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Structural Rehabilitation Historical Buildings Affected by Subsidence in Mexico City

R. Meli and A.R. Sánchez-Ramírez
Institute of Engineering, National University of Mexico (UNAM)

ABSTRACT: Structural hazard imposed to ancient stone masonry buildings by ground subsidence is particularly severe in Mexico City where subsidence has been aggravated by excessive extraction of underground water. Under these conditions, structural rehabilitation programs for affected buildings must be based on detailed studies of subsoil, of materials, and of past structural performance, aiming at assessing future evolution of differential settlements and their effects on the structure. After a general description of the different causes of differential settlements, new techniques developed and validated for correcting historic trends of differential settlements, and for improving structural behavior are discussed. As an example, a recent rehabilitation performed by the authors is briefly described emphasizing criteria and techniques adopted, and the studies and analyses they were based on.

1 HAZARDS AND VULNERABILITIES OF HISTORIC COLONIAL BUILDINGS

A large number of religious and civil constructions built in colonial times, from XVI to XVIII century, still subsist in Mexico. The basic construction material of these historical buildings is a masonry conglomerate, constituted by stones of different sizes, agglutinated by lime-sand mortar. Light weight stones were most commonly used because of ease of transportation and carving. Specifically in Mexico City, a very light porous volcanic stone was generally used since the end of XVI century in order to reduce the weight of the building and the pressure it exerts on the soil. This heterogeneous masonry constitutes a kind of low-strength concrete that is lighter than normal stone masonry, and has a greater tensile strength than brick masonry, due mainly to absence of weak planes constituted by mortar layers. Vaults, domes and arches were initially also built with this masonry, but later most commonly with clay bricks or ashlars.

Most severe hazard to stability of these constructions in Mexico City is the great regional subsidence of the ground. Building settlements were a common problem for the original builders, leading to constant repairs or modifications, and frequently to total reconstruction. This situation has continued up to our times, despite of the development of ingenious foundation solutions.

2 CAUSES AND EFFECTS OF DIFFERENTIAL SETTLEMENTS

Differential settlements of ancient buildings have different causes whose significance must be carefully identified in each case, in order to take correct decisions about remedial measures. The initial cause of settlements was the great weight of the building inducing high pressures on the very deformable clay soil. Heavy buildings of moderate in plan dimensions, which are rather stiff to in plane bending, produce an almost uniform settlement; many of these buildings have sank up several meters under the ground level, with great problems to the building operation but with little structural harm. Buildings distributed over large areas do not possess enough in plane stiffness to generate a uniform pressure on the soil; therefore, they tend to show a typical concave configuration of settlements (Fig. 1); nevertheless, very frequently, the weight of the building is not uniformly distributed over the ground, but is concentrated in its periphery, as in temples of large nave span or in palaces and convents with large internal courtyards. In these cases pressures on the soil are smaller in the central part of the lot than in its periphery, thus generating a convex pattern of settlements which is particularly armful to the building structure, because it produces an outwards rotation of the supporting walls which adds to that of the thrust of vaulted roofs.

Previously described basic patterns of differential settlements are commonly altered by heterogeneities in soil deformability, mainly derived by differences in degree of preconsolidation of clay layers under different parts of the building; this is a very common situation, because most important colonial buildings were constructed in land plots previously occupied by heavy Aztec constructions that were demolished and whose foundation, and parts of the construction itself, were left under the new construction. Weight of these previous buildings and of their remains consolidated the clay creating “hard zones” whose rate of settlement is smaller than for the rest of the plot.

Since the middle of last century, a different factor has been the major cause of differential settlements. Accelerated population growth has generated an increasing need for potable water and, consequently, an intense extraction of water from underground which has further consolidated clay layers, due to migration of their water content to deeper permeable layers. A view of the severity of this problem is given by the following figures: ground level in the downtown area has descended about 8 m, from the beginning of last century to nowadays, and ground subsidence rate in this area is still on the average 85 mm/year (Fig. 2). The amount of ground subsidence generated by water extraction is far from being uniform in downtown area, mainly because of already mentioned differences in degree of consolidations of clay layers, which have created hard zones with much smaller settlement rates. For this reason, areas that were originally flat, show now increasing, irregular slopes, and buildings located over them show leaning and distortions. Building settlements are now much less related to the amount of pressure generated on the soil by the weight of the buildings resting on them, than to differences in soil consolidations, because of history of loads generated by the different buildings previously existing on each area.

