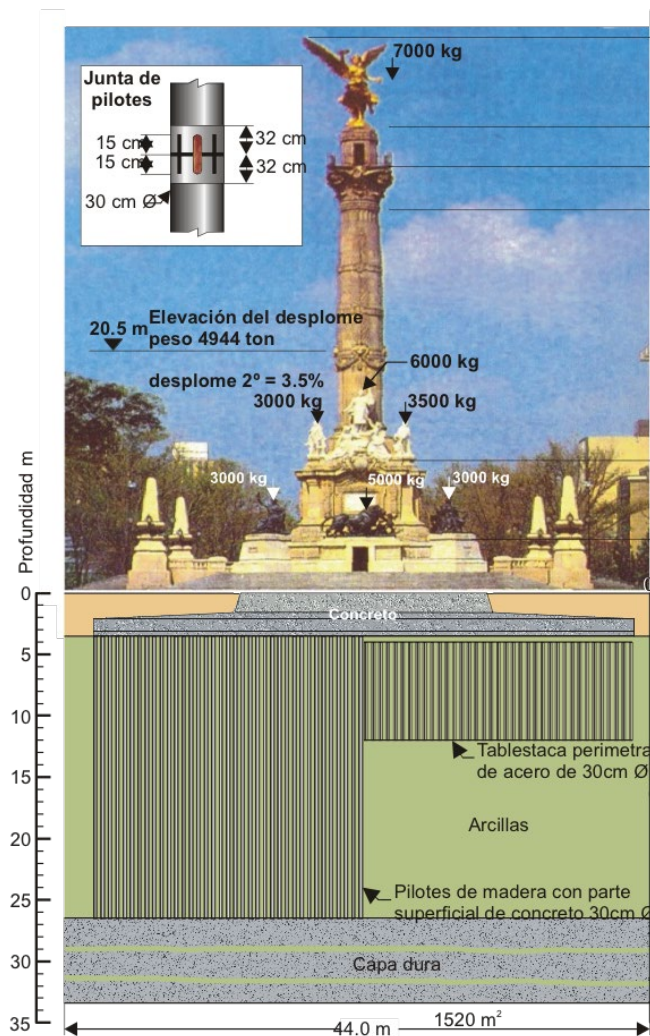


Figure 13 *Point bearing piles used as the foundation system in the monument to the Independence of Mexico*

built, it began to settle differentially and when it was about 12 m tall, tilts and settlements became intolerable. The technical staff headed by Architect Antonio Rivas-Mercado, decided to demolish the tower and decided to rebuild it from scratch. Although there are no records of the actual construction works, it has been estimated that 4.670 wooden piles were driven down to the first hard layer (Santoyo et al, 2005). The photographs of Figure 12 show the monument shortly after its inauguration in 1910 as well as the monument as it stands now-a-day. Its relative emergence is quite evident albeit no measurable tilts or differential settlements have occurred, to this Author's knowledge. Figure 13 gives a conceptual sketch of its foundation

Control piles

Another common solution for reducing or preventing the apparition of differential settlements is the use of control piles. These are point bearing piles with control elements on the pile heads, as shown in Figure14. As seen there, piles are not directly linked to the foundation slab. Instead, the pile heads are provided with a rigid steel frame anchored to the slab. Deformable elements are placed between the pile head and the steel frame. These are wooden cubes that are meant to behave as elasto-plastic materials. Their yield stress is then used to limit the load transmitted to the piles. As the cubes yield, the load on the pile head is constant while accumulating deformations until, eventually, the cubes must be replaced. There are quite a few buildings founded on control piles in the city including some heritage buildings as well. In the Metropolitan Cathedral, 390 control piles were installed as well as 129 in adjoining Sagrario Church, from 1972 to 1975. The piles were intended to "reduce load demands on the foundation in about 25 %, to adjust the descent of the building with respect its surroundings and to achieve a uniform distribution of settlements". Practical difficulties impeded the adequate installation of many of the piles. Indeed, it was estimated that only 27% of the piles were properly supported by the First Hard Layer at the Cathedral and just 11% at the Sagrario (Santoyo & Ovando-Shelley, 2004) and that is why differential settlements could not be corrected nor prevented and their overall effect was negligible.

