Foundation engineering answers to subsidence problem in Mexico City

W.I. Paniagua, *Pilotec*, & J.L. Rangel, *UAM-Azcapotzalco*

ABSTRACT: Regional subsidence in Mexico City is a problem for foundation engineering since mid-twentieth century. Early solutions include friction piles, compensated foundations and control piles. However, after several years, some improvements have been presented, including overlapped piles, better control piles, rigid inclusions, soil improvement and cut-off barriers. A descriptive review is presented for the above mentioned solutions.

1 INTRODUCTION

Since early twentieth century, Mexico City´s consumption water is extracted from local wells. Pumping of water has produced an important piezometric level drop, with consequent increase in effective stress, and consolidation of clay layers as well, and regional surface subsidence in produced.

Relation between subsidence and pumping was first established by Carrillo in 1947. To give an idea of the magnitude of the problem, fig 1 shows observed settlements in Mexico City downtown; there are locations where 40 cm/year are observed, and other with settlements of up to 8 m.

Even with high drops in pore water pressure in depth are measured, water table has remained almost constant, probably due to the surface recharge and through pervious layers interbedded in the upper portion of the soil (Zeevaert, 1982).

Besides subsidence, pumping is generating cracks in the soil mass, with consequences in foundations and municipal facilities.

Furthermore, soil mechanical characteristics are evolving with time: water content, shear strength, compressibility and dynamic properties.

The biggest impact of this phenomena is caused to foundations, producing changes in the effective stress (affecting compensated and friction pile foundations) and exceeding preconsolidation load, increasing the amount of settlement. As to point bearing piles, negative skin friction is presented, reducing total load capacity.

Differential settlements are presented between neighboring structures; for instance, presence of a building in point bearing piles cause cracks and differential settlements in light structures in the vicinity.

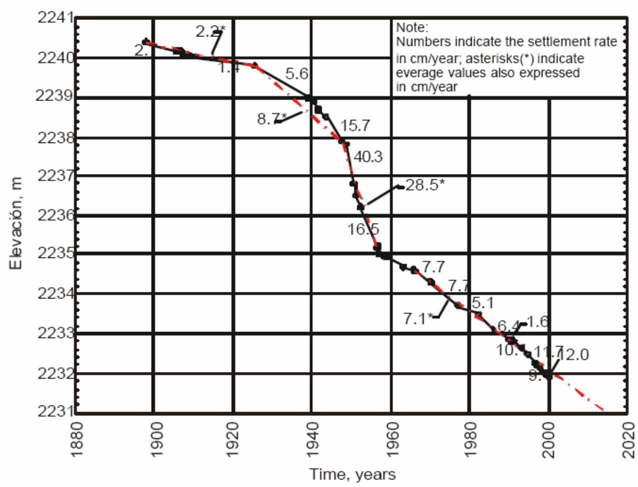


Fig 1, Settlement vs time measurements in Mexico City downtown, after Santoyo and Ovando (2006)

Buildings on point bearing piles or overcompensated foundations “emerge” with respect to the soil due to the relief of stresses in the soil.

Before this situation, foundation engineering has overcome with several solutions for this problems; in this paper, they are divided in:

a) Design solutions, which were conceived since the early design process, and take into account regional subsidence
b) Corrective solutions, product of one or several of the problems above mentioned, including underpinning
c) Cut-off barriers, as a dramatic way to make foundations of close structures to work independently

d) Soil improvement techniques, intended to modify the soil properties

A general description of each solution is included, not pretending to be an exhaustive review; however, some details are mentioned, considered of general interest.

It is noticed that some of this solutions may be combined with other, or used in different stages of the life of the structure; i.e., in the design stage, as well as a process of underpinning.

2. DESIGN SOLUTIONS

Foundations in Mexico City´s soft clay have evolved progressively, to achieve the needs for higher, larger and heavier constructions. Solutions in this stage are mentioned by Auvinet (2006), fig 2:

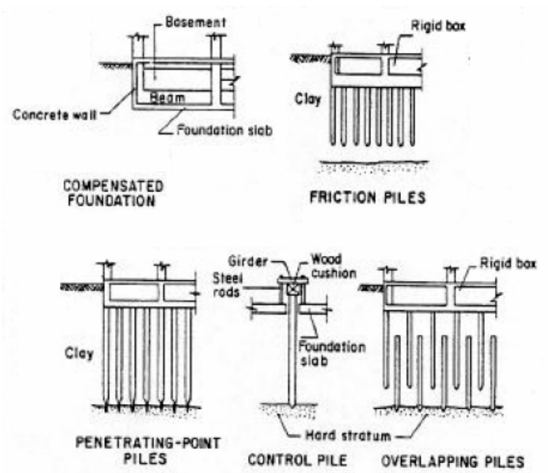


Fig 2, Foundations used for regional subsidence control, after Auvinet (2006)

Compensated foundations. The compensated (or "floating") foundation technique consists of designing the foundation, generally a box-type structure, in such a way that the mass of excavated soil will be comparable to the mass of the building. Theoretically, if both weights are equal, the soil below the foundation is not submitted to any net stress and no significant settlement should develop. When the weight of the soil is smaller than the weight of the building, the foundation is *partially compensated*; in the opposite case, it is *overcompensated*. This latter case is used for regional subsidence situations (Zeevaert, 1982).

