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Underpinning and Releveling of a Building Using Control Piles and Sub-Excavation

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Abstract. Control piles are a special foundation consisting of point-bearing piles that freely penetrate the foundation slab, at the head of which is placed a device to control the pile load and the settlement of a structure. These devices eventually allow the pile to be completely unloaded to induce corrective movements in the case of buildings with differential settlements or apparent protruding. Therefore, control piles have been widely used in Mexico City for the underpinning of buildings with problems of differential settlements and tiltings. In this paper, the case of a building with a foundation that was underpinned with control piles to correct a maximum differential settlement of approximately 1 m is briefly described. The underpinning was combined with the sub-excavation technique to accelerate the process of the releveling of the building. Both the underpinning and the releveling were carried out within a year.

Keywords. Control piles, settlement control, underpinning, releveling, sub-excavation.

1. Introduction

In Mexico City, there are a large number of buildings with foundations that consist of a box-type foundation complemented by friction piles [1]. Most of these buildings have been underpinned with control piles to address problems of differential settlements and tilts [2]. These problems are caused by the regional subsidence in the basin of Mexico generated by water extraction from deep aquifers, which, in turn, has modified the geotechnical conditions of the basin's subsoil [3, 4]. Control piles are a useful foundation for solving these type of problems, since they allow the descent of the structure according to the regional subsidence.

The control pile system was created by the Mexican engineer González-Flores in 1948 [5]. Since then, this system has been used to underpin more than 700 buildings in Mexico City. Control piles are point-bearing piles that freely penetrate the foundation slab, at the head of which is a load frame rigidly anchored to the structure [6]. A deformable cell consisting of a set of wooden cubes of 5 cm on each side is placed between the load frame and the pile, with which it is possible to control the load transmitted to the pile and the settlements of the building [7]. The said load is equivalent to the yield load of the set of wooden cubes [8]. The objective of using wood is to ensure

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that the pile works at a constant load once the deformable cell reaches its yield point [7], which is possible due to the elastoplastic behavior of the wood.

The control piles are designed to penetrate through the base slab of the box-type foundation to compress the wooden cubes in an equal proportion to the regional subsidence [9], allowing the structure to descend in such a way that it reaches the ground to transmit load to it (Figure 1). The penetration of the pile depends on two sets of factors: those related to the subsoil of the site (regional subsidence and bearing capacity of soil) and those related to the building (differential settlements or unevenness and tilting of the building). Based on these factors, the load of each pile [7] is calculated, which defines the number of wooden cubes needed in a deformable cell. Once the pile load is defined, the deformable cell is placed between the pile head and the load frame. Subsequently, a preload is applied so that the pile contributes immediately to the support of the building [2].

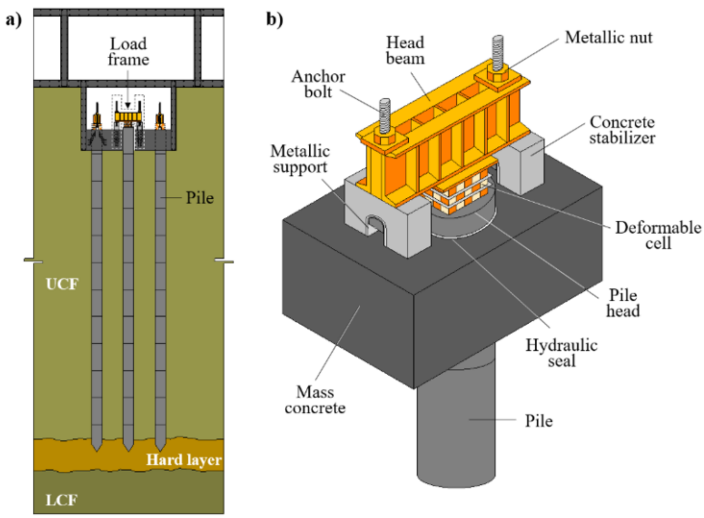

Figure 1. a) Schematic cross-section of a control pile device in a building and b) components of a control pile (Source: Author's own figure).