Figure 1 : Great distortion of the old School of Mines without visible cracking in stone masonry

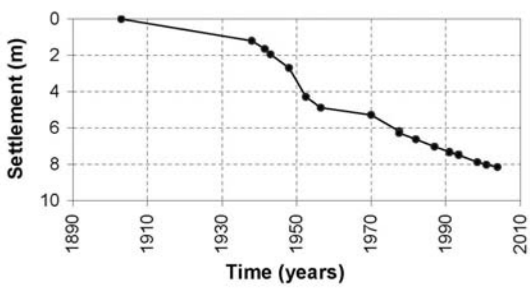

Figure 2 : Evolution of subsidence in downtown Mexico City throughout the 20th Century (adapted from Santoyo et al., 2005)

In the last decades another factor affecting pattern of differential settlements of some colonial buildings has been construction, in nearby land plots, of modern, tall buildings founded on point bearing piles resting on deep stiff soil layers. Such buildings do not follow the regional subsidence of the ground and show an apparent emersion; nevertheless, soil surrounding their foundation hangs from the piles due to, so called, negative friction, and forms around the building a mound with continuously increasing slopes. These slopes are transferred to adjacent buildings founded on shallow layers of soil, causing additional differential settlements.

Differential settlements within the building plane, caused by the aforementioned factors, have reached two or more meters (Fig. 3), and despite of frequent restorations, almost all ancient buildings show extensive cracking and out of plumb in their structural members, significantly impairing their safety.

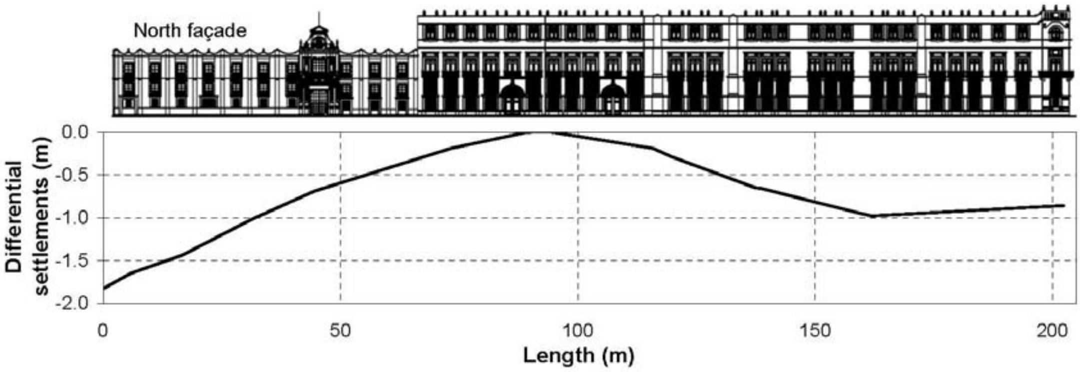

Figure 3 : Differential settlements along the façade of the National Palace

3 STRUCTURAL VULNERABILITY OF TYPICAL BUILDINGS

A systematic study of damage patterns of typical colonial buildings submitted to intense earthquake motions and/or to severe differential settlements has been performed in the last two decades at the Institute of Engineering at the National University of Mexico (UNAM); its main conclusions are summarized as follows.

Undulations of the ground, derived from different rates of settlements along the length of a building, generate bending and distortion of walls and consequently tensile stresses tending to produce vertical or diagonal cracking. Stone masonry walls have been found to possess a surprisingly high capacity to absorb large in plane distortions when these evolve very slowly, as is the case for effects of differential settlements due to consolidation of clay layers; deformations are concentrated in mortar joints that can sustain significant strains and, when cracked, can be easily repaired (Fig. 1). Flexural cracking is commonly concentrated in a few large cracks tending to produce a separation of the building in almost independent parts.