In practice, even perfectly compensated foundations suffer some total and differential vertical movements due to soil elastic deformation, to soil disturbance during construction and to static soil-structure interaction thereafter. Furthermore, constructing this type of foundation is not straightforward since a deep excavation in soft soil is generally required with the associated problems of stability of earth slopes or support systems and to bottom expansion or failure. Water tightness of the foundation is also a critical factor for compensated foundations; in many cases, this type of foundation must be equipped with a permanent pumping system to control infiltrations.

Friction piles. Friction piles are generally used to transfer stresses induced by shallow or partially compensated foundations to deeper, less compressible layers of the subsoil, and to reduce settlements. Not so often, they constitute the main foundation system and the stability of the structure is made dependent on the bearing capacity of the piles.

Pile with penetrating point. This type of pile was conceived to increase the bearing-capacity of friction piles with a controlled contribution of the point. The diameter of the point is smaller than the rest of the pile in order to facilitate penetration in the hard layer under the combined effect of loading and negative skin friction and to avoid emersion.
The point can be made of reinforced concrete or steel. In the latter case, the bearing capacity of the pile can be better controlled by using a point with a pre-established failure load. Flexibility of the point constitutes however a problem during installation of piles, and preboring is a common solution to this issue.

Negative skin friction piles. Those are simply point-bearing piles that penetrate freely through the foundation slab. They can contribute to reduce significantly the settlements due to negative skin friction that develops on the shaft of the piles under the combined effect of the structural load and the consolidation of the clay layer. Spacing of the piles appears to be the most significant design parameter.

Control piles. The so-called "control piles" are similar to the previous ones but they are equipped in their upper part with a mechanism that controls the load received by each pile. Each pile can also be unloaded by removing the mechanism in order to correct any tilt ing of the building. Those systems have sometimes been installed during the life of the structure as part of an underpinning process. The different available control mechanisms have been reviewed by different authors, and some are shownn in fig 3. In seismic conditions some of these special systems can be vulnerable and suffer damage going from simple deformations to total collapse. Lack of maintenance can also be a problem.

Efforts to found a solution to seismic behavior were focused in two directions (Santoyo and Segovia, 1995): a) subsitute the deformable cells in the head for materials with more defined load-deformation laws or mechanical adjust systems; and b) substitution of the reactions bridge and deformable cell for another mechanisms that can bear tensions and overturning moments. Not a single practical application of this mechanisms is known.

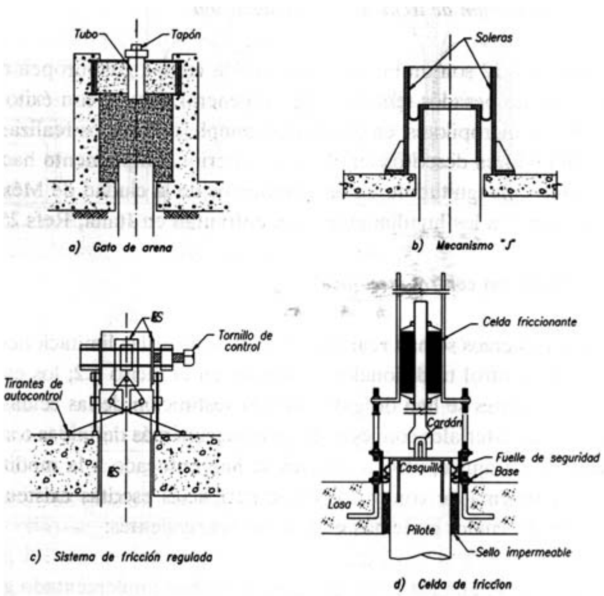


Fig 3, Different pile control systemes, Santoyo and Segovia (1995)

Telescopic piles. These are tubular piles with a piston-like cylindrical point lying on the hard layer. The tubular portion of the pile is partly filled with sand. When sand reaches a certain level, an arching effect develops and both parts of the piles work as a unit. If necessary, sand can be removed to free the point and avoid emersion of the foundation.

Overlapping piles. This type of foundation includes conventional friction piles (A Piles) together with negative skin friction piles (B piles) lying on the hard layer. This arrangement reduces the increment of stresses in the soil and the corresponding settlements. Emersion is also avoided.

The use of overlapping piles has renewed, with different design approaches (Menache, 2002). This piles were out of practice over a decade, but are again in common use since 1990´s.

Piles with sleeve. Point bearing piles with outer sleeves are used to avoid the effects of negative skin friction (due to regional subsidence). Sleeves may be in one portion of the pile, or along it. Another version of this solution are coated piles, but are not used commonly in Mexico City.

Fig 4 shows an example with pile sections connected with neoprene sleeves, designed to absorb the deformations induced by regional subsidence; the annular space between the pile shaft and the pipe is filled with grease.

Rigid inclusions. Inclusions can be defined as elements that are installed in the soil, without connection with the foundation, and can be built using different techniques.