This paper briefly describes the case of a building located in the Lacustrine Zone of Mexico City that was evacuated because of an earthquake that occurred on September 19, 2017. Before the earthquake, the building had already experienced a differential settlement and a tilt that were greater than those admissible by the construction code of Mexico City [10]. The earthquake contributed to increase the problematic of the building. The building was then underpinned and releveled by the use of control piles in combination with the sub-excavation technique, as explained below.

2. General information of the case study

The analyzed structure was designed in 1980. It is part of a set of nine buildings in communication with each other (by means of constructive joints) but with independent foundations that are located in Mexico City. The building has six levels with a total height of 24.60 m and an area of 4245.8 m^2 (Figure 2). In addition, it has an underground parking lot. The original foundation consists of a box-type foundation complemented with 227 square section friction piles of 0.4×0.4 m and a length of 26.5 m. According to the Geotechnical Zoning of Mexico City, the building is located in the so-called Zone III, Lacustrine [11], characterized by sequences of very soft clay and clay sediments, widely known for their high water content and high compressibility, interspersed by units of cemented clastic material [12].

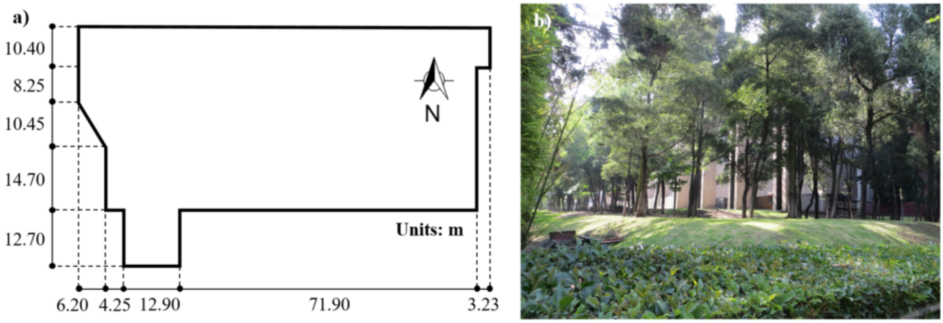

Figure 2. a) Dimensions of the building subjected to the intervention, and b) Facade of the building and embankment located in the north-west zone of the study site (September 2018).

Table 1 provides the index and mechanical properties of the site's subsoil, obtained from geotechnical exploration campaigns carried out in 1980, 1981, 2005, and 2007. The results of the surveys determined that the stratigraphy of the site is composed of the following strata: surface crust (SC), upper clayey formation (UCF), hard layer (HL), lower clayey formation (LCF), and deep deposits (DD). Likewise, it was determined that the HL on which the control piles are supported is located approximately 34 m deep on the east side and 36 m on the west side of the building.

Table 1. Index and mechanical properties of the site's subsoil [13].

Stratum	**Z (m)**	**γ (kN/m³)**	***w* (%)**	**Cr**	**Cc**	**OCR**	**c_u (kPa)**
SC1	0 - 3	14.7	---	---	---	---	111.2
SC2	3 - 5	14.7	---	---	---	---	111.2
UCF1	5 - 19	11.1	429	0.42	9.43	1.3	41.7
UCF2	19 - 34	11.9	293	0.27	6.45	1.2	67.5
HL	34 - 37	20.0	---	---	---	---	---
LCF1	37 - 49	12.0	210	0.21	3.73	1.3	101.7

Note: Z = depth, γ = volumetric weight, *w* = water content, Cr = recompression index, Cc = compression index, OCR = overconsolidation ratio, c_u = apparent cohesion.

