

JACK-ASSISTED LEVELING PROCESS OF AN ACTUAL 17-STORY BUILDING

*Juan F. Correal¹, Juan C. Reyes², Juan S. Echeverry³, Andres C. Riaño⁴, Armando Palomino⁵, Álvaro Peláez⁶ and Gustavo Gastelbondo⁷

^{1,2,3,4}Dept. of Civil and Environmental Engineering, Universidad de los Andes, Colombia; ⁵P&P Proyectos, Colombia; ^{6,7}Cusezar S.A., Colombia

*Corresponding Author, Received: 9 July 2017, Revised: 24 Aug. 2017, Accepted: 10 Nov. 2017

ABSTRACT: Foundation problems during building construction may cause important structural and nonstructural damage, and compromise the building serviceability. This paper presents a case study of a jack-assisted leveling process implemented on a 17-story reinforced concrete building that suffered important differential settlements during its construction. It is the first time a leveling solution for just a group of piles is implemented, since previous studies considered intervening all foundation piles. The procedure consists on cutting a small slice of the piles in the unsettled side of the building, equivalent to the necessary descent for leveling the settlements in the opposite end, and lowering the unsettled part by a controlled maneuver with hydraulic jacks. Prior to its execution, a numerical model was developed for predicting the effectiveness of the descent maneuver indicating that the leveling process would correct the tilt of the building. The solution was successfully implemented and the building is now in service.

Keywords: Leveling process, Differential settlements, Pile cutting, Hydraulic jack, Foundation piles

1. INTRODUCTION

Geotechnical conditions and foundation construction processes have an important effect on the stability of buildings. Large settlements at the foundation level may induce overstresses in the structure, which can produce damage of structural and nonstructural components, and even collapse. Furthermore, differential settlements lead to unfavourable serviceability conditions such as tilt of the building and discomfort of the occupants [1], [2]. In many cases, settlements may be mitigated or corrected by intervening the foundation [3]-[6]. However, depending on the stage of the building (whether it occurs during construction or during occupancy) or the type of foundation (shallow or deep foundations), these solutions may require complex engineering interventions, and could represent important additional costs.

A 17-story reinforced concrete apartment building in Bogotá, Colombia, founded over 20 m-long concrete piles, suffered important differential settlements during its construction, which caused a tilt of the building. Due to the high stiffness of the 1.5 m-thick transition slab at the ground level, the structure rotated as a rigid body towards the southeastern end, reaching a differential displacement between the east and west side of approximately 31 cm in 30 m of horizontal length of the floor plan. These large settlements were attributed to poor and heterogeneous soil conditions, as the piles in the east end did not reach the competent argillite layer.

In order to stop the increasing settlements of the building, the project owner and consulting design team decided to construct additional micropiles in the east side, linked to the existing pile caps. This solution succeeded in providing stability to the building, and the final differential settlements reached a maximum of 33 cm between the east and west side. However, the project owner considered imperative to correct the excessive tilt of the building for improving serviceability conditions. Therefore, a solution for leveling the building was proposed and implemented. The solution consisted in cutting a small portion of the piles in the unsettled (west side) end of the building, equivalent to the necessary descent for leveling the settlements in the east end, and lowering the west side by using hydraulic jacks. To the authors' best knowledge, it is the first time this leveling solution for just a group of piles was implemented, since previous studies considered intervening all the foundation piles [3]-[6].

The leveling solution was executed successfully, reducing the foundation slope from 1.21% to 0.04% in the east-west direction, while maintaining the slope in the north-south direction (0.37%). This paper presents the details of the jack-assisted leveling procedure, including the predictions prior to its execution, and the final conditions of the building after the leveling process. Field data and computational simulations indicate that this jack-assisted leveling procedure leads to a successful correction of the building's inclination by performing an intervention of a limited group of

piles, and therefore reducing the costs of the leveling solution.