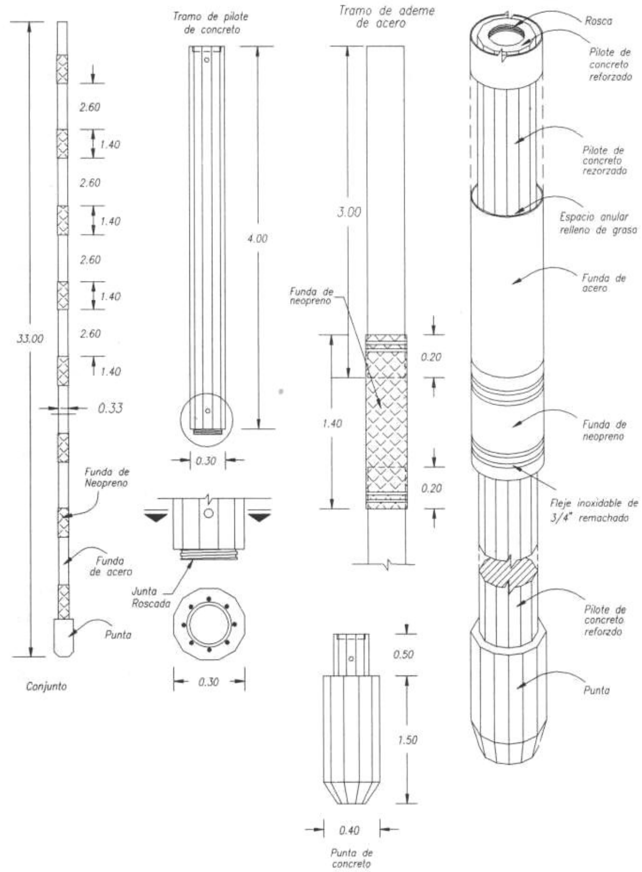


Fig 4, Sleeve piles, Santoyo and Segovia (1995)

It´s use has become popular to solve problems related with settlement reduction, as well as increase of the safety factor against bearing capacity failure, both in slope stability and shallow foundations (Paniagua et al, 2008).

When used for settlement reduction (Paniagua, 2005), rigid inclusions are often mentioned as negative friction piles, since the slab pressure that is transmited to the soil is taken by the inclusion by the skin friction that is developed when avoiding the descent of the soil surrounding the inclusion (soil-inclusion interaction, fig 5).

In general, four working conditions are considered (fig 6):

- With support in the head of the inclusion (type A).
- With support in the tip of the inclusion (type B).
- With support in the tip and the head of the inclusion.
- Without support.

For regional subsidence control, conditions A and B are more often used. Presently, there is a trend to use type A inclusions; however, further research is needed, to define the optimum condition for a certain problem.

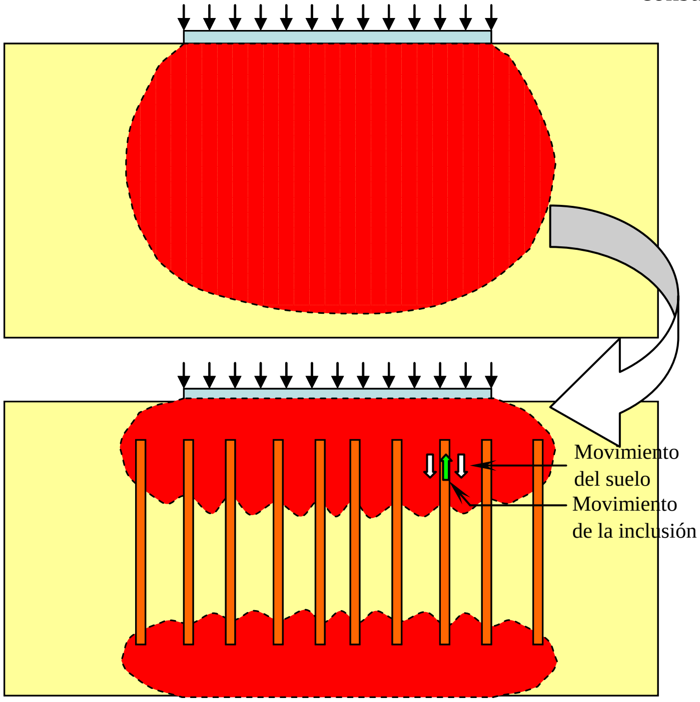


Fig 5, Scheme of slab load transfer to the soil, and soil to inclusion

On the other hand, when settlement reduction of clay strata is seeked, inclusions type B or without support have been used.

There are several construction procedures for rigid inclusions, but can be clasified in three groups: driven, cast in place, and drilled displacement piles. First group can be of precast piles (wood, pipe or concrete); second group could be using low pressure grouting techniques, jet grouting, etc. Third group is discussed outside this paper (Paniagua, 2006)

3. CORRECTIVE SOLUTIONS

Micropiles. As an answer to underpinning problems, micropiles have been developed for give additional support to structure and monument foundations, and even for new foundations. Different techniques have been adopted, mostly european, with adjustments for local conditions, fig 7. Mainly, they work as friction piles, eventhough in some cases have been used as point bearing elements. It can be used as anchors, inclusions or with soil nailing concept.