During the first evaluation of the building's behavior in 2005, a differential settlement with a north-west orientation of approximately 80.0 cm was observed. This settlement continued to increase until reaching 90.7 cm in 2014. The increase in differential settlement is attributed to: a) the weight generated by an embankment (placed in 1981) located in the north-west zone of the study site (Figure 2b), and b) the high compressibility of the clays from the UCF, which is thicker on the north-west side of the building (below the embankment). It should be noted that the building presented no damage of structural elements (beams, columns and slabs) despite the magnitude of the differential settlement.

Different measures were considered to solve this issue, including a) the placement of rigid inclusions on the eastern side of the building (the zone with the largest settlement) and b) to underpin the foundation with control piles [13]. After the earthquake of September 19, 2017 (with an epicenter in Axochiapan, Morelos, 120 km from Mexico City and an M7.1 magnitude) [14], it was decided to underpin the foundation with control piles. This earthquake contributed to the increase in the maximum differential settlement and tilt in the corners of the building (in some places greater than 1% of the height of the building) (see Figure 3), exceeding the permissible limits of the existing construction code of Mexico City for that year [10]. This earthquake caused significant damage and the collapse of several buildings in Mexico City [15,16]. However, the geotechnical damage was considerably less than that of the earthquake of September 19, 1985 [1].

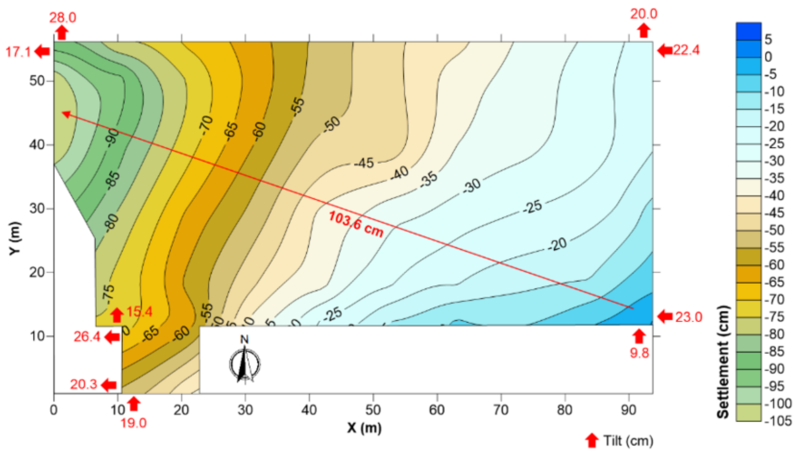

Figure 3. Differential settlement and tilt in the corners of the building under study before underpinning and releveling (November 2017).

3. Underpinning and releveling of the building

3.1. Underpinning works

The underpinning project consisted of placing 192 new point-bearing piles with a control device in the existing box-type foundation of the building. For the installation of the control devices, the foundation was reinforced with 192 mass concrete elements structurally linked to the base slab of the box-type foundation and to the existing supports.

Once the 192 mass concrete elements were constructed, the following works were carried out:

- Assembly and leveling of the mechanical drilling device to drill until reaching the resistant layer (HL, approximately 34 m).
- Pile driving into soil under pressure (45 cm in diameter and sectioned in segments of 91 cm) by a system consisting of a load frame and hydraulic jack. The piles were installed with 3/8" rods placed in their central part.

- Placement of the deformable cell (formed by an arrangement of three levels of 6×6 *caobilla* cubes) and the load frame in the control system for later preloading using a system called a *double bridge*.

These works were executed over a period of eight months (December 2017 to July 2018). By the previous procedure, 192 new control piles were installed with a nominal load of 980 kN (100 t) per pile.

3.2. Releveling works

The releveling works consisted of lowering the highest part of the building. For this, it was necessary to a) dig tunnels under the base slab of the box-type foundation (Figure 4 and Figure 5a) to reach the shaft of the original foundation friction piles and b) disconnect some of the original friction piles located in strategic zones (Figure 5b) to allow the vertical movement of the structure.