2. PROBLEM DESCRIPTION

2.1 Structure and Foundation

The building analyzed in this study is a 17-story RC structure, located in Bogotá, Colombia, comprised of industrialized cast-in-place concrete walls along its entire height, with thicknesses ranging from 12 cm to 20 cm, and a RC joist floor system of 30 cm in depth, with ribs spaced between 65 and 100 cm on centers. The clear height (floor-to-ceiling) of all stories is 2.40 m. A 1.5 m-thick transition slab (comprised of a 10 cm-thick solid slab over 1.40 m-deep beams) is located at the ground level, and serves as a coupling structure between the 17-story building and the parking basement level (Fig. 1). This transition slab is supported on 40-by-120 cm columns and 15 cm-to 25 cm-thick walls. Specified concrete strength varies between elements, as follows: 35 MPa concrete is used for walls between the transition slab and seventh floor; 28 MPa concrete is used for structural elements within and below the transition slab and from the seventh floor to the roof; all other floor slabs use 21 MPa concrete.

The foundation of the building is comprised of 49 cast-in-place concrete piles with diameters ranging from 0.50 m to 1.20 m with 1.0 m-thick pile caps and connected with 0.40-by-1.0 m grade beams, and 25 cm-thick foundation walls (Fig. 2a). In order to reach the competent argillite layer, depth of the piles varies from 18.0 m to 21.0 m depending on the location on the foundation plan. This system is similar to piled raft foundations used in other countries, for reaching competent subsoil layers [7], [8]. Numbering of the foundation piles, as well as floor plan axes used in this study are included in Fig. 2(a).

2.2 Settlements

Periodical land surveying controls registered increasing differential settlements towards the southeastern end of the building. This was identified as critical at the seventh month, when the construction of the structure was completed, and construction of masonry partitions and façade walls had started. Additional soil surveys confirmed that foundation piles in the east side of the building had not reached the competent supporting layer at a depth of 21.0 m, which caused the settlement of the structure. Fig. 3 presents a scheme of the location of the competent supporting layer (as estimated from soil surveys) and the depth of piles.

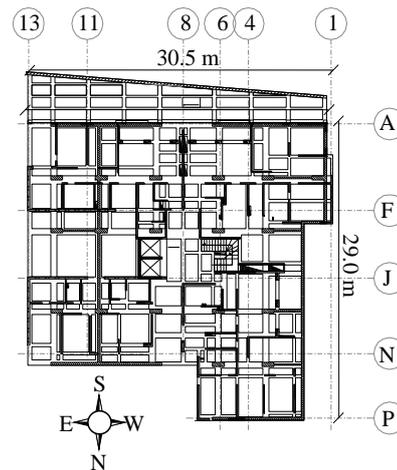


Fig. 1 Building transition slab floor plan

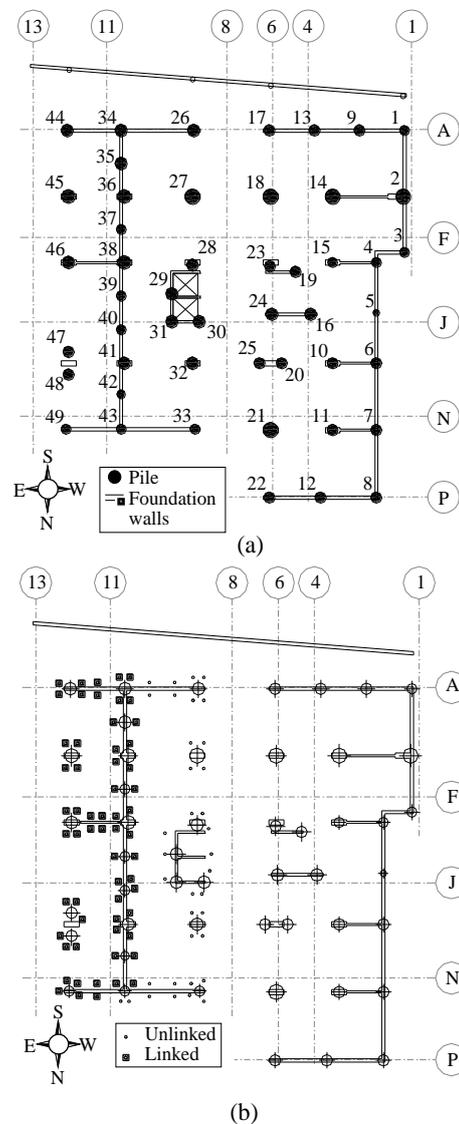


Fig.2 Foundation floor plan: (a) location of piles and numbering; (b) location of micropiles

