Use of Sub-Excavation Method for Foundation Remediation; A Case Study

R.B. Moghaddam
Department of Civil and Environmental Engineering, Texas Tech University, Lubbock, Texas, USA

C. Yzquierdo L.
YZMO GEOTECNIA, S.C., Mexico City, Mexico

P. W. Jayawickrama
Department of Civil and Environmental Engineering, Texas Tech University, Lubbock, Texas, USA

ABSTRACT: The sub-excavation method has been used to remediate a number of historical monuments that suffered large differential settlements. Among the most well-known structures are Italy's *Leaning Tower of Pisa* and Mexico City's *Metropolitan Cathedral*. In general, sub-excavation (also known as soil extraction or under-excavation) involves removal of soil from underneath the building foundation. This paper describes a case study involving the application of the sub-excavation method to a seven story structure that suffered severe differential settlement following the 1985 earthquake in Mexico City, Mexico. The differential settlements increased throughout the years due to Mexico City's regional settlement creating inclinations ranging from 241mm to 310mm to the north and 69mm to 98mm to the east. Due to these movements, the building was declared to be in an unserviceable conditions by Mexico City's authorities. This structure was selected to be rehabilitated by using the sub-excavation method combined with horizontal micro-excavations. This paper describes the details and results of the sub-excavation procedure.

1 INTRODUCTION

The subsurface conditions of Mexico City present special challenges for structural and geotechnical engineers. Thick deposits of clay, regional water extraction, high seismic activity combined with pre-19th century historical monuments, have resulted in challenging infrastructure projects to be designed, modified or remodeled. Due to major structural damage suffered during the 1985 earthquake, a significant number of buildings were classified as non-operational. Some of these structures were demolished and replaced with new buildings, while a few were classified as historic buildings and were remodeled to be kept as historic landmarks and museums. Few of these structures were selected to be rehabilitated in order to be serviceable.

This paper describes the details and the work completed during the use of the sub-excavation method to remediate a seven story structure that suffered differential settlement following the 1985 earthquake and regional settlement in Mexico City, Mexico. The building experienced large differential settlements with inclinations ranging from 241mm to 310mm to the north and 69mm to 98mm to the east. The approach that was selected for rehabilitating this structure used a combination of sub-excavation and horizontal micro-excavations.

The tilting of structures built on shallow foundations is mainly caused by the consolidation of the soil layers beneath the foundation (Ranzini, 2001). Different factors such as the structure's shape, eccentricity in loading, groundwater extraction, and construction in the vicinity can contribute to the consolidation process and hence the differential movements. A series of studies and analyses have been performed to predict these settlements and minimize their impact on the serviceability of these structures. Similarly, major research projects have been undertaken with the objective of remediation of differential settlements, using different methods and techniques.

A method that has been used successfully in Mexico City during 1980s, is the sub-excavation method. This method, also known as soil extraction or under-excavation, was first proposed by Fernando Terracina in 1962 for stabilization of the *Tower of Pisa*. However, for reasons outside of the scope of this paper, the process was not applied to the tilted monument. For the particular case of the Pisa Tower, Terracina (1962) believed that increasing pressure at the north end of the Tower, that suffered smaller settlement, could relieve pressure at the south end of the Tower that suffered greater settlement. If this condition is achieved, then the tower's inclination as well as the pressures at the southern edge of the foundation can be reduced (Terracina, 1962). After successful application of Terracina's soil extraction method to the Mexico City's Metropolitan Cathedral in 1996, a series of inclined auger holes with variable length were completed and volumes of soil were removed from underneath of the foundation of the Tower of Pisa, (Burland et al., 1998). This process resulted in arresting further tilting of the Tower of Pisa. After the positive results obtained from the above mentioned projects, the sub-excavation method was applied to a number of different structures in Mexico City to achieve verticality.

2 CHARACTERISTICS OF THE BUILDING

The case study described in this paper involves a building located on Juarez Avenue, near the Alameda Central Park, and two blocks west of the *Latino Americana Tower*. The building lost its verticality after Mexico City's 1985 earthquake. Multiple structural revisions determined that the leaning structure doesn't exceed the allowable inclination marked by the building code at that time. However, after several years, due to the regional settlement, the differential settlements further increased with components of inclination ranging from 241mm (10in) to 310mm (12in) to the north and 69mm (2.8in) to 98mm (3.9in) to the east.