Dead weight. Use of dead weight has been reported several times (i.e. Cuevas et al, 1990) alone or combined with other techniques, such as pumping and/or piles. The main purpose is to place additional weight to the foundation to equilibrate eccentricities and recover the building tilting. Usually, large periods of time are consumed.

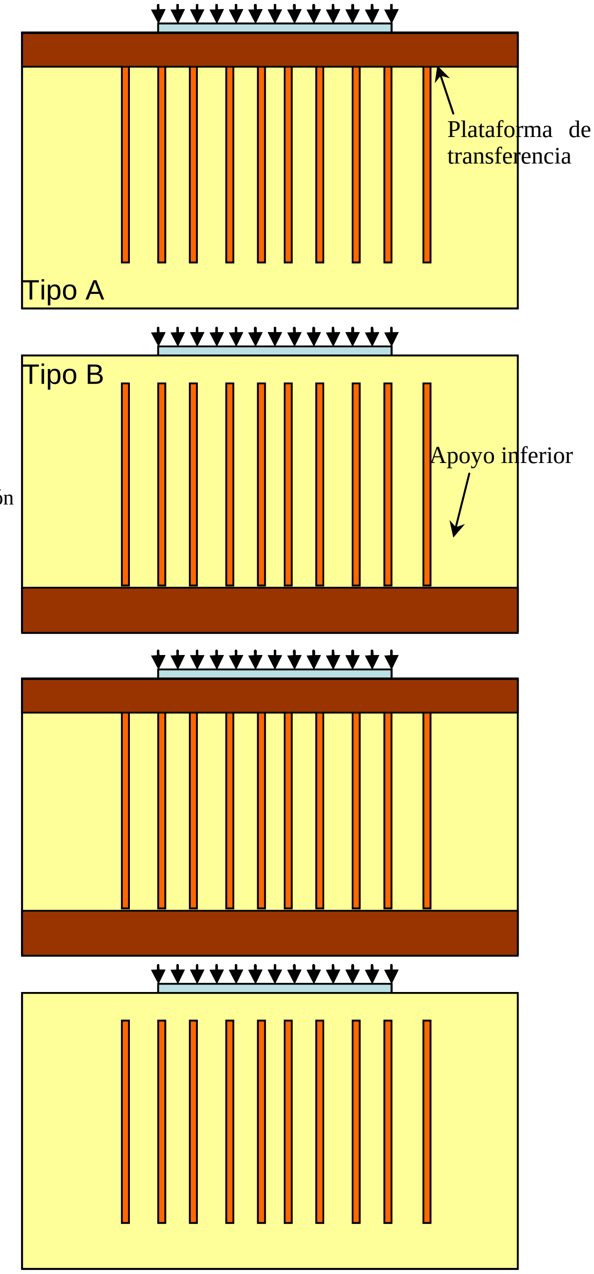


Fig 6, Working conditions for rigid inclusions

Fig 7, Micopiles under construction in Mexico City

Pumping. Another method to increase the load in one side of the foundation, without adding weight, is to pump water from the soil, from one side of the building, to cause additional increase in the effective stress of the soil, thus increasing the rate of settlement on that side. Several examples are known, generally combined with other thecniques, as additional piling (i.e. Hjort et al, 1990, Tamez, 1990).

An effort that has been looked over the years in Mexico City includes electroosmotic pumping, but is not longer used.

Underexcavation. The technique consists in drillng small horizontal or inclined tunnels (around 10cm in diameter) in the soft soil beneath the foundation. The borehole is closed due to the vertical stress in the soil, and this process induces a correction settlement in the surface. Once the hole is closed, a new drilling is made, repeating as many times as necessary to achieve the desired movement (Santoyo et al, 2005).

This solution has been used many years ago (Santoyo et al, 1990), but has reached its most important job in the Metropolitan Cathedral, fig 8.

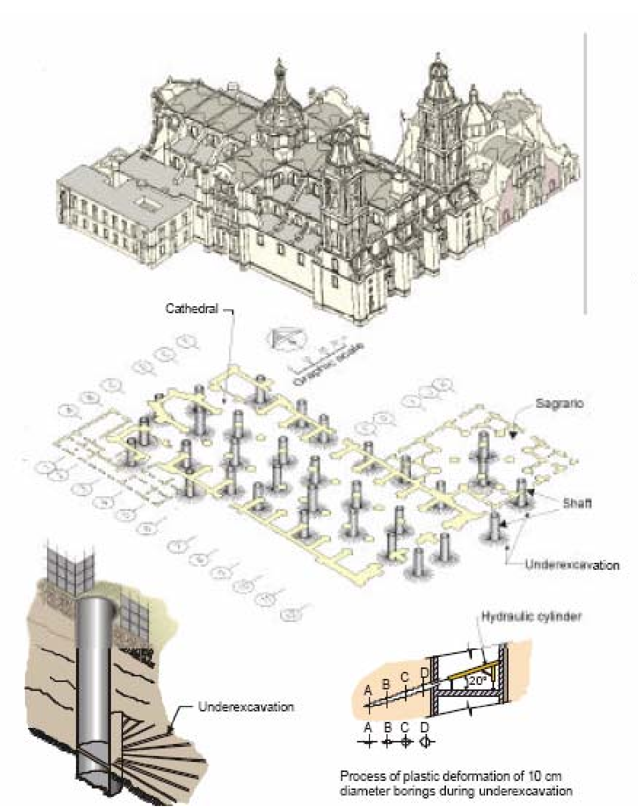


Fig 8, Underexcavation for Metropolitan Cathedral, Santoyo et al, 2006)

Other drilling techniques have been developed, following the above mentioned procedure, i.e. with directional drilling, fig 9 (Menache, 2005).