Control piles have serious drawbacks when subjected to seismic loads since they can only sustain compressive loads. In tall, slender buildings subjected to strong overturning moments during earthquakes, this can be a serious limitation. Also, their capacity for resisting seismic base shears is also limited. Finally, the capacity of the wooden cubes used to control loads on the pile heads will also be substantially reduced when wetted.

Figure 14 *Components of the device to control settlements in "control piles" (After Santoyo et al, 2005)*

Under excavation

Underexcavation is a corrective measure that was used empirically in the UK and in at least three other European countries in the XIXth century, as described by Johnston & Burland (2000). In Mexico City, it was used in the Guadalupe Shrine, a non-documented project, before it was applied in the Metropolitan Cathedral, between 1993 and 1998 (Santoyo & Ovando-Shelley,2004). Later, the method was modified

and adapted in the Tower of Pisa where it was applied between 1999 and 2001. The Geometrical Correction of Mexico City's Metropolitan Cathedral and the Sagrario Church is an iconic project in which the method was applied successfully and has been referenced extensively (Ovando-Shelley et al., 2015; Tamez et al, 1997; Ovando-Shelley & Santoyo, 2020).

Underexcavation has been regarded as a "soft" procedure in that it can be applied at adequate rates, depending on soil type, soil history and effective soil stress conditions. The type and structural characteristics of the intervened building must also be considered. The term "soft" also relates to the fact that the procedure is carried stepwise so that after each underexcavation cycle, sufficient time is allowed to assess its effects, by means of adequate instrumentation systems. That is, the control of an underexcavation project should rely heavily on the application of the Observational Method. In this regard, it must also be recognized that the analytical assessments of the effects of underexcavation can be extremely difficult and on many occasions, imprecise.

Underexcavation in the Metropolitan Cathedral and the adjoining Sagrario Church was carried out from the bottom of 32 concrete-lined shafts with which 4.220 m³ of soil were extracted, inducing corrective differential settlements (see Figure 15). The procedure was monitored performing fortnightly precision levellings and by instrumented plumb lines (tele-coordinometers) installed in both towers, the transept, and the apse. Induced corrective settlements are illustrated in Figure 16. The maximum differential settlement at the beginning of the project was 240 cm, between the apse and the base of the western tower and, as seen in Figure 16, the induced corrective settlement after underexcavation was 85 cm. Underexcavation was suspended in 1998 to avoid unwanted structural damage.

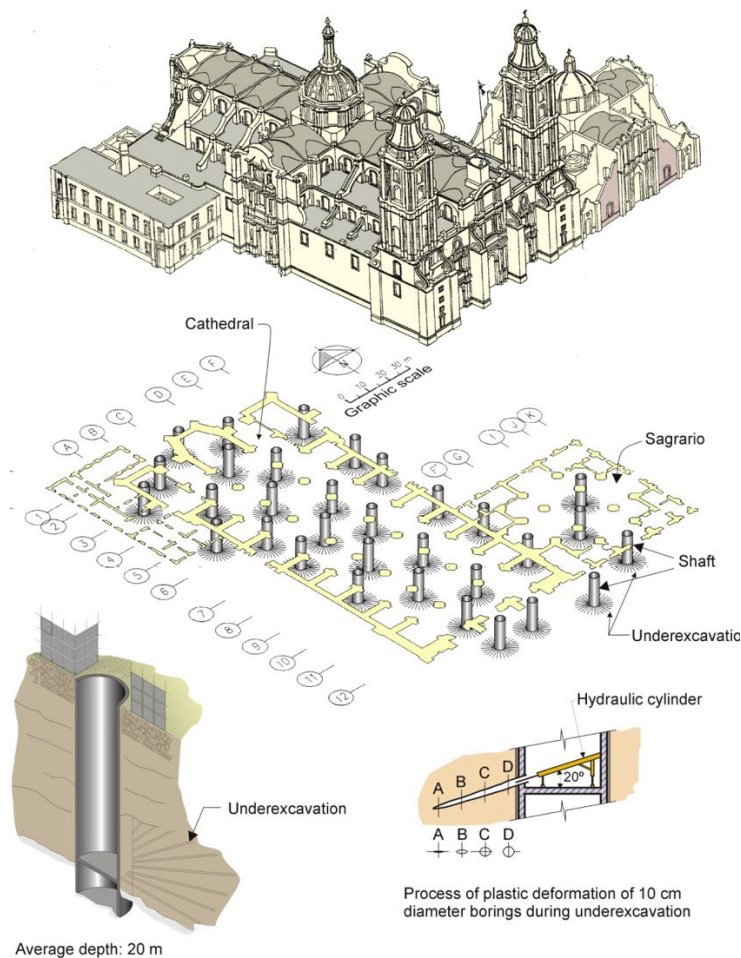


Figure 15 Schematic representation of underexcavation at the Metropolitan Cathedral (After Ovando-Shelley & Santoyo, 2020)