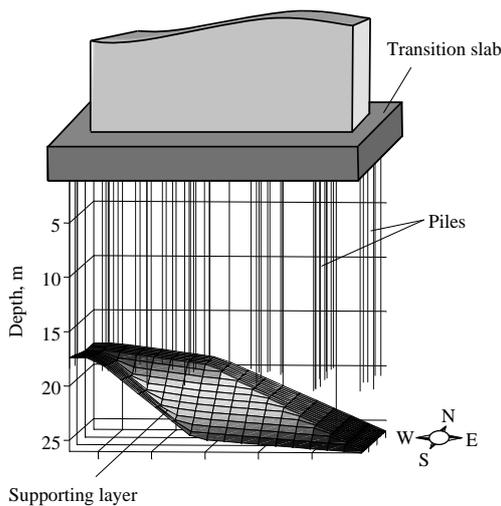


Fig.3 Scheme of supporting soil layer and pile depth

In order to prevent further settlements, the consulting design team recommended the construction of 96 micropiles with 20 cm in diameter on the east side of the foundation (between axes 8 and 13 in Fig. 2(b)), which should penetrate in the argillite layer. However, only 60 of the 96 micropiles were linked to the existing foundation because it was observed that these were enough to stop the settlement. Fig. 2(b) presents a schematic plan of the location of micropiles highlighting those that were linked to the foundation by casting a new cap with its steel reinforcement anchored to the original pile cap using epoxy anchors; each original pile was supported by three or four micropiles, depending on its location.

Settlements (u) registered during the first eighteen months of construction are shown in Fig. 4. Accelerated increments occurred during the first seven months, until the micropiles were constructed in the eighth month. After this intervention, the settlement rate decreased significantly. Final differential settlements were 32.8 cm and 8.73 cm in the east–west and north–south directions, respectively; these settlements represent floor plan slopes of 1.21% and 0.37%.

In addition to topographic land surveying, a hydrostatic level comparison system was installed during the construction of micropiles. Both systems confirmed that the tilt of the building (after the increase in settlements were controlled) was not appropriate according to serviceability provisions of the Colombian Building Code NSR–10 [9], and therefore an intervention had to be conducted in order to correct this issue.

3. LEVELING PROCESS

The leveling procedure for correcting the tilt of the structure was defined after the analysis of different alternatives conducted for similar cases

available in the literature [3]-[6]. Initially, a solution consisting in injecting pressurized water through drilled holes around the foundation piles on the west side was considered. However, this solution was discarded since it involved an additional risk of softening the soil layer below the piles of the east side and, therefore, compromised the stability of the entire structure. A second alternative consisting in drilling six holes with 0.20 m in diameter around each pile on the west side, to a depth of 0.50 m below the bottom of the pile. This drilling program was executed for some piles, but had no effect on the bearing capacity of the argillite layer below the piles, and therefore was discarded.

The third and definite solution consisted in reducing the length of the foundation piles on the west side by cutting a small portion below the concrete pile caps. This portion would be equivalent to the desired descent length of the unsettled side to achieve a maximum plan slope of 0.40% in the east–west direction as permitted by NSR–10 [9]. The fifteen piles listed in Table 1 (between axes 1 to 4 and A through P of Fig. 2(b)) were selected for this procedure; Table 1 presents the proposed total descent u for each pile. Although pile No. 5 was cut, it is excluded from the group of piles to be leveled since it would not be reconstructed after the process. The implementation of this leveling procedure was possible due to the presence of the 1.5 m–thick transition slab for allowing the rotation of the entire structure as a rigid body as the movement of the piles in the west end was conducted.

