General Bearing Capacity Theory and Soil Extraction Method for the Mitigation of Differential Settlements

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ABSTRACT

Differential settlements experienced by a number of historic monuments have been remediated using the soil-extraction method. Italy's *leaning Tower of Pisa* and the Mexico City's *Metropolitan Cathedral* are two well-known structures where the soil-extraction method was applied to address issues associated with differential settlements. This paper describes a case study for a seven-story building in Mexico City, where differential settlements generated vertical inclinations ranging from 241-mm (9.5-in) to 310-mm (12.0-in) to the north, and 70-mm (2.75-in) to 98-mm (3.9-in) to the east. For the remediation of these inclinations, the soil-extraction method was applied through rectangular cavities excavated underneath the foundation element. The general bearing capacity theory was used to determine the location and dimensions of these cavities. After finalizing the soil-extraction process, an average settlement and upward movement of 87-mm (3.5-in) and 24-mm (1.1-in) were recorded, respectively. After the completion of the soil-extraction process, all deformations were brought within tolerable limits specified by the local building code.

INTRODUCTION

This paper presents the work completed for soil-extraction method applied to a seven-story building located in Mexico City, Mexico. Furthermore, the general theory of bearing capacity and its application to the soil-extraction method is described. Finally, results from surveying and monitoring are presented and discussed.

Thick deposits of compressible clays, regional water extraction, and high seismic activity combined with pre-19th century historical monuments, have created a difficult and challenging environment for geotechnical engineers in Mexico City, (Ovando et al. 2001). From building inspections completed after the Mexico City 1985-earthquake, a significant number of buildings suffered differential settlements after the earthquake. However, a number of these structures did not surpass the serviceability criterion mandated by local codes, and continued service operations for years after.

A seven-story building lost its verticality during the Mexico City's 1985-earthquake and continued operations until 2005 when due to the regional subsidence, deformations exceeded the tolerable limit. Based on surveying and monitoring results, the building experienced differential settlements leading to vertical inclinations ranging from 241-mm (9.5-in) to 310-mm (12.0-in) to the north,

and 70-mm (2.75-in) to 98-mm (3.9-in) to the east. To remediate differential settlements and further bring displacements within serviceability limits, the soil-extraction method was analyzed and implemented.

According to Ranzini (2001) most of differential settlements and the tilting of the structures built on shallow foundations, are closely related to the consolidation process of the soil layers beneath the foundation. Other factors such as shape of the structures, eccentricity in loading, groundwater extraction, and construction in the vicinity contribute to the consolidation creating settlements. Research studies and detailed analyses have been completed to create predictive models for these settlements and further minimize their impact on the serviceability of structures. Furthermore, research projects have been performed to study the remediation of differential settlements.

One method used in Mexico City during 1990s, was the soil-extraction method applied to the Metropolitan Cathedral. This method was first proposed by Fernando Terracina (1962) for stabilization of the Tower of Pisa, but for reasons outside of the scope of this paper, the process was not applied to the tilted monument. For the particular case of the Tower of Pisa, Terracina (1962) proposed the soil-extraction method based on the assumption that increasing pressure at the north end of the Tower, could relieve pressure at the south end of the Tower that suffered greater settlements. If this condition was achieved, then the tower's inclination as well as the pressures at the southern edge of the foundation will be reduced (Terracina, 1962).

Mexico City's Metropolitan Cathedral

The construction of Mexico City's Metropolitan Cathedral was completed in multiple phases starting in 1573 and finishing in 1813. This heavy structure is located in downtown Mexico City and atop of Aztec's *Templo Mayor*, Figure 1. After conquering the *Aztec Empire*, Hernan Cortes and the Conquistadors started the construction of a church at the site of *Templo* Mayor using stones from a former Aztec temple to further consolidate the Spanish Power, (Santoyo et al. 2008). After additions and modifications, this initial church became the Metropolitan Cathedral and currently considered the *largest* Cathedral in the America, (Aguilera 2013). The heavy structure has suffered differential settlements mainly caused by Mexico City's subsidence and the consolidation of large compressible clays located underneath the structure.