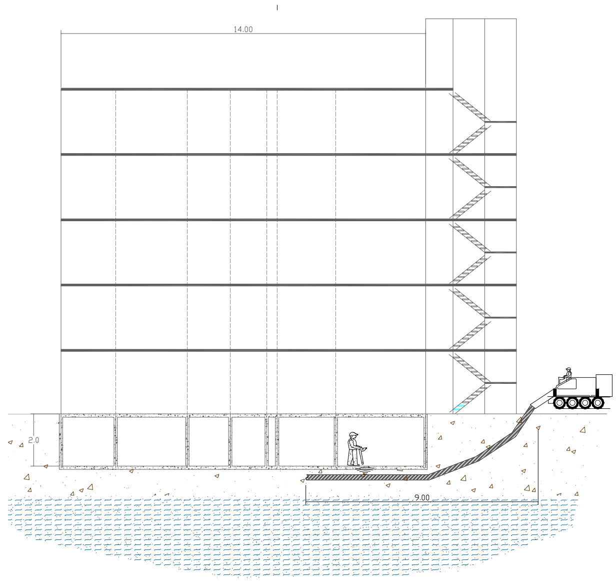


Fig 9, Underexcavation with aid of directional drilling

Water infiltration. Partial recover of the piezometric levels in the soil has been tried since 1978, for the National Palace, with moderate success. The system induces additional pore water pressure to the soil, at the level of the infiltration well, thus reducing the settlement.

Additional works have been done for Foreign Relations Tower, fig 10, that include both pumping and infiltration wells, Figueroa et al (1998).

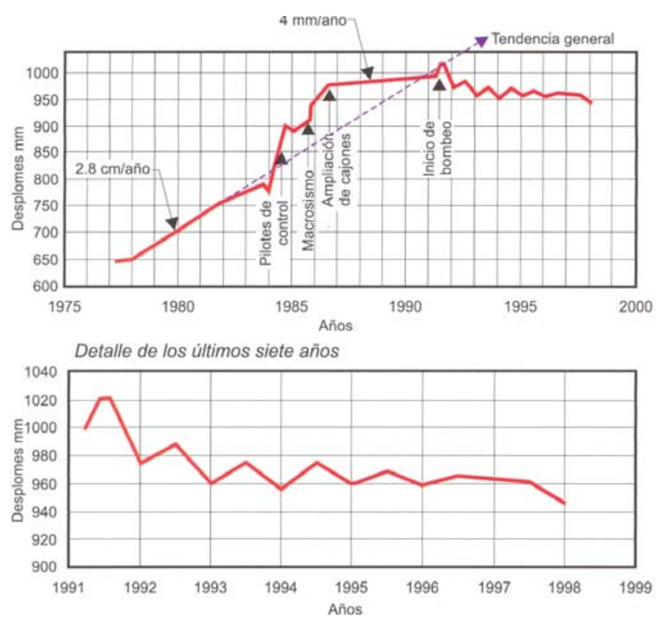
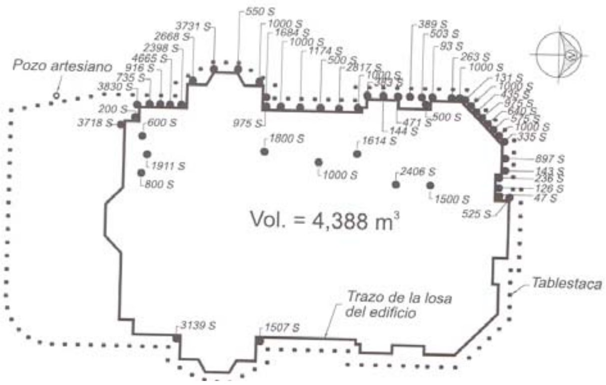


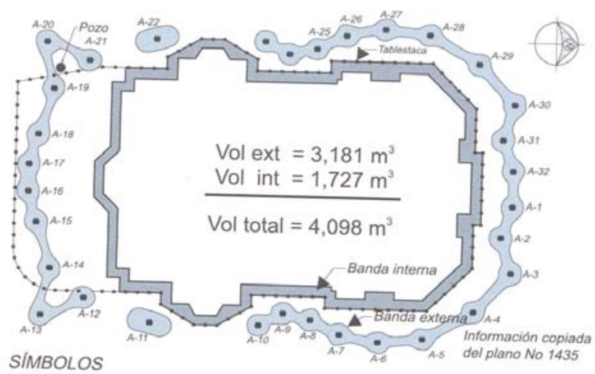
Fig 10, Water infiltration for Foreign Relations Tower, after Figueroa et al, cited by Santoyo et al (2005)

Grouting. Grouting has been implemented in Mexico City clay since early twentieth century. Its final purpose is to improve the mechanical properties of the soil, to reduce settlement and improve shear strength in the soft clay; several methods have been tried:

i) <u>Mortar grouting</u>. Used in the Palace of Fine Arts, as described by Santoyo et al (1995), fig 11.