This structure is a seven story building with rectangular footprint with a total area of 488.0m² (5253ft^2). Its skeleton is formed of reinforced concrete frames with 0.40m (16in) thick slabs and supported by a reinforced concrete cell foundation with a depth of 2.23m (7.30ft) below the sidewalk. The building is adjacent to a 3-story building to the east, empty lot (at the time of re-leveling) to the west and south, and Juarez Av. to the north. According to structural information, the net pressure transferred to the soil is 6.0 ton/m² (1.23ksf) which was increased to 8.0 ton/m^2 (1.64ksf) once the maneuver tunnels were excavated.

3 SUBSURFACE CONDITIONS

In addition to existing geotechnical information, from previous explorations, one hand auger-boring (POS-1) and two test pits were completed to depths of 6.10m (20ft) and 2.0m (6.6ft) each, respectively. To determine soil index and strength parameters, disturbed and undisturbed samples were obtained and tested in the laboratory. According to field visual description and laboratory tests, the soil immediately beneath the foundation slab is classified as light brown silty sand (SM) with an average water content of 25%. This layer extends to a depth of 4.0m (13ft) below the foundation slab. Following the silty sand layer and extending to a depth of 5.25m (17ft), is a low to high plasticity brown sandy silt (ML-MH) with 64% of fines and an average water content of 50%. At the bottom of the boring with a thickness of 0.85m (2.8ft) a green to light gray sandy clay (CL) with an average water content of 70% was located. Based on laboratory tests, a cohesion of c = 1.5 ton/m² (0.31ksf), an angle of friction $\phi = 28°$, and a unit weight of 1.55 ton/m^3 (97pcf) were assigned to the silty sand material.

4 SUB-EXCAVATION METHOD

Considering the inclination of the building towards north and east, it was determined that the sub-excavation will be conducted within a trapezoidal area representing approximately 2/3 of the total footprint area of the building (See Figure 1). To achieve this, eight 1.0m (3.3ft) x 2.0m (6.6ft) access pits were opened to a depth of 2.0m (6.6ft), through the foundation slab. Then maneuver tunnels were advanced using multiple excavation fronts starting from different access points and continuing until convergence was achieved. Advance cycle for the tunnels was estimated as 1.5m (5ft) and during each cycle peripheral walls were protected with shotcrete layers and bracing system. The shotcrete consisted of a 70mm (2.75in) thick mortar shotcrete placed in two layers with a 6x6-6/6 wire mesh in between. The bracing system consisted of 100mm×300mm (4in×12in wood beams placed vertically (similar to soldier piles) and braced with 100mm (4in) diameter struts in two levels (See Fig. 2). Once all three maneuver tunnels were completed and protected, eight 120mm (4.75in) micro-excavations (sub-excavation windows) were excavated between the tunnels, as shown in Fig. 1 and 2. These windows were gradually widened until the designed deformations were achieved. During and after the completion of the sub-excavation process, the movements associated with the structure were monitored and recorded. The results from the monitoring process and the deflections achieved from the sub-excavation process are discussed in the following section.

It is important to mention that after the process of sub-excavation, the foundation of the structure was modified to deep foundation to prevent further settlement in the future. Details related to the

foundat
paper.