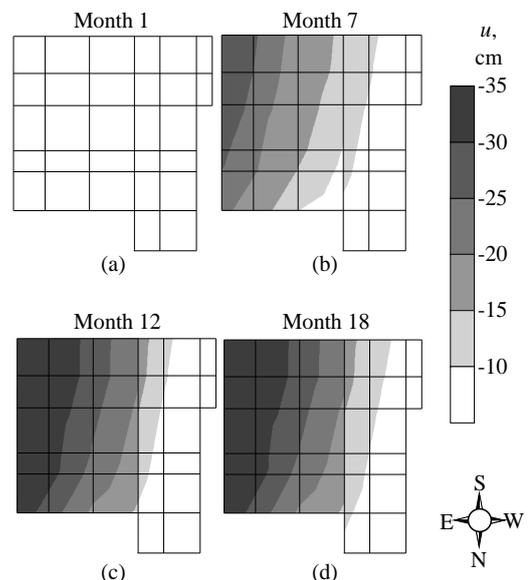


Fig. 4 Settlements registered at foundation plan during construction (cm)

Table 1 Descent, stiffnesses and loads for cut piles

Item	Pile No.															
	1	2	3	4	6	7	8	9	10	11	12	13	14	15	22	
Proposed descent (cm)	34.4	33.4	32.7	32.0	30.8	29.4	28.1	29.8	26.5	26.1	24.5	25.2	26.3	27.0	21.2	
Pile stiffness, K (MN/m)	107	230	72	115	155	140	100	101	173	194	170	104	230	126	141	
Release load (kN)	1103	3080	221	2090	1097	294	662	552	2629	920	755	2600	5062	922	2723	
Achieved descent (cm)	33.8	32.9	33.0	29.9	30.2	30.1	31.5	29.8	24.4	26.6	25.3	23.9	25.1	24.4	19.7	
Achieved/proposed	0.98	0.99	1.01	0.93	0.98	1.02	1.12	1.00	0.92	1.02	1.03	0.95	0.95	0.90	0.93	

4. COMPUTATIONAL SIMULATIONS PRIOR TO THE LEVELING PROCESS

In order to validate the feasibility and effectiveness of the leveling process prior to its execution, the Materials and Civil Infrastructure Research Center (CIMOC) from Universidad de los Andes, Bogotá, Colombia, conducted a numerical study of the solution. A detailed computational model of the building was developed and calibrated to represent the measured settlements during the first twelve months of construction. This model was then used to predict the final condition of the building after implementing the leveling process.

4.1 Computational Model

Analyzed by the SAP2000® computer program [10], the building was modeled as follows. (1) Frame elements were used to model ribs, beams and columns. (2) Shell elements were used to represent walls, slabs and pile caps in the structure. (3) Foundation piles and micropiles were modeled as nonlinear link elements, in order to consider the static soil–structure interaction effects. (4) The model had a total of 12016 nodes, 13894 frame elements, 9804 shell elements, and 109 links.

Vertical loads over the structure include the selfweight of all structural elements and the effective weight of masonry walls built until the seventh month of construction, which was estimated as 54% of the total weight of partition and façade walls (first ten stories). This additional weight was included as a surface load over floor shell elements. Vertical load over the building model was compared with the total vertical load obtained from the structural design model excluding the live load and remaining masonry walls to be constructed. Support reactions were 8% smaller than the design vertical loads of the piles

(106,920 kN); this was judged appropriate considering the overestimation of these loads during the design process.

4.2 Calibration Process

The calibration of the building model consisted in determining the appropriate stiffness of the foundation piles to represent the settlements measured before the intervention for the leveling process. This calibration considered the settlements reached at the seventh month of construction (before the construction of the micropiles), and settlements at the twelfth month (after the micropiles were constructed) when the building was stabilized. The calibration process was implemented by the following steps:

1. Estimate support reactions R at each pile considering a building model with fixed supports in all piles subjected to settlements measured at the seventh month.
2. Calculate vertical displacements of the piles from a building model that considers piles and micropiles as springs, and includes staged construction. Spring stiffness K for each pile is calculated as $f \times R/u$, where u is the measured settlement at the seventh month and f is a redistribution constant initially assumed as 1.0. Micropiles stiffness is estimated from field tests. Note that because staged construction is included, micropiles will appear in the model at the eighth month.
3. Compute the error ε_u as the difference between the estimated vertical displacements from step 2 and the measurements at the twelfth month.
4. Adjust the values of the redistribution factors f and repeat steps 2 and 3 until ε_u is less than a tolerance value.