(a) Grouting campaign 1910, 12 and 13



(b) Grouting campaign 1924-25

Fig 11, Grouting in the Palace of Fine Arts

An alternate procedure for mortar grouting, is to induce hydraulic fracture in the clay. The concept is to grout the softest areas of the subsoil to form a structure based on vertical sheets of mortar inserted into the soil mass; the grouted areas and the schematics of the mortar sheets are shown in fig. 12. This grouting modifies the behavior of the soil, although other opinions give more credit to the inclusions formed at the beginning of the process (Auvinet, 2005).

ii) <u>Jet grouting</u>. It has not been extensively used as a soil improvement method, due to the lack of equipment in the country; however, some tests have been made, as the one reported by Sámano (1998).

In Mexico City clay, it has been used to improve the in/out portal for tunnel shields, instead of traditional soil replacement technique.

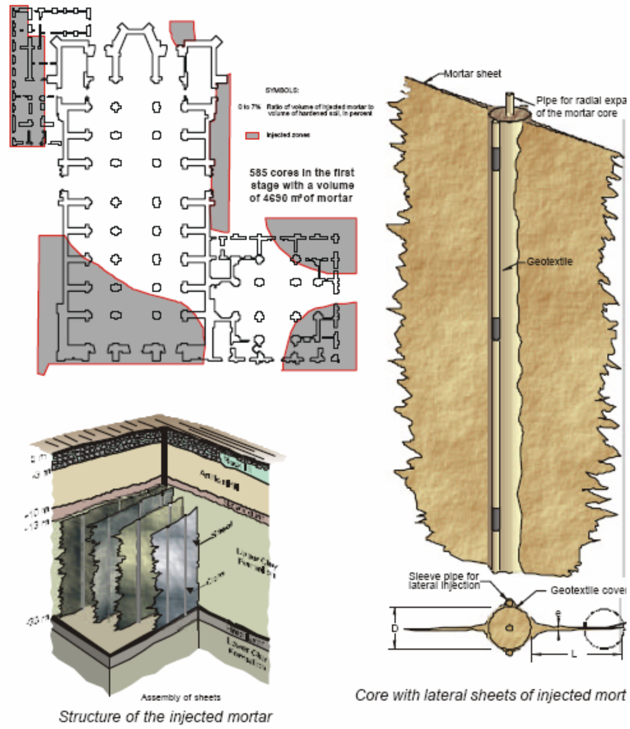


Fig 12, Mortar grouting under Cathedral, Santoyo et al (2006)

4. CUT-OFF BARRIERS

Anti-friction membranes. Using a diaphragm wall excavation, two polietilene membranes are placed with the aid of a roller, as is shown in fig 13. In between the two layers, grease can be placed, to aid in the separation process. A test has been made, in an excavation of 1.7m width and 16m depth, placing the membrane in bentonite mud stabilized trench (Santoyo, 2002). Until now, it has not been used in a practical case.

Water injection. This procedure induces a cut-off surface along the soil mass; it was developed to separate the behavior from the Cathedral and Line 2 subway, though it has been used successfully in Corpus Christi church, Independence Memorial, Los Azulejos restaurant, and Las Animas chappel (Segovia, 2008).

A series of vertical drillings is made, to place in each one a *tube a manchette*, with depth equal to the crack that is intended to provoque; number of pipes and its separation are function of the length of the crack, and the shear strength resistance of the clay, fig 14. Soil stress analyisis allows to determine the water pressure, and the frequency of water injection.