During 1980s and 1990s, due to severe structural damage and the risk of losing a historic monument, a rehabilitation and restoration plan was presented to the Mexico City's government. During a surveying and monitoring project carried out from 1989 to 1990, the settlement rates and differential settlements were determined. After determining the final average annual settlement and the critical points throughout the Cathedral, Terracina's soil-extraction method was applied to the Mexico City's Metropolitan Cathedral starting in 1993. The process consisted of creating a series of radial 100-mm (4-in) diameter auger holes at different levels beneath the foundation system and completed from inside of vertical circular shafts installed throughout the Cathedral, Figure 2. These auger holes were eventually closed due to the clay's plastic flow, creating vertical displacements at the surface level.
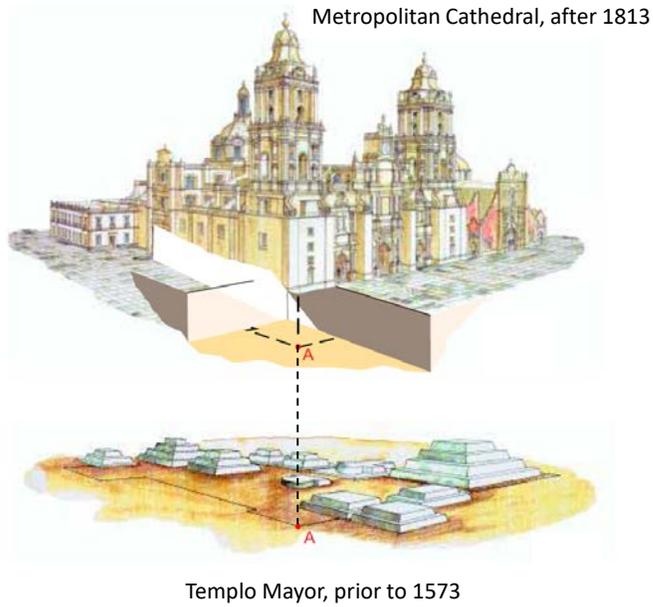
Metropolitan Cathedral, after 1813

Templo Mayor, prior to 1573

Figure 1. Mexico City's Metropolitan Cathedral atop of Aztec's Templo Mayor (Santoyo et al. 2008)

Vertical Access Shafts

Radial Auger Holes

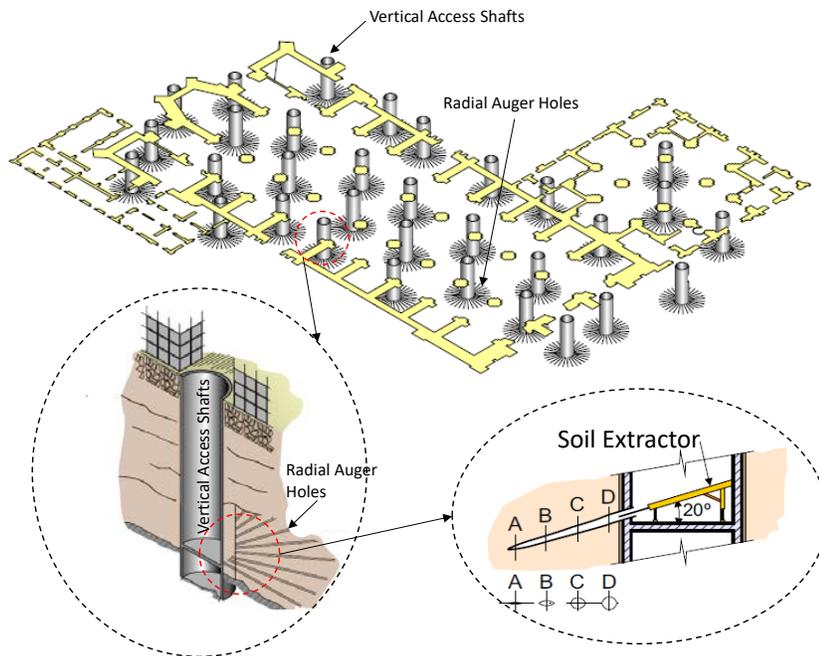Vertical Access Shafts

Radial Auger Holes

Soil Extractor

A B C D

20°

A B C D

Figure 2. Soil-extraction method and details applied to Mexico City's Metropolitan Cathedral (Santoyo et al. 2008)