Subsequently, the technique of manual sub-excavation was applied in the higher areas or those with less settlement (Figure 4 and Figure 5c), and a volume of approximately 210.3 m^3 of soil was removed under the base slab of the box-type foundation to induce the vertical movement of the structure. The sub-excavation was complemented by the release of the metallic nuts of the control system to favor the descent of the structure until reaching the desired level. Once this level was reached, the heads of the control piles were cut, with the purpose of having a separation of 10 millimeters between the head beam and the concrete stabilizers. Then, each pile was preloaded up to its nominal load of 980 kN (100 t).

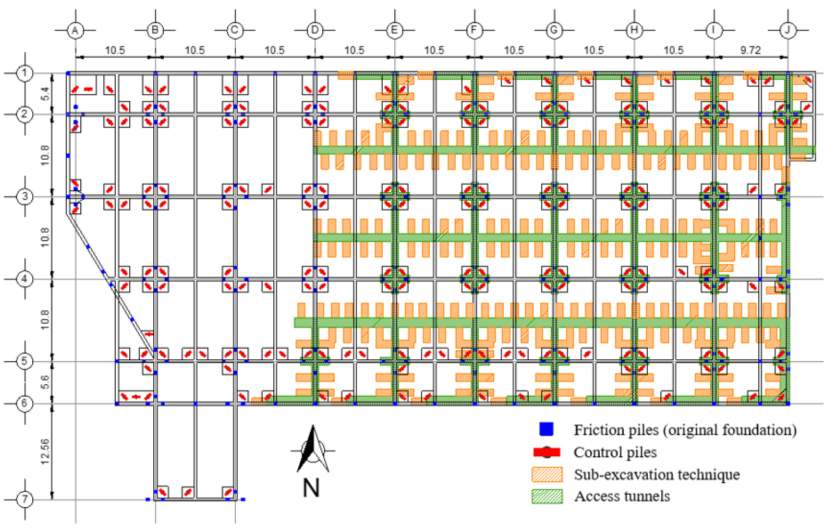

Figure 4. Locations of access tunnels and sub-excavation zones.

The sub-excavation technique consists of removing a specific volume of foundation soil (underneath the base slab of the box-type foundation) in the area with the least settlement to induce the vertical displacement of a building (Figure 6). Sub-excavation can be carried out manually, or with conventional drills or with equipment designed for this purpose [17]. This technique was implemented in Mexico in the Church of San

Antonio Abad in 1990 [18] and years later in the Metropolitan Cathedral of Mexico City [19].

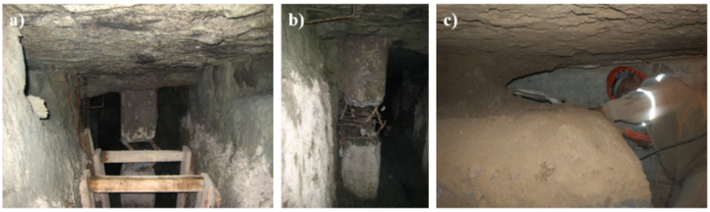

Figure 5. a) Access tunnels and sub-excavation zones, b) disconnection of a friction pile from the original foundation, and c) manual sub-excavation technique (Source: Author's own photograph).

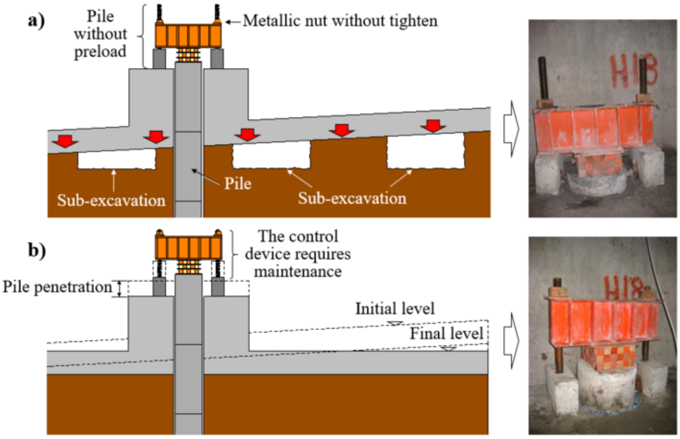

Figure 6. Sub-excavation process: a) initial condition and b) after applying the sub-excavation technique.