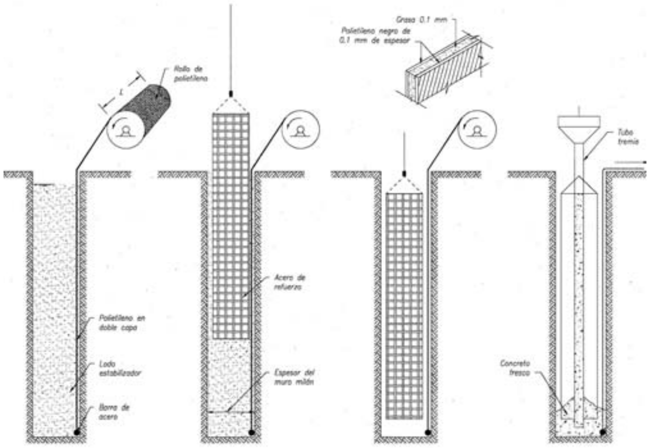


Fig 13, Membrane to reduce negative skin friction

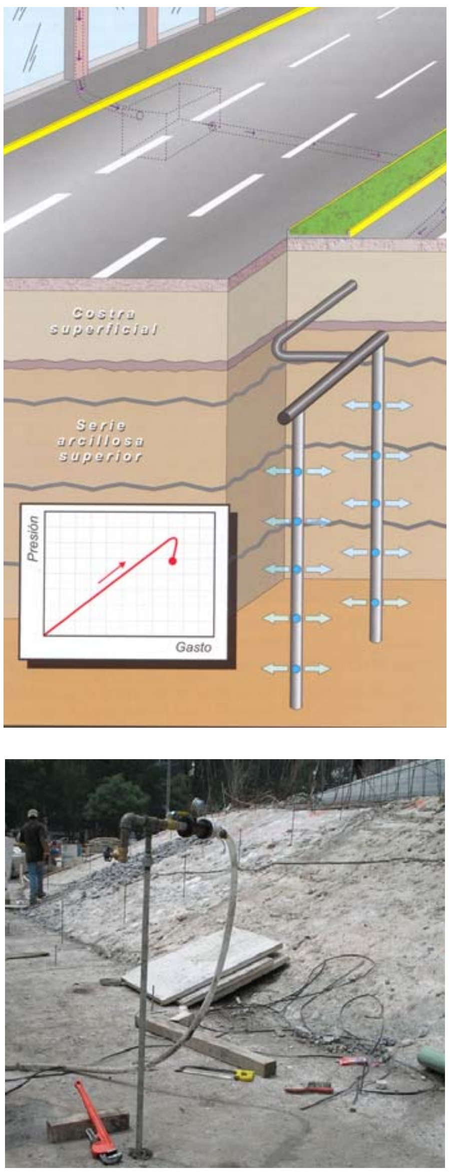


Fig 14, Water injection into the soil, Santoyo et al (2005)

Coated walls. Similar to coated piles, coated walls try to diminish the friction between the soil and a wall, to allow relative movement between foundations with different behavior, i.e. compensated foundations and point bearing piles.

Fig 15 shows an example built near Alameda Park, where the latter case was presented. A separation wall was excavated, using slurry walls technique, and prefabricated pannels were prepared, adding a coating material in the outer surface.

(a) Preparation of panels

(b) Panels after installation

Fig 15, Separation wall panels

5. SOIL IMPROVEMENT

In previous sections, different procedures to eliminate or diminish the effects of regional subsidence were presented, without modifying the causes that originate the problem. In other countries, the countermeasures used for regional subsidence, that go to the root of the problem are (Poland, 1984):

- Reduction of the volume of water extracted from the aquifier
- Artificial surcharge of the aquifier and recover of the piezometric levels
- Restriction of the construction area, where the phenomena is presented
- Increase the pressure of the aquifier

On the other hand, there are alternatives to counterattack or diminish the negative effects of regional subsidence with and without incide in the origin or the settlement. This alternatives are based in soil improvement techniques, which modify the mechanical properties of the soil. Some procedures will be commented:

- Soil replacement
- Introduction of chemical-biological agents
- Preload, with vertical drains

Each of this techniques produces changes in soil proporties: permeability, shear resistance, deformability, dynamic response, chemical composition of the soil, and/or combination of them. For regional subsidence case, deformability is the main goal, although in some cases permeability is seeked, to accelerate consolidation process. It is important to take into account the secondary effects that may be caused with certain procedure.

Soil replacement. This solution has been already treated, in different procedures: rigid inclusions, grouting, hydraulic fracturing, jet grouting. In Mexico City this techniques have been used as corrective measures, although inclusions are used since original design stage.

Other techniques, such as soil mixing, have not been used in Mexico City yet.

A major disadvantage of this procedure is that it is not reversible by 100%, thus if the behavior is inadequate, i.e. emersion is observed, final solution can be complex and expensive.

Introduction of chemical-biological agents. By adding chemical or biological agents to the soil, its possible to modify its mechanical properties, or to accelerate hardening process.

Traditionally, new materials as cement, lime or asphalt are added to the soil, using mixing when fine soils are found, or infiltration, in granular soils; however, in clayey soils the process becomes difficult, because soil structure should be preserved, to avoid settlements.

An alternative to this process is to make it in a nano scale, using microorganisms, as bacteria, to accelerate the production of substances, as calcium carbonate, to connect or bond the soil particles.

Bacteria can modify the mechanical properties of the soil, by two main process:

- Bio-stimulation. Necessary nutrients are added to the soil, to activate the microorganisms
- Bio-concentrator. Bacteria are added to the soil, to perform a certain job

As bacteria interact with the soil minerals, the soil particle surface is altered, new minerals are precipitated between close particles, such as $CaCO3$, which produces that close particles are connected, either to increase the shear resistance (*bio-hardening*), or to diminish the soil permeability (*bio-seal*), Fig 16.

Bio hardening has not been applied to regional subsidence problems, since is a still developed technique, but its potential is high, since it's a reversible process, and its possible to stop it at any stage of the process, because it depends on the nutrients grouted into the soil.

The design of the nutrient grouting depends on the permeability of the soil, quantity of transportation, bacteria growth and reaction velocity.

Preload with vertical drains. With this procedure, the goal is to accelerate the development of the consolidation of the soil. Then it is possible to place the foundation without danger of possible total or differential settlements. Also, to increase the undrained shear strength of the soil, and thus, the bearing capacity of the soil.