The construction of the eight-level Tower of Pisa with approximately 60-m (200-ft) in height started in 1173 with the belfry completed between 1360 and 1370. According to Salgado (2008), the foundation soil of the tower consisted of approximately 300-m (984-ft) of sediments deposited by *Arno River* and the Tyrrhenian Sea (dated back to the time when the sea on the west coast of Italy, reached the city of Pisa). Soil layers nearby the ground surface can be described as a 9-m (30-ft) thick silty-sandy soil followed by approximately 30-m (100-ft) of marine clay. Due to higher compressibility of the silt material located towards the south of the tower, settlements were developed faster compared to the north end part of the tower, Figure 4 (a). To prevent the tower to experience further settlements in the south and to preserve the historic monument, the soil extraction method was applied for the stabilization of the Tower of Pisa. The removal of volumes of soil from underneath of the foundation and took place at the north-end of the Tower, (Burland et al., 2002). The process consisted of drilling auger holes from the surface (Burland et al. 2009) with an inclination of 20° to 30° from the horizontal and extending to a maximum length of 22-m (73-ft), Figure 4. These dimensions located the cylindrical soil extractors at approximately 4.5-m (15-ft) below the center of the tower's foundation, Figure 3. This process did not *correct* the inclination of the tower but it did achieve the objective of the project which was the *stabilization* of the tower.
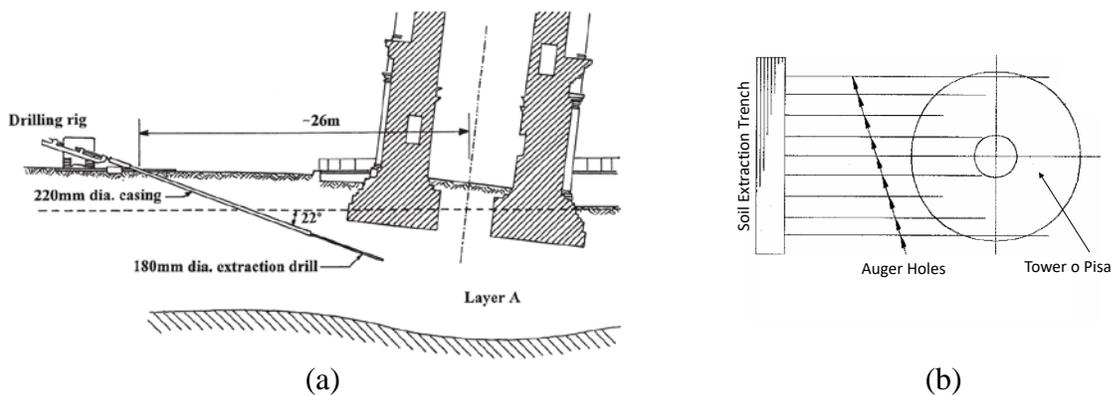

(a)   (b)

Figure 3. Soil-Extraction method applied to the Tower of Pisa (a) Section View, (Burland et al. 1998) and (b) Plan View (Terracina 1962)

CHARACTERISTICS OF THE BUILDING

The case study presented in this paper is for a seven-story building formed by reinforced concrete frames and slabs, constructed in a rectangular area of 488.0-m^2 (5253-ft^2), and supported by a reinforced concreted cell-foundation (i.e. compensated foundation). During the site reconnaissance the depth of foundation was measured at 2.23-m (7.30-ft) below the ground surface. According to structural information, the net pressure transferred to the foundation soil was approximately 60-kPa (1250-psf).

Results from surveying and monitoring prior to any work related to the rehabilitation of the structure showed that the differential settlements experienced by the building generated vertical