Out plane bending of walls is very frequent because most of building weight is concentrated in its peripheral walls, thus tending to produce a convex shape of differential settlements. Outwards inclination and overturning of walls supporting vaults and arches, is critical because effects of differential settlements add to those caused by thrust produced by the weight of the roof. Inclinations up to 2 or 3% have been found in several cases. The possibility of overturning of large parts of walls, façades and bell towers is certainly the most critical hazard in this kind of structure. Small tensile strength of masonry favors separation of façades and external walls from the main body of the building, progressively turning them into free standing walls.

Damage of arches, vaults and domes results from the same pattern of convex ground settlement causing outwards rotation of supporting walls, and opening of vaulted structures. Arched elements can withstand large openings before becoming unstable due to formation of a failure mechanism; cracking lines constitute hinges possessing large rotation capacity, because level of axial compressive load is sufficiently large to maintain the integrity of the elements, but low enough to avoid possibility of early crushing. This situation allows detecting progressive loss of form and taking corrective measures before the roof reaches an unstable geometry.

There is a great similarity among patterns of damage and mechanisms of collapse due to seismic forces and to differential settlements. This fact gives rise to a cumulative effect of both hazards, and implies that buildings affected by significant differential settlements become much more vulnerable to earthquake actions. Masonry deformation capacity under dynamic loads, such as those induced by earthquakes, is much smaller than for slowly increasing effects, as those generated by subsidence due to clay consolidation; cracks appear from smaller distortions. Additionally, alternating direction of deformations produced by earthquake vibration favors a more complex pattern of damage, and separation of the structure in parts which can be analyzed independently in order to study their vulnerability and safety conditions.

4 MONITORING SETTLEMENTS FOR ASSESSMENT OF STRUCTURAL SAFETY

For a proper diagnosis of the structural safety of a building it is important to correlate its present state of distress to the history of its past differential settlements, as well as to estimate future effects of the evolution of these settlements, by evaluating the contribution of their three possible causes: building weight, regional subsidence, and interaction with nearby constructions. To achieve this knowledge, an in depth survey of the construction accompanied by a careful study of historic documents is necessary for detecting, for instance, differences in levels and inclinations of parts of the building of different age, or differences in paths of cracking repaired in different times. For evaluation of future evolutions, main factors affecting structural behavior must be monitored over a time span that does not need to be very long, because differential settlements increase at rates that are frequently of a dozen of mm/yr; therefore, their basic pattern of growth rate can be clearly established by differences in a one year term; nevertheless, measurements over greater time spans are needed to detect variations due to changing local conditions. Monitoring should provide a detailed mapping of growth rate of differential settlements as well as of tilts of main structural members, and crack widths and lengths.

Most complete case of monitoring and follow up of a historic building in Mexico City has been related to the rehabilitation of its Cathedral (Meli and Sánchez-Ramírez, 1997; Santoyo and Ovando-Shelley, 2002). From the experience in this project, authors of this paper have designed and are carrying out a monitoring program for the conservation of ten very important colonial buildings which originally housed several schools, libraries and museums of the National University of Mexico (UNAM). Their construction history, emphasizing structural damage suffered and strengthening interventions, is being recovered along with the evolution of differential settlements and out of plumb of main structural elements; a program for monitoring structural behavior of each building has been established, and a file containing all relevant information related to structural safety is being integrated for each building.

5 RECENT DEVELOPMENTS IN REDUCTION OF DIFFERENTIAL SETTLEMENTS

For reducing growth rate of differential settlements in existing modern and ancient buildings, friction piles under the areas with highest rate of settlements had been until recently the most common solution. Point bearing piles have been less widely used, because of the great depth of firm layers they need to reach, and of the large concentrations of forces they induce in foundation and structure. Some techniques recently developed and successfully applied will be briefly described in the following paragraphs.