The consolidation process can be speeded using vertical drains, built with stone columns, or wicked drains, fig 17.

Few applications of this procedure are known in Mexico City (Auvinet, 1979), although it was used to solve the settlement problem of a certain structure, not a regional subsidence problem.

Building construction, performed since the Aztec period, has served as preload, particularly in downtown Mexico City, where old buildings are founded. Pumping of water itself, is another form of preloading.

Some cases are reported, where it has been used as a correction procedure (releveling) from regional subsidence effects.

7. COMMENTS

Foundation engineering has dealed with regional subsidence problems since early effects were noticed. Several solutions have been developed, due to economic growth of Mexico City, which require satisfactory behavior of buildings, bridges, tunnels and other structures.

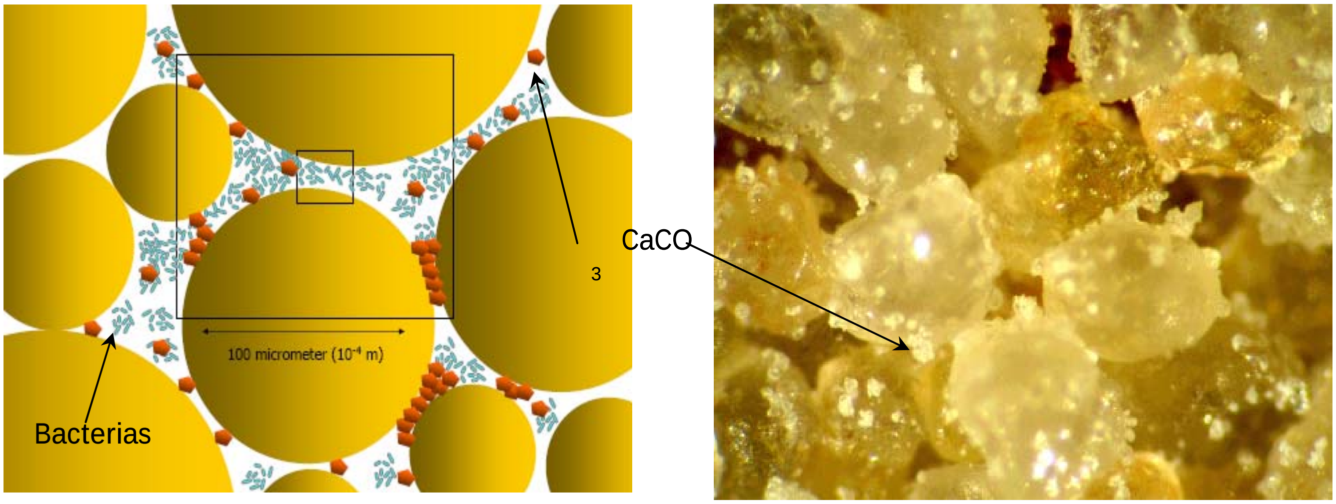


Fig 16, Scheme and microscope view of the interaction between bacteria and soil particles, in the formation of $CaCO_3$

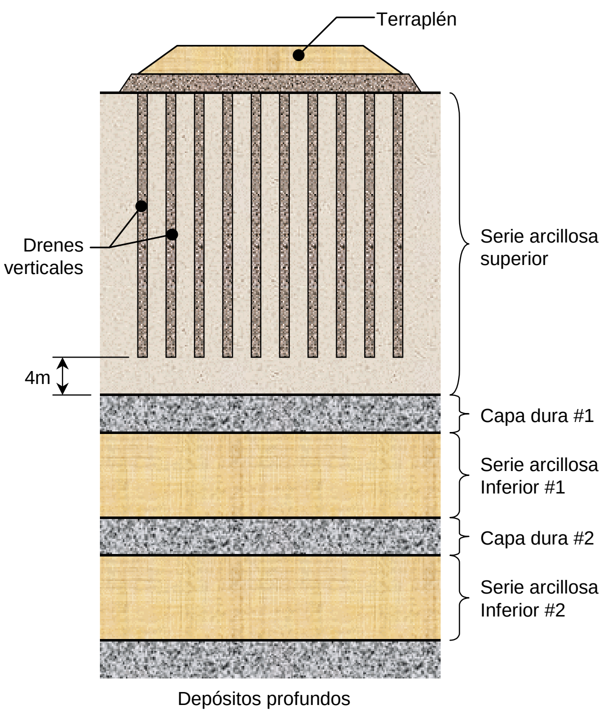


Fig 17, Preload with vertical drains, Auvinet et al (2002)

Particularly, the presence of historic monuments gives additional relevance to the search of new solutions.

Old solutions have been reviewed, after major events, such as 1985 earthquake, including friction piles, control piles and overlapped piles.

New procedures are now used in common practice, as micropiles and rigid inclusions. Others need further research, as bacteria soil improvement.

It is important to notice that none of the methods mentioned in this paper solves the bottom line problem: regional subsidence is due to pumping of water for human consumption. Reducing this activity plus surcharging of the aquifiers are the most urgent solutions to achieve.

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