inclinations which ranged from 241-mm (9.5-in) to 310-mm (12.0-in) to the north, and 70-mm (2.75-in) to 98-mm (3.9-in) to the east, Figure 4.
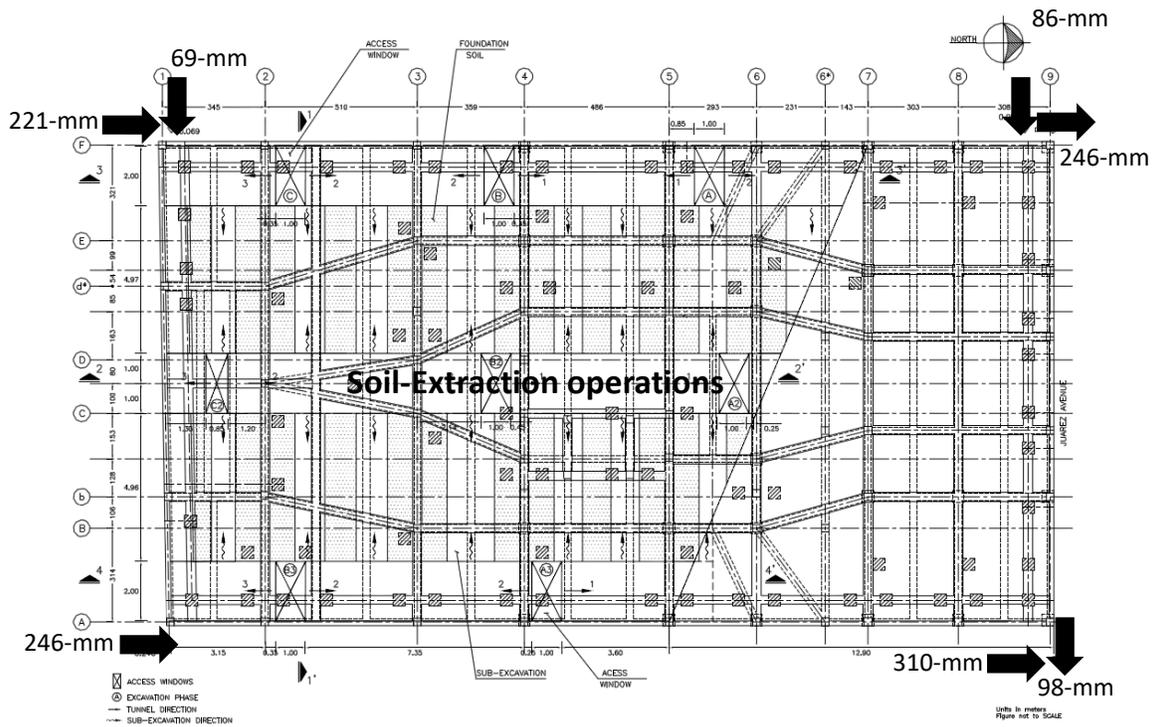

Figure 4. Vertical Inclinations recorded at each corner of the building

SUBSURFACE CONDITIONS

In addition to existing geotechnical information, one auger-boring (POS-1) and two test pits were completed to depths of 6.10-m (20-ft) and 2.0-m (6.6-ft), respectively. Disturbed and undisturbed samples were recovered and tested in the laboratory. According to field visual description and laboratory tests, the soil immediately beneath the foundation's bottom slab consisted of a light brown silty sand (SM) with an average water content of 25% which extended to a depth of 4.0-m (13.0-ft). Following the silty sand layer and with a thickness of 1.25-m (4.1-ft), a low to high plasticity brown sandy silt (ML-MH) with 64% of fines, and average water content of 50% was encountered. A green to light gray sandy clay (CL) with an average water content of 70% was located between 5.25-m (17.2-ft) and the maximum depth of boring. From laboratory testing an average cohesion c = 15 kPa (317-psf), an angle of friction ϕ = 28°, and a unit weight of 16 kN/m^3 (102-pcf) were assigned to the material below the foundation's bottom slab.

SOIL-EXTRACTION METHOD

Based on vertical inclinations of the building, it was determined that the soil-extraction operations will be conducted within the trapezoidal area representing approximately 2/3 of the total footprint area of the building, Figure 5. Considering that the tilting of the building was mainly towards northeast, it was reasonably assumed that increasing pressures in the south and southwest of the structure will create settlements and will reduce inclinations of the building registered at the north side of the structure. Basically, the objective of the soil-extraction operation was to create settlements in the south and southwest portion of the structure, and upward movements in the north and northeast of the building.