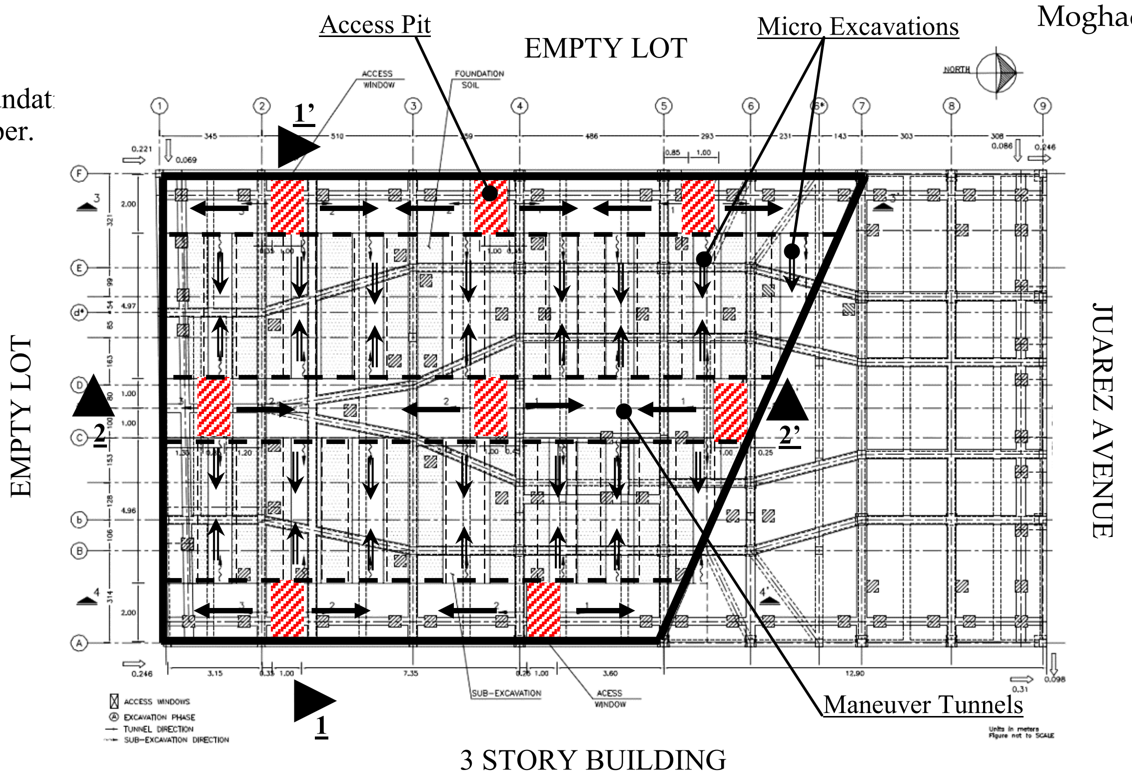


Fig. 1 Access Pits, Maneuver tunnels, and Micro-Excavations

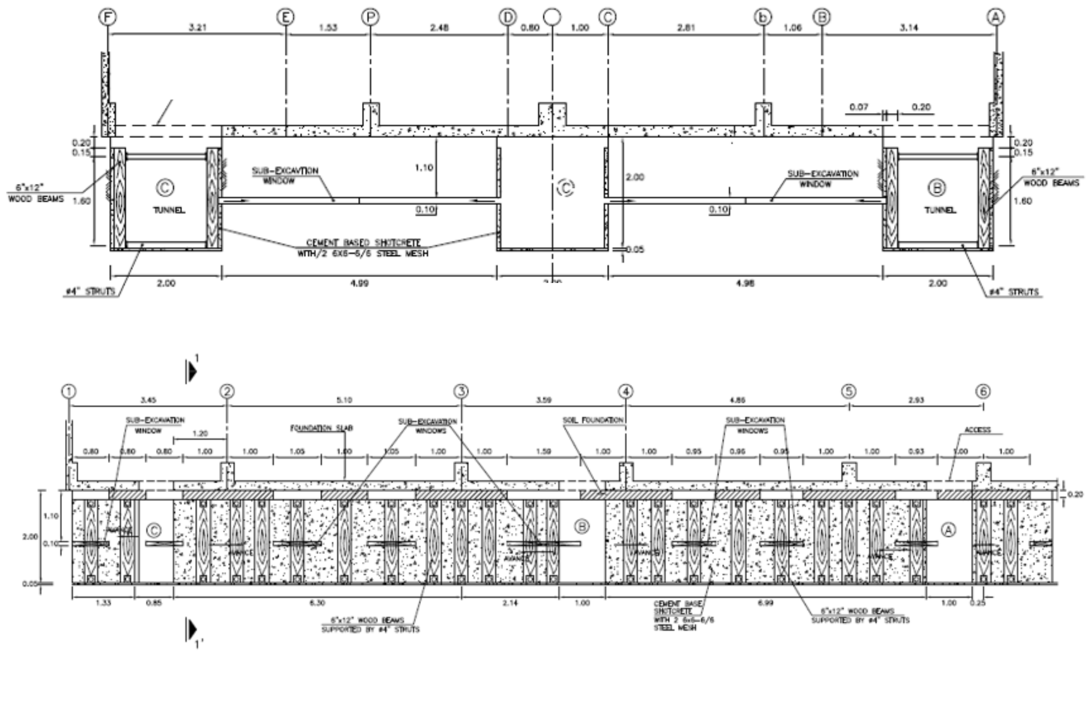


Fig. 2 Top: Maneuver Tunnels and sub-excavation windows, Bottom: Retaining system and details

5 RESULTS FROM MONITORING

The sub-excavation process initiated with the excavation of maneuver tunnels in the trapezoidal area as shown in Fig. 1. A total of 49 surveying points were marked and monitored during the sub-excavation process. Monitoring points were installed at major Axis intersections (i.e. F-1 to F-2) with average distance of 3.5m (11.5ft) in the longitudinal direction and 4m (13.0ft) in the transversal direction. Movements associated with the building were recorded daily. As expected, during the initial excavation process (excavation of maneuver tunnels), the building experienced an upward movement due to the soil's elastic response (See Fig. 3). For a period of three months the building presented an average upward movement of 12mm (0.5in), mainly in the south end. This upward movement gradually turned to a settlement once all the micro-excavations where completed.

Based on the surveying data, the results of the sub-excavation process became evident almost immediately. Survey data revealed vertical downward movements towards the south and west of the building. Maximum deflections recorded during the sub-excavation process are shown in Table 1, and the monitoring plot corresponding to the two axes with major deflections are shown in Fig. 3.