The goals set by a team of architectural conservationists as well as structural and geotechnical engineers were: 1) to sink the apse from 80 to 95 cm, following as much as possible a rigid body movement; 2) to induce a complementary closing or rotation of the lateral walls to reinforce the confinement of the “counteracting belt” constituted by the interior walls of the chapels and by the walls along the perimeter of the church; and 3) to rotate the *Sagrario* church sinking 30 cm its northern side

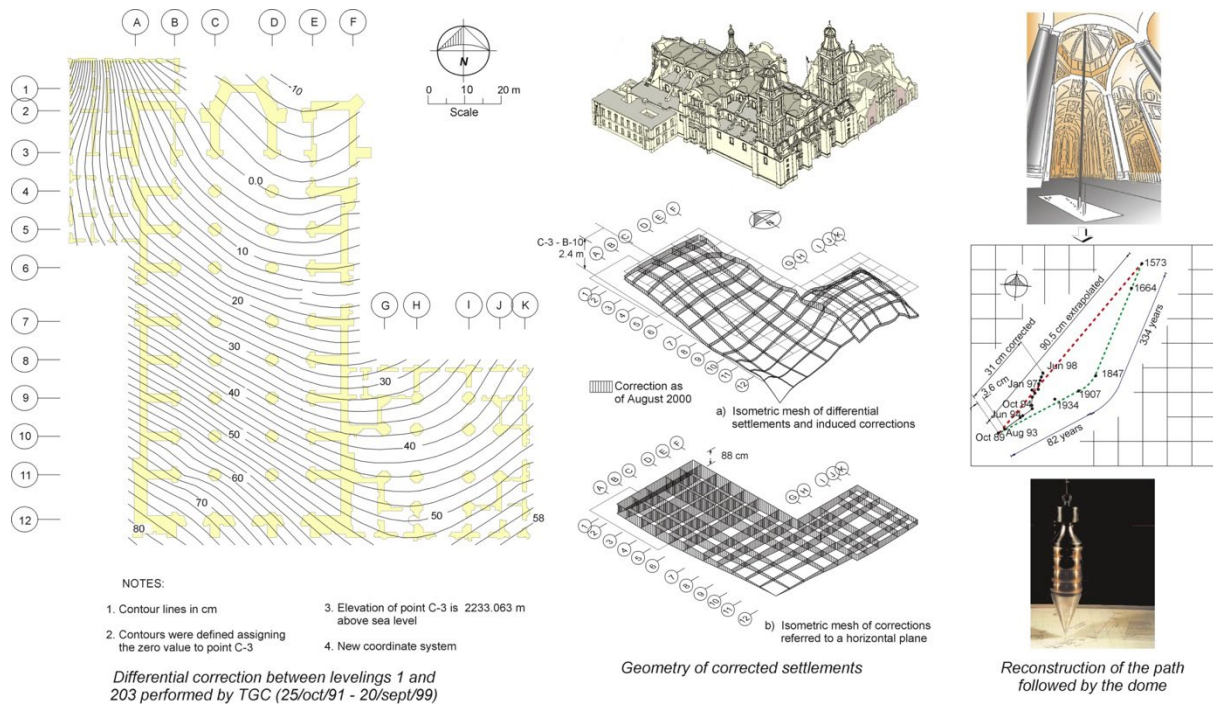


Figure 16 Corrective settlements achieved by underexcavation (After Ovando-Shelley & Santoyo, 2020)

The techniques and the method developed and applied in the Metropolitan Cathedral demonstrated that underexcavation can be safely applied as a corrective measure that can also be adapted to the solution of specific individual cases. The method has been applied in Mexico City to induce corrective settlements in many structures, not exclusively in those regarded as Heritage Buildings.