3.3. Current condition of the building

After the underpinning and releveling works, based on a topographic survey carried out in December 2018, a maximum differential settlement of 50.7 cm was estimated. With the installation of the control piles complemented by the sub-excavation, the differential settlement decreased by 50% in approximately one year (Figure 7). Based on the last topographic survey, it was determined that the building is within the parameters established by the current regulations [11]. A maximum differential settlement of 0.004 (which is the maximum permissible value for buildings with rigid concrete frames), as well as a tilt in the corners of the building of less than 1% of the total height of the building were estimated. Due to the structure is part of a set of nine buildings connected to each other by means of constructive joints, it was not possible to reach a null level in the first work stage, because this would hinder the access to the adjacent buildings. Initially, the placement of access ramps was required (Figure 8); however, these ramps will not be necessary when the remaining buildings are underpinned and releveled.

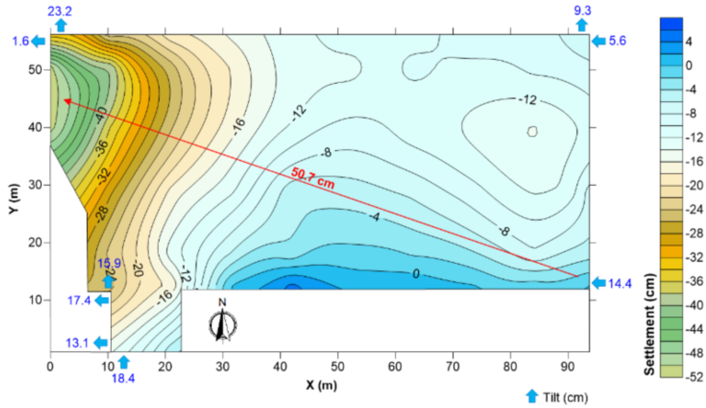

Figure 7. Differential settlement and tilt in the corners of the building under study after its underpinning and releveling (December 2018).

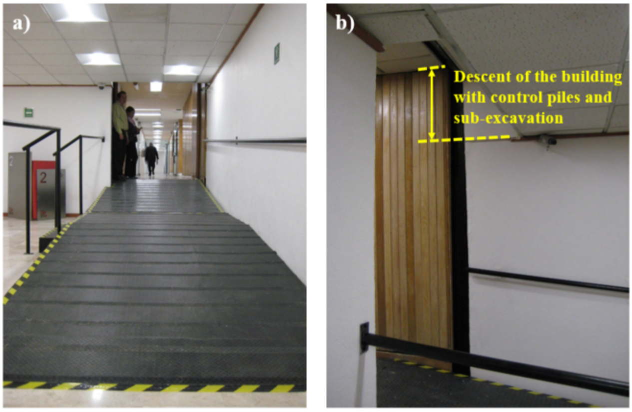

Figure 8. Current condition of one of the corridors communicating with an adjacent building (November 2018): a) front view and b) side view.

4. Conclusions

In this paper, we briefly described the case of a building whose foundation was underpinned using 192 control piles supported on a resistant layer. In addition, the building was releveled by means of adjusting the control devices in combination with the sub-excavation technique. With this previous procedure, it was possible to reduce the maximum differential settlement of the building by 50% in approximately one year.

According to practical experience in Mexico City, the releveling of buildings may take over three years. The sub-excavation technique allows the reduction of this time and contributes to the leveling of the buildings. The sub-excavation is possible if the foundation is supported by a system that controls the vertical displacements of the building, such as the control piles. If the vertical movements during the underpinning are not monitored and controlled, there is a risk that considerable immediate settlements will occur.

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