Micropiles cast in perforations through original masonry foundation have shown advantages over friction piles of typical dimensions, because of their simpler construction procedure and more effective connection to existing structure. Injections of cement mortars in the most deformable parts of the soil have been successful in reducing differential settlements. One version includes a central micropile from which radial mortar fins are formed by fracturing the soil through high pressure injections, as shown in Fig. 4 (Santoyo et al. 2005). A mesh of vertical thin mortar plates is formed in the soil, thus increasing its stiffness and reducing its rate of settlement.

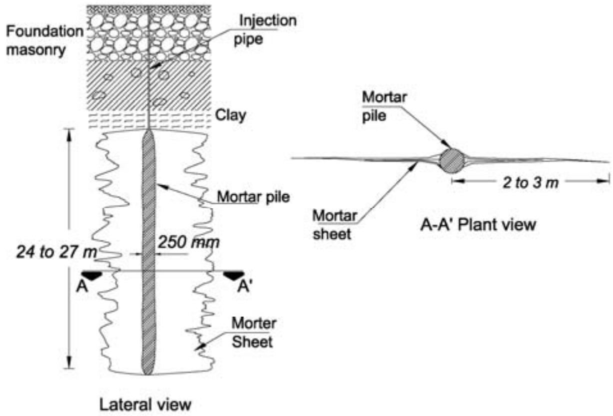

Figure 4 : Mortar inclusions for reducing soil compressibility (adapted from Santoyo et al., 2005)

Several techniques have been developed for correcting existing differential settlements and for uprighting inclined buildings. Jacketing from pile heads was used in several occasions in the past, but in recent times the most widely used technique has been "underexcavation", consisting of extracting soil below areas showing lowest rates of settlements, to produce predetermined and controlled settlements that correct, at least partially, previous differences with the rest of the building. Another technique that has given good results in some cases is based on pumping out water from underneath the layers of clay, in areas smaller settlement rates, and injecting it in other with greater rates. Aiming at eliminating restrictions imposed to settlements, by nearby buildings founded by point bearing piles, an "isolating trench" has been built around the perimeter of the affected building, by close thin perforations producing a continuous crack in the soil, that is then injected with a slurry or a non setting gel; such a trench breaks the effect of the negative friction and allows a more uniform settlement of the building.

An alternative approach for reducing differential settlements is by increasing flexural stiffness of the existing foundation, usually by forming a grillage of continuous reinforced concrete beams with enough flexural and torsional stiffness to limit differential settlements and rotations of walls or columns, especially at the periphery of the building. The most efficient procedure for that purpose is by casting accompanying reinforced concrete walls at both sides of the existing masonry footing, duly connected to masonry by shear keys, and preferably by crossing beams; a particularly cumbersome task is to provide continuity at the crossing of the footings. Effectiveness of above mentioned measures decreases as the size of the building increases; therefore, in several cases it has been preferred to separate the building in independent bodies, by cutting both the foundation and the structure with construction joints. Difficulties have been often encountered in achieving a true separation in all elements throughout the structure.

6 TECHNIQUES FOR IMPROVING STRUCTURAL CAPACITY

Most frequent and important structural problems to be solved in rehabilitation of buildings affected by subsidence or by earthquakes are those related to avoiding overturning or excessive inclination of walls and columns, and consequently, collapse of roofs and floors they are supporting. The most common solution in last decades has been by placing at the top of walls reinforced concrete ring beams, whose purpose is to distribute load concentrations, as well as to connect and provide some confinement to load bearing walls. In intermediate floors a similar function has been assigned to beams surrounding concrete slabs constituting horizontal diaphragms. Frequently, the connection between concrete beams and masonry walls has not been properly solved, thus impairing efficiency of the solution; moreover, no proper care has been taken to provide durability to concrete work, which starts to show signs of decay a few decades after rehabilitation.

External tie bars anchored to walls are increasingly accepted by conservationists and are becoming the most common measure to absorb lateral thrust. Common steel bars are used for external ties whereas, when bars are to be embedded in masonry, stainless steel is used. Welded wire meshes with a concrete mortar rendering over the masonry walls were rather common in the recent past for strengthening and connecting masonry walls, but its use has been strongly objected, and the technique is being abandoned. For pillars, grout injections and replacement of degraded mortars and stones has been the most common procedures, along with confinement by external steel rings or plates. No application of new materials, as resins or high strength fibers, is known to have been performed in Mexico, except for a few cases of resin injections in fractured stones; early signs of resin degradation have been detected at least in one case.