SELECTVIE HARDENING

Since the harmful effects of the regional subsidence turned up again upon suspension of the underexcavation works in June 1998, part of the corrections achieved was lost. Additional underexcavation cycles would have been required to preserve the corrections achieved (Tamez et al, 1997). Instead, it was decided to grout the softest areas of the subsoil in order to reduce the compressibility of the soil treated in this manner. Injections of setting mortars have traditionally been used in geotechnical applications mainly to produce impermeable barriers in the foundations of dams or other larger structures. Recently, “compensation grouting” has been used reduce settlements induced by tunnelling in overconsolidated clays (e.g., Harris et al, 2000). Very seldom have grouts been used in very soft normally consolidated clays.

The authors studied in detail the case of the Palacio de Bellas Artes (Palace of fine Arts) where, during the construction of its foundation slab in 1906, large differential settlements began to accumulate. Because of this, it was decided to harden the subsoil by means of setting mortars, first with a cement grout and later with a fluid mortar possibly made with lime and sand. The objective sought for with those injections that took place from 1910 to 1925 was to radically arrest the total settlements, although to no avail. It must now be acknowledged that a great success was achieved through the grouting because,

although the settlements were not stopped, they became uniform and structural damages to the theater were avoided.

Fluids injected under pressure into soft materials having low shear strengths, like Mexico City clay, produce hydraulic fracturing. Injected grout penetrates into the fissures and cracks and when it sets, the compressibility of the soil treated in this way will reduce. Mortars injected into the soil form sheets whose orientations depend on the stress state within the soil. Basic fracture mechanics showed that in this case (normally consolidated or lightly overconsolidated materials) they would be vertical or nearly so whereas in highly overconsolidated soils, the sheets turn out being horizontal.

First stage of subsoil hardening. Deformable mortar was injected from 571 cores with their respective clusters of lateral sheets. These cores were introduced at the Upper Clay Formation as follows: 419 at the Cathedral, 111 at the *Sagrario*, and 41 at the museum building (see Figure 17). Grouts were distributed in terms of the zoning determined for the subsoil compressibility and was adjusted applying the observational method. The volume of mortar required to be injected amounts to 6934 m³.

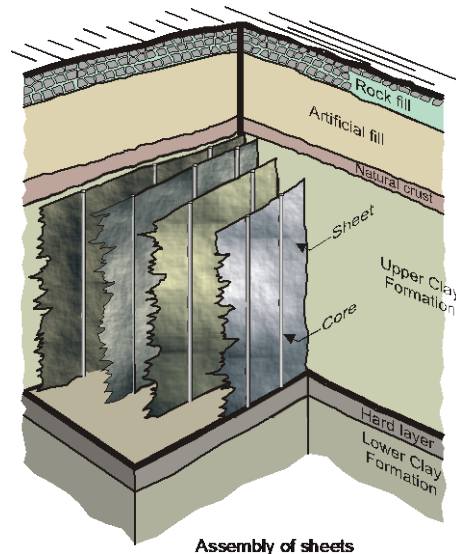


Figure 17 Mortar sheets injected by hydraulic fracturing under the Cathedral (After Ovando-Shelley & Santoyo, 2020)

Second stage of subsoil hardening. From September 8, 1998 to June 4, 1999 the southwestern part of the Cathedral was grouted as well as the northeast and southeast corners of the *Sagrario*. The southwest corner of the Cathedral was injected in two stages with a consumption of 50% of the total grout mix applied to each. Subsequently, from June 7 to September 9, 1999 the south zone was grouted with 2%; finally, in December 2000 the same thing was done at the northeast corner, although the volume of grout was of only a fraction of the total planned. The injection of grout sheets at the northeast part finished in December 2000 and in the museum a year later.

Isolation and separation trenches

Separation trenches have been used by the authors to modify the manner in which two adjoining structures interact. A trench is opened in the ground (30 to 60 cm wide) down to an adequate depth and it is filled with a non-setting gel which is not capable of bearing shear stresses. As a result, the displacement fields of both structures will be modified and a redistribution of stresses inside the soil will occur. Alternatively, a series of injection wells can be utilized to create the weak no-shear-stress plane using the hydro fracturing mechanism described previously albeit this technique can in theory only be used at sites with normally consolidated materials or materials only slightly overconsolidated.