By the end of the sub-excavation process, 87.0mm (3.5 in) settlement for the point F-1 located at the southwest corner of the structure and 27.0mm (1.10in) 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 1-Points A-1 to F-1), and ending with slight upward movements in the north side (Fig. 1-Points A-9 to F-9).

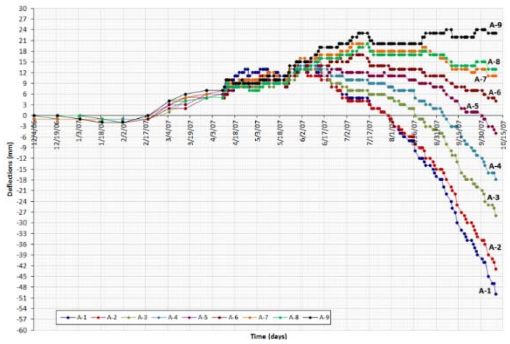
Table 1. Maximum Deflections recorded at each survey point

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

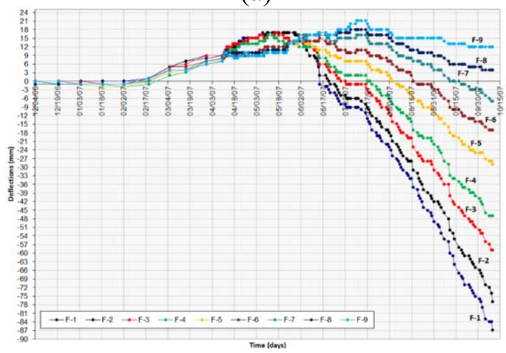
6 CONCLUSIONS

Applying the sub-excavation method to leaning structures requires careful monitoring and rigorous engineering analyses before and during the process. The sub-excavation method was successfully implemented in the project described in this paper. At the completion of the remedial process, the building's deflections were brought within tolerable limits. Any structural damage reported were minimal.

It is important to mention that in order to prevent further tilting and movements in the future, this building was provided with a deep foundation system.



(a)



(b)

Fig 3. Monitoring plots corresponding to (a) Axis A and (b) axis F

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