7 REHABILITATION OF THE OLD SCHOOL OF MEDICINE OF UNAM

As an example of application of aforementioned rehabilitation criteria and procedures, one case whose rehabilitation is in progress will be briefly described. This huge palace was built from 1736 to 1739, to house the ominous Tribunal of Inquisition, which was abolished in 1813; some years later it was given to the School of Medicine which was based there until 1954, when was moved to the newly built University City. In XIX century it underwent several modifications to fulfill the changing needs of medical education. A major restoration was carried out around 1960 to return it near to its original shape and condition.

The building is located in a corner plot that had a long history of previous constructions; among others, it had been part of the palace of the last Aztec emperor, and in early colonial times, part of the convent of the Dominican friars. Unevenly distributed loads from these previous constructions produced different levels of consolidation of the underlying soft clay layers; moreover, remains of foundations of buildings from different ages were partially taken advantage of, for the foundation of the present construction. This situation set the basis for a long history of significant differential settlements of the building.

The main entrance to the building is on the corner of its two long façades, and leads to the main courtyard, surrounded by arcades supported by solid stone columns (Fig. 6). Around another smaller courtyard, an eastern wing has been partially separated from the main building by means of construction joints, as an attempt to deal with problems derived from differential settlements. Masonry of different kinds and qualities was used in the building: ashlars for columns and arcades and stone conglomerate for walls, frequently with rubble from previous constructions. Floors and roofs were by clay tiles over closely spaced wooden beams.

Figure 5 : View of the Old School of Medicine

Figure 6 : Arcade of the main courtyard. Damaged zone is highlighted

Due to damage from differential settlements, frequent restorations for safeguarding building integrity have been required. In recent times three major programs were undertaken. Examples of measures taken in the two former ones, in 1967 and 1979, are substitution of original wooden floors by concrete slabs, strengthening of stone pillars by inserting steel or reinforced concrete cores, and addition of concrete or steel beams at the top of walls. Deformations and cracking in the building continued, and in 2004 significant increase of the size of some cracks in arches, pillars and walls, as well as of out of plumb in arcades surrounding the main courtyard motivated a thorough evaluation of the structural integrity of the building and, subsequently a program for its structural rehabilitation.

First, available information about evolution of differential settlements and out of plumb, as well as of cracks width and length, together with other signs of damage and degrading, was collected; from it, configurations of accumulated differential settlements in each floor and, more importantly, of their present growth rate were mapped and correlated to observed cracking patterns. Future evolution of differential settlements and out of plumb was estimated and possible conditions of instability of structural member or parts of the building were postulated.

Results showed that differential settlement between northwest and southeast corners of the main building has reached 1 m; additionally, present configuration of settlement is quite different from the historic one, reaching a maximum at southwest corner and a minimum at the center of the building; annual rate of differential settlement among these two points is now 10 mm/yr.

Vertical and diagonal cracking in walls due to in plane distortions was widespread; additionally, slipping of beams over their supports, detachments of parts of the structure and separation among adjacent walls were a result of the general distortion of the building. These types of damage could be clearly correlated to the measured pattern of differential settlements. Based on the severity of the observed damage, and most of all, on its increase projected to a 20 years time span assuming that rate of growth of settlements will remain constant, a rehabilitation program was implemented. It must be said that during the execution of rehabilitation works, additional damages and sources of weakness were detected, and the number of strengthening measures, as well as their scope, were significantly increased.

Aiming at reducing settlement rate in areas of their maximum growth, micropiles were placed under external walls of southwest corner and in eastern part of the north facade. To reduce differential settlements in the main courtyard, which had severely affected its arcades, a confining belt was provided in the foundation by placing two parallel companion reinforced concrete beams connected to the isolated masonry footings under each column (Fig. 7). These beams were extended and connected to the foundation of the main body of the building in each of its four sides.