Terzaghi (1943) developed the ultimate capacity theory by demonstrating that for a loaded footing with width "B", the failure surface beneath the footing is comprehended as a plastic equilibrium zone represented by the area *"abcde"* which was further divided into 3 main zones: Zone I. Triangular wedge under the foundation base, Zone II. Zones of radial shear intersecting the horizontal at angles 45°- φ/2, and Zone III. Passive Rankine zones, Figure 5.
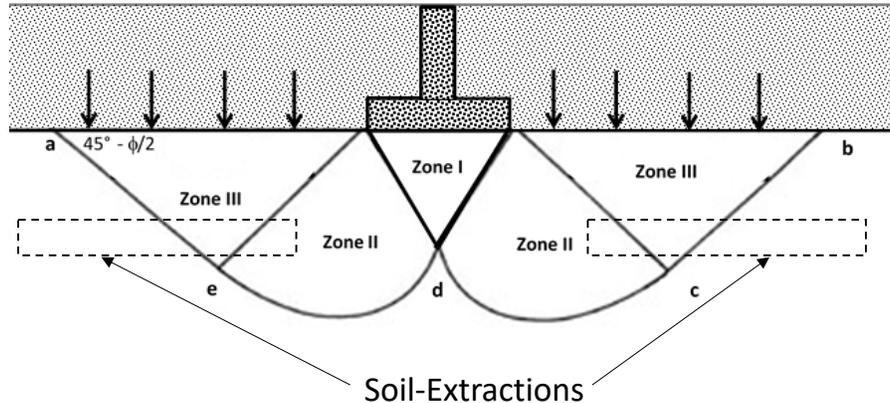

Figure 5. Schematics of Terzaghi's general bearing capacity theory

Applying the theory of static equilibrium to the triangle wedge (Zone I), it is observed that for the Zone I to remain in equilibrium, the sum of vertical components of the resistances sourced to the shear strength parameters (c, φ) and the Rankine passive forces (P_{pn}), should be equal to the sum of the load applied to the foundation (P) and the weight of the soil wedge (W_w), Figure 7 (b). According to this, if any of the resistance sources is reduced to a level where the static equilibrium is no longer satisfied, then Zone I will have a downward movement creating deformations at the surface and the base of the foundation. It is reasonably assumed that by removing volumes of soil from zones II and III, Figure 6, the resultant force (P_P) shown in Figure 7, will be gradually reduced to a level where the static equilibrium is not satisfied, and Zone I will move downwards creating settlements at the surface.

The foundation of the building consisted of cell-foundation i.e., compensated foundation with top and bottom rigid slabs. The soil-extraction method was implemented beneath the bottom slab and to apply the general bearing capacity theory, it was reasonably assumed that the bottom slab consisted of a series of footings placed at a very close distance, and for each footing the Terzaghi's general bearing capacity theory would apply, Figure 8.

As previously discussed, by creating cavities (i.e. soil-extractions) within the zone of shear resistance (Zone II) and Rankine's passive resistance (Zone III), the static equilibrium for the soil wedge (Zone I) becomes unbalanced, and settlements are generated at the surface. Based on this approach, the soil-extraction method using the general bearing capacity theory was implemented for the project described in this paper.
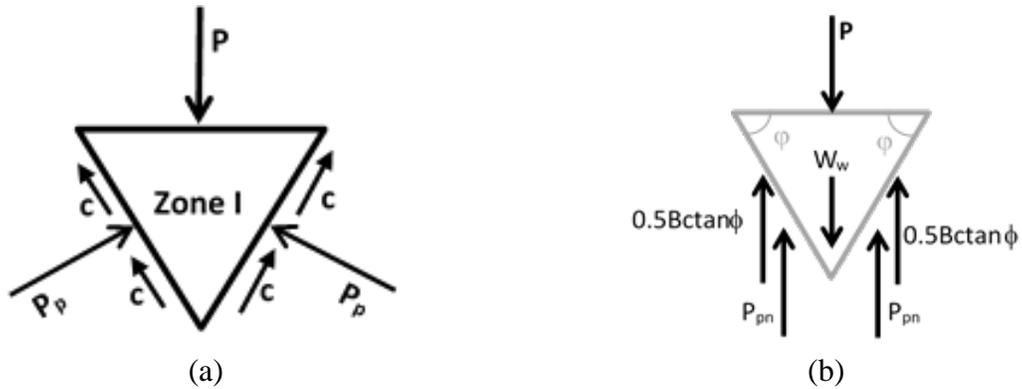
(a)   (b)