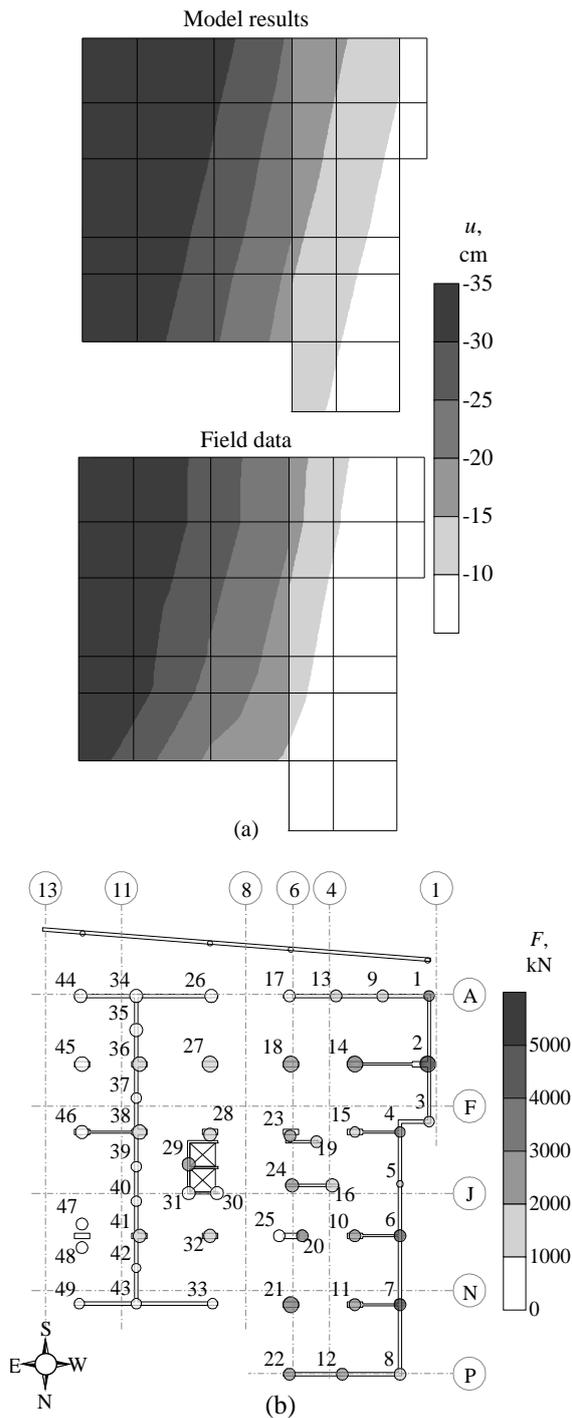


Fig. 5 Results of calibrated model: (a) settlement comparison with field data (cm); (b) forces over piles (kN)

The resulting estimated stiffnesses K for each pile after this iterative process are presented in Table 1. This distribution of different stiffnesses in the model represents the heterogeneous supporting conditions due to the depth of piles with respect to the competent layer. A comparison of model displacements versus measured settlements for each

pile (u) at the twelfth month of construction is presented in Fig. 5(a), showing good agreement between model results and the available field data. Forces over each pile (F) were also estimated from the calibrated model, and results are shown in Fig. 5(b). This analysis showed that some piles in the west end were significantly overloaded before executing the leveling process, compared to the forces estimated in the original design process (fixed-based model).

4.3 Predictions

The calibrated model was used to evaluate the efficacy of the leveling process. Links for the piles in the west end were replaced by gap elements, with an opening equal to the proposed descent value, and elastic stiffness equal to the initial stiffness K of the link. Descents for each pile were estimated from the required distance to reach 33 cm of descent for pile No. 8 (northwest corner), assuming the foundation plan as a perfect plane.