The sketch in Figure 18 shows schematically a site undergoing regional subsidence where a modern building founded on point bearing piles is emerging relative to its surroundings and by doing so is affecting an adjoining monument. Point 4 under the monument on the right settles faster than point 2 which affected by the settlement trough produced by the tall building. Injection wells on and along point

5 create a weak plane thus allowing the monument to settle freely. Stress redistribution also occurs. Corrective differential settlements in the monument ensue.

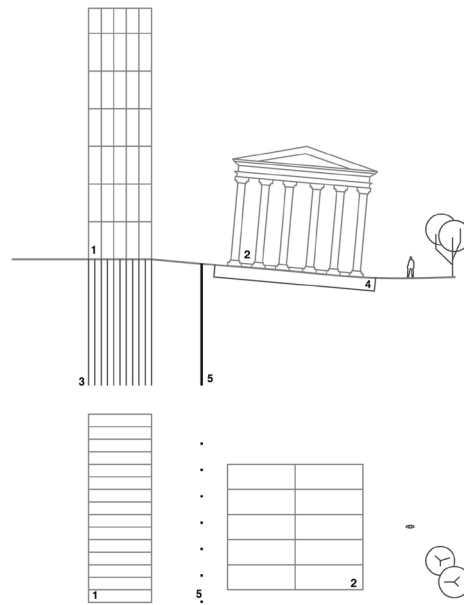


Figure 18 Schematic illustration of the use of separation trenches to correct tilts in buildings

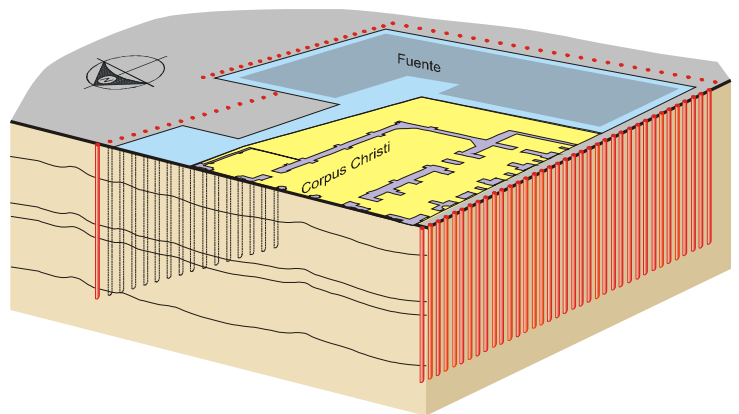


Figure 19 Separation trench used the church of Corpus Christi in central Mexico City

CONCLUSIONS

This paper reviewed the factors that can damage patrimonial buildings in a city subjected to extensive regional subsidence and underlain by exceedingly soft clays which is also affected by large magnitude earthquakes. Making reference to the special case of Mexico City, these factors must be carefully assessed in order to put forth solutions that are technically feasible and, also, acceptable from the view point of conservationists, archaeologists, historians and even politicians.

The effects of regional subsidence on heritage buildings were illustrated showing the detrimental effects of differential settlements induced by regional subsidence. Effective stress changes induced by it also modify some of the soils' mechanical properties, a situation that affects their dynamic properties as well.

Changes in seismic site response may act favourably or detrimentally on the behaviour of these structures during earthquakes, depending on how the soil strata will evolve in the future and on the structural health of individual buildings.

Distinctions were made as to the nature of the interventions that have been applied in the past in the city: those aimed at correcting or at least mitigating the effects of the damaging agents or interventions aimed at preventing damage or preventing the accumulation of additional damage. Many of the interventions that have been used in the city have been taken from classical Foundation Engineering, adapted to the circumstances inherent in projects aimed at the preservation of architectonic monuments. Other less common solutions were also reviewed, some of which were developed by local engineers. Control piles developed locally were described as well as their advantages and limitations. Underexcavation, a corrective measure, was also reviewed making reference to the iconic case of Mexico City's Metropolitan Cathedral, followed by mortar injections with hydro fracturing. The use of isolation trenches which modify in situ stress states and/or soil properties to induce corrective settlements was also described.

Finally, the paper has shown that the role of Geotechnical Engineering for the preservation of buildings in a sinking city is of paramount importance.

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