Figure 6. Free body diagram for Zone I (a) Resultant forces (b) Vertical components
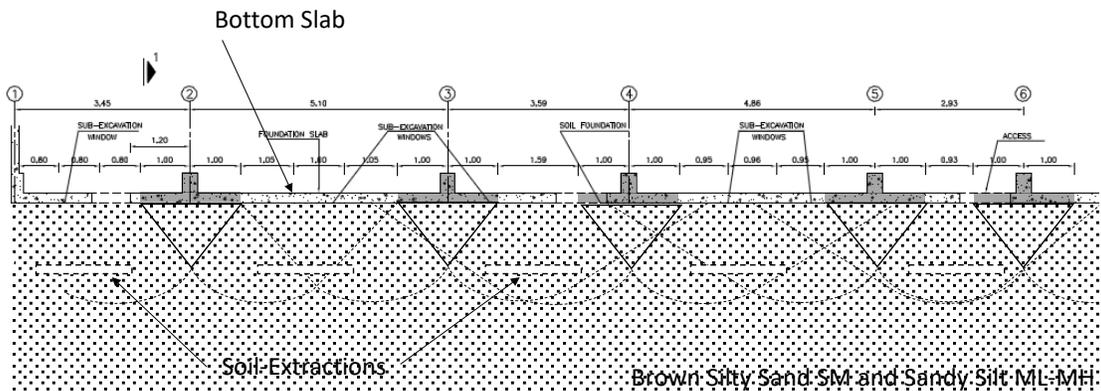

Figure 7. Bottom slab of the foundation hypothesized as a series of footings

Soil-Extraction construction procedure

Considering space limitation due to adjacent in-service buildings, the soil-extraction process was carried out from underneath the building. The process was completed in three phases: (1) Excavation of Access pits and Maneuver tunnels (2) Protection of the tunnel walls, and (3) excavation of cavities, i.e. soil-extractions.