Results of this predictive model in terms of final settlements (u) and forces (F) over each pile are presented in Fig. 6. From these simulations, the effectiveness of the leveling solution was confirmed, since the tilt of the building would be corrected without major damage. However, a major concern arose with respect to forces on some of the piles towards the middle of the building. For this rigid-body rotation of the structure, piles around axis No. 6 would be significantly loaded, since these would act as a pivot to the building's rotation. Additional monitoring measurements were recommended for these piles.

5. EXECUTION OF THE LEVELING PROCESS AND FINAL CONDITION OF THE STRUCTURE

Following the computational simulations, the construction and execution of the jack-assisted maneuver was conducted. A detailed description of the leveling process is presented below.

The maneuver goal was to conduct a controlled descent with hydraulic jacks located between two RC cylindrical caps (inner diameter of 1.20 m, outside diameter of 2.0 m and depth between 0.50 m and 0.70 m). The process started with the excavation of the area below the foundation level to leave approximately 2.5 m clear in depth for the intervention of the piles. Then, the cylindrical caps were built. These caps were connected to each pile above and below the sliced portion, and additional mechanical jacks were installed to support the pile when the hydraulic system was released (Fig. 7). Steel plates were located in the faces of the cylindrical caps in order to provide a leveled surface for the support of the jacks. High-strength 32 mm

Dywidag steel bars were installed between the cylindrical caps to provide tensile capacity to the pile during the intervention; these would also serve as reinforcement after the descending maneuver was completed. During the cutting procedure, the hydraulic jacks registered the axial load over each pile in terms of the hydraulic pressure necessary to bear the tributary weight of the building. These release loads are indicated for each pile in Table 1.

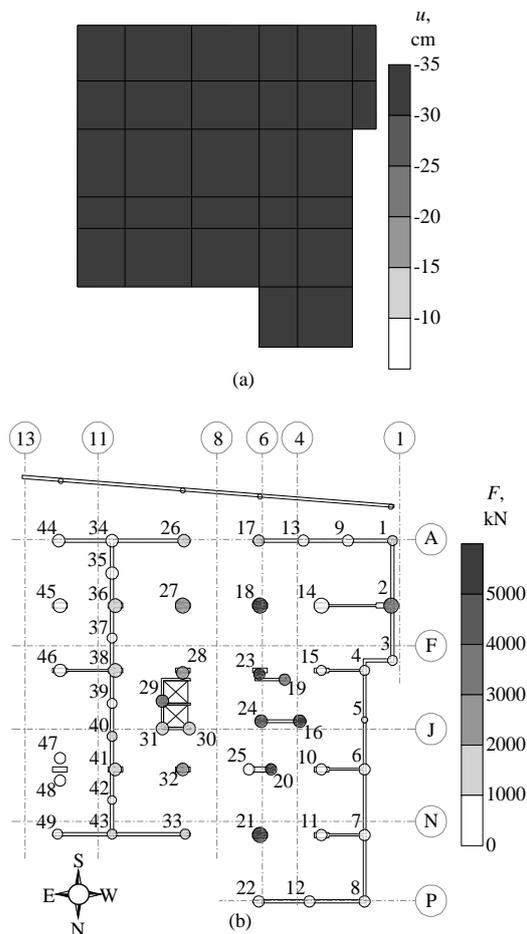


Fig. 6 Results of predictive model: (a) settlement after leveling (cm); (b) forces over piles after leveling (kN)

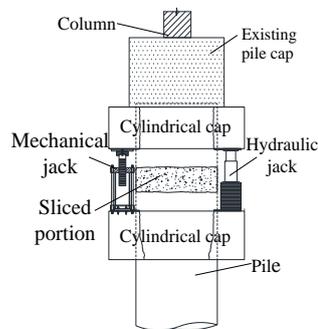


Fig. 7 Location of hydraulic and mechanical jacks between cylindrical caps

The descent procedure was conducted gradually limiting maximum displacements per pile to 2 cm per day, and performing the maneuver as follows. First, pressure was applied to the hydraulic jacks until the mechanical jacks were entirely released from the load of the structure. This load was registered as the current load of each pile. The mechanical jacks were then adjusted at a fixed distance according to the desired descent for the day, measured from the surface of the top cylindrical cap to the face of the jack. Once all distances for the first group of piles were defined, the hydraulic jacks were gradually depressurized, until the cylindrical cap was entirely supported over the mechanical jacks, verifying that the registered pressure in the hydraulic unit dropped to zero. During the entire maneuver, relative horizontal and vertical displacement between cylindrical caps, and absolute displacement (with respect to a control topographic level) were registered.