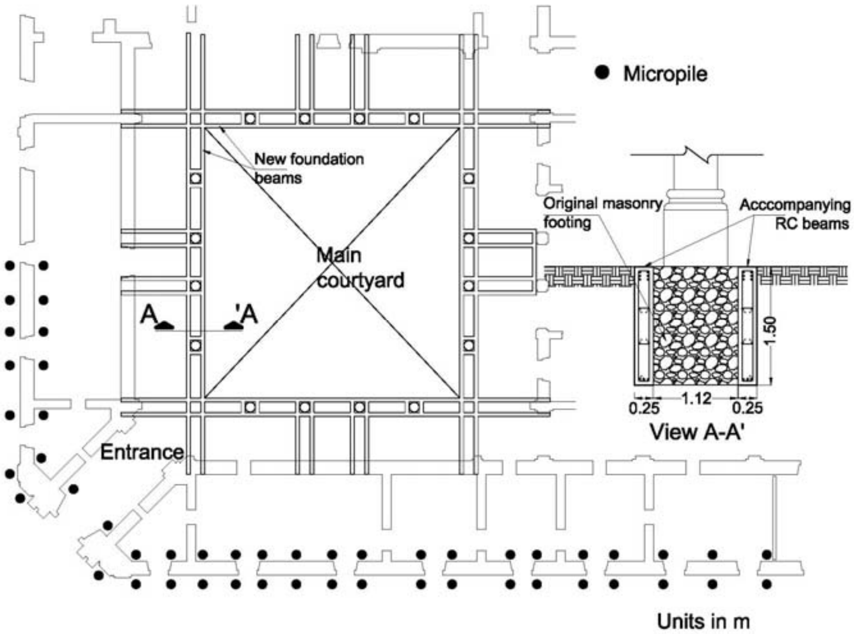

Figure 7 : Foundation strengthening with micropiles and accompanying RC beams

With the purpose of avoiding overturning of the arcades, an additional belt was formed along the corridor of the first floor, whose existing concrete slab was given continuity, and was connected to arches and walls of the main body of the building. At roof level a tie beam was placed only on the eastern side of the courtyard which has been the one most severely affected. The southern arch of the east side was thoroughly rehabilitated, by substituting affected ashlars and by confining a damaged column with steel bands in its lower half (Fig. 8).

To restrain south facade against overturning, three transverse walls that had been demolished several years ago, were rebuilt and properly connected to the façade and to the main body of the building through horizontal concrete beams at their top and mid height. Many other local repairs had to be executed, mainly consisting in mortar injections of cracks and removal of previous repairs that had been poorly executed.

Effect of works performed on foundation for reducing differential settlements can be appreciated in Fig. 9, where evolution of settlement of the four corners relatively to the center of the building is shown. After an initial sharp increase of differential settlements due to excavation work and to added weight of micropiles on the soil, the rate of relative settlements in the four corners shows a significant reduction.

Figure 8 : Confinement with steel plates of a damaged arcade column

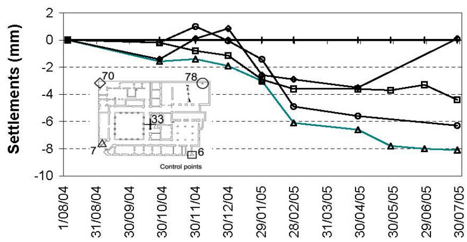

Figure 9 : Evolution of differential settlements during and immediately after installing micropiles

8 CONCLUDING REMARKS

As could be appreciated from what described in this paper, preservation of structural integrity and safety of historical buildings submitted to such a high rate of differential settlements constitutes a severe challenge that could only be met by complex and expensive measures in soil, foundation and structure; nevertheless, because it is not likely that amount of water extraction will diminish in the near future, general subsidence of ground in downtown area of Mexico City will continue approximately at same rate as today, and no solution can be considered as definitive. Through a careful choice of measures to reduce both, differential settlements and vulnerability of the structure to them, it can be hoped to significantly lengthen time before a new rehabilitation be needed.

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