As part of Phase (1), eight access pits were identified throughout the bottom slab and excavated to a depth of 2.0-m (6.5-ft). From each access pit, maneuver tunnels were excavated until convergence, Figure 9. Phase (1) and (2) were simultaneous activities, where the tunnel was excavated and the walls were protected. The protection system consisted of 70-mm (2.75-in) thick mortar shotcrete placed in two layers with a 6x6-6/6 wire mesh in between and reinforced with bracing systems comprising 100-mm×300-mm (4-in×12-in) wood beams placed vertically (similar to soldier piles) and braced with 100-mm (4-in) diameter struts in two levels, Figure 10.
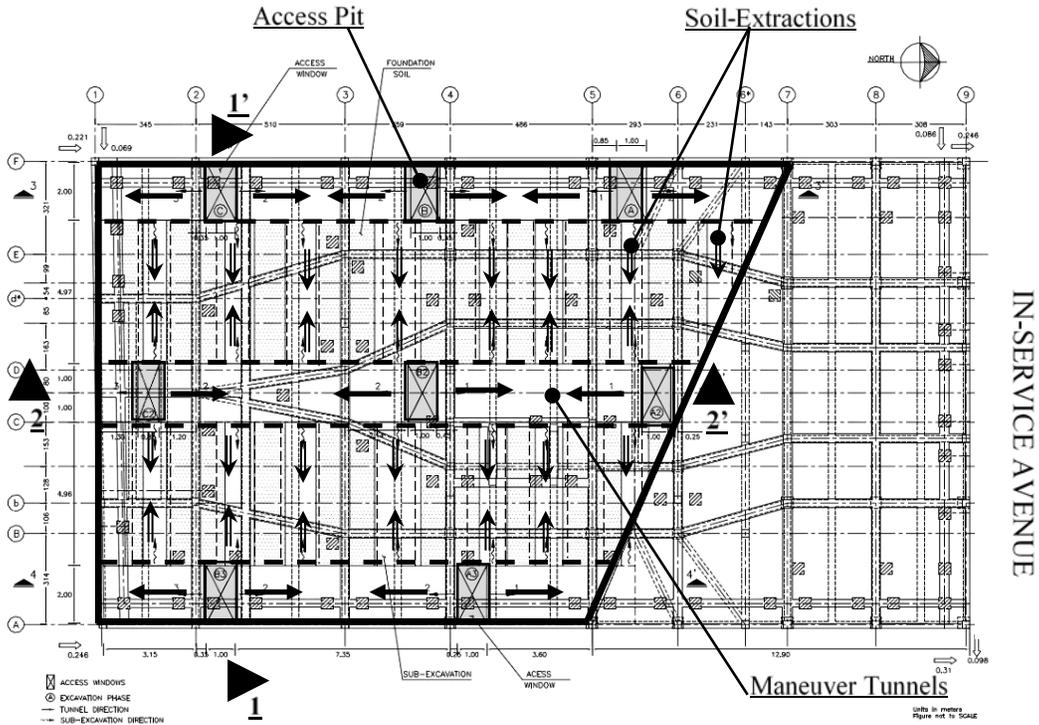
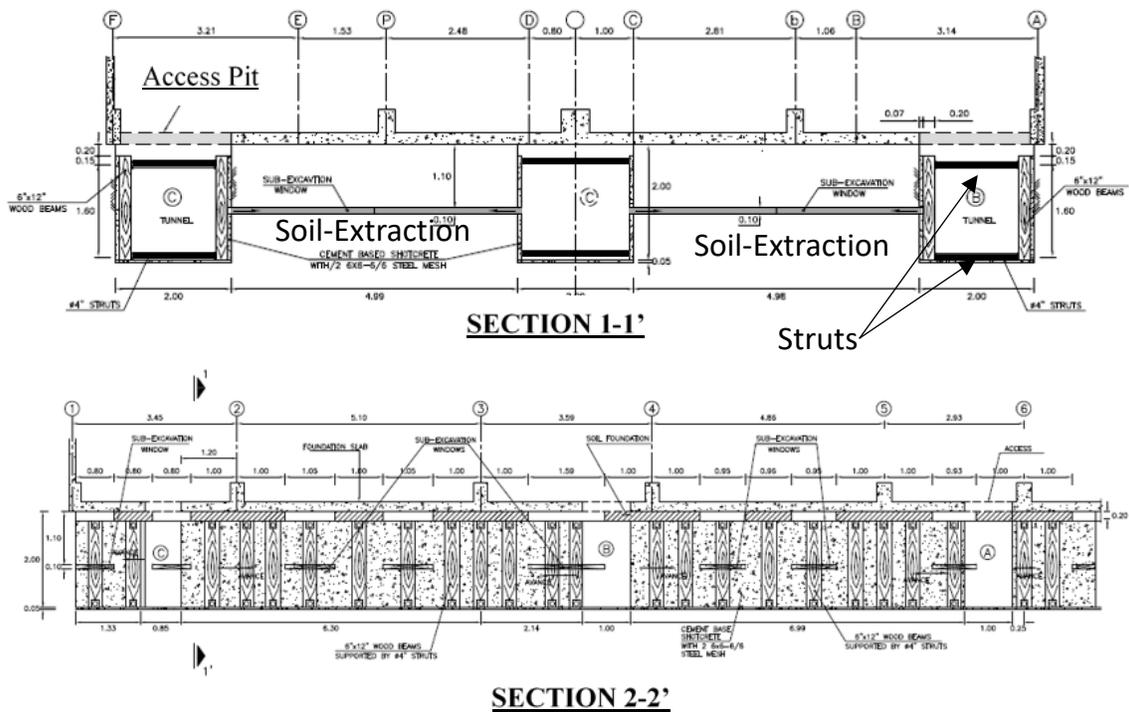**Figure 8.** Access Pits, Maneuver Tunnels, and Soil-Extractions

Figure 9. Section view of the soil-extraction process

MONITORING AND RESULTS

A total of 49 surveying points were marked and monitored during the sub-excavation process, and vertical displacements associated with the building were recorded daily. During the initial excavation process (Phase 1 and Phase 2), the building experienced an upward movement due to the soil's elastic response, Figure 11. The building presented an average upward movement of 12-mm (0.5-in) measured in a period of three months, with major concentration in the south and southwest of the structure. The upward movement gradually shifted to a settlement, after all soil-extraction cavities were completed. Maximum deflections recorded during the soil-extraction process are summarized in Table 1, and the monitoring plot corresponding to the two axes with major deflections are shown in Figure 11.