The leveling process started at the eighteenth month of construction and took 27 workdays for its completion. Weekends and holidays were useful for giving to the foundation some time to settle down. The total descent achieved for each of the fifteen piles in the west end after the leveling process is presented in the third row of Table 1.

Once the tilt of the structure was corrected, the reconstruction of the foundation piles started. This reconstruction consisted in casting the entire volume between the two cylindrical caps, and connecting the top of the pile with the remaining buried length. Mechanical jacks were removed, and replaced by hollow steel tubes with variable length (according to the clear height between the caps) welded to the steel plates in the caps' surfaces. These steel tubes served as reinforcement, along with the Dywidag bars, after the reconstruction (Fig. 8(a)). Using an acrylic sheet as formwork, the sliced portion of the original pile was casted with high strength cement mortar. The acrylic sheet allowed the visual inspection of the filling process. Hydraulic jacks were removed gradually until the pressure dropped to zero; at this moment, the continuity of the piles was attained, and the structure was directly supported over the original foundation. Additional reinforcement was placed around the original pile and the cylindrical caps (Fig. 8(b)). Finally, the volume between the two cylindrical caps was casted, completing the reconstruction of the piles. The excavated area below the foundation level was filled with soil, and compacted by layers (Fig. 8(c)). After the leveling process in both plan directions was completed, the tilt of the building was successfully corrected under the acceptable levels established by Colombian Building Code NSR-10 [9]; the final slope of the floor plan was 0.04% and 0.36% in the east-west and north-south directions, respectively.

A detailed inspection record of cracks in structural walls was conducted after the leveling process. Cracks were mainly observed in foundation walls, and first, second and top (seventeenth) story walls (Fig. 9). However, 95% of the observed cracks were below 0.6 mm, and are considered minor cracks, which are easily repairable. Most of these were observed in window openings, or at the intersection of perpendicular walls, due to expected stress concentration in these particular locations.



Fig. 8 Reconstruction of piles after the leveling process: (a) Dywidag bars and steel tubes between caps; (b) reinforcement around pile and caps; (c) final condition and soil infill

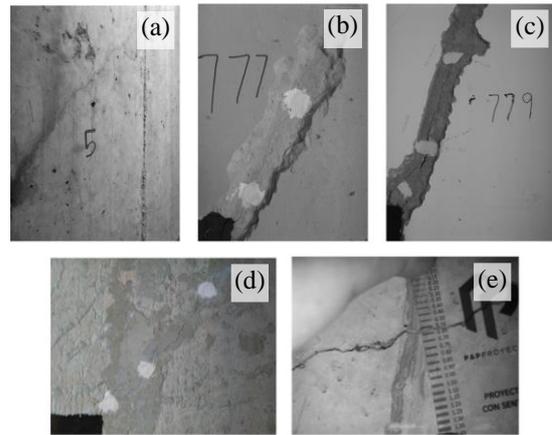


Fig. 9 Observed cracks during inspection after leveling process: (a) top story – 0.60 mm; (b) first story – 0.40 mm; (c) first story – 0.15 mm; (d) second story – 0.25 mm; (e) crack width measurement

6. CONCLUSIONS

This paper presents the leveling process of a 17-story RC building in Bogotá, Colombia, to correct an important tilt of the structure during its construction, due to settlements over 30 cm towards one end of the building. This leveling process consisted in intervening a group of foundation piles towards the unsettled end of the building, by cutting a slice equal to the necessary distance in order to level the floor plan, and conducting a jack-assisted descent of this side of the building. A computational model was developed for