At the end of the soil-extraction process, 87.0-mm (3.5-in) settlement for point F-1 located at the southwest corner of the structure and 27.0-mm (1.10-in) upward movement for the point A-9 located at the northeast corner of the structure, were recorded. As it is noted in Table 1, all movements indicate a deflection pattern starting with major settlements in the south side of the structure (Figure 9-Points A-1 to F-1), and ending with slight upward movements in the north side (Figure 9-Points A-9 to F-9). From these movements and at the end of the process, the inclinations of the superstructure were within tolerable limits.

Table 1. Maximum Deflections recorded at each survey point

Axis	Deformations (mm)	Axis	Deformations (mm)
A-1	- 50	D-3	-46
A-9	+22	D′-6	-10
B-3	-35	d-1	-82
B-6	+1	d′-9	+17
b-1	-61	E-3	-51
b′-6	+17	E-6	-12
C′-2	-58	F-1	-87
C′-9	+18	F-9	+12

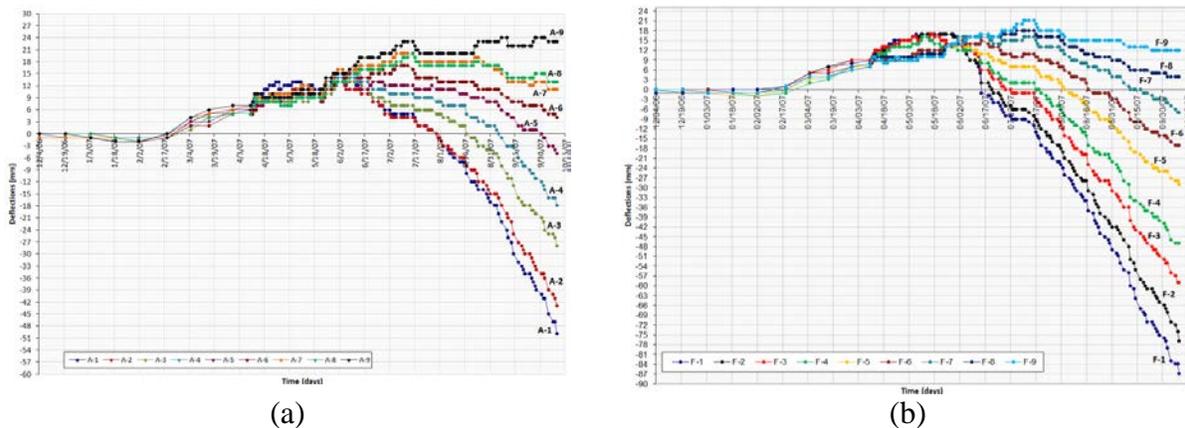
(a)   (b)

Figure 10. Monitored Settlements for (a) Axis A and (b) Axis F

SUMMARY AND CONCLUSIONS

This paper presented the case of seven-story building which lost its verticality after Mexico City's 1985 earthquake with the vertical inclinations surpassing the tolerable limits in 2005. For the rehabilitation and stabilization of this building and its associated vertical inclinations, the soil-extraction method was proposed and implemented.

Due to space limitation and adjacent structures, the soil-extraction method was not implemented using auger holes and drilling operations. Instead of generating plastic flow in the material beneath the foundation through circular auger holes, the general bearing capacity theory was used to determine the location and dimensions of the soil extraction cavities excavated in rectangular shapes. The soil-extraction process was completed in three main phases where the access pits and maneuver tunnels were excavated followed by the protection of the tunnel walls, and finally the excavation of the soil-extraction cavities.

Results from monitoring and surveying showed that at the end of the soil-extraction process, a total of 87.0-mm (3.5-in) settlement for point F-1 located at the southwest corner of the structure and 27.0-mm (1.10-in) upward movement for and point A-9 located at the northeast corner of the structure were recorded.

Soil-extraction method and its application to leaning structures requires careful monitoring and rigorous engineering analyses, prior and during the process. The soil-extraction method was successfully implemented for the project presented in this paper and at the end of the soil-extraction process, the building's deflections were brought within tolerable limits. Furthermore, this study confirms the shear zone and Rankine's passive zone, outlined in the general bearing capacity theory, can be weaken by manipulating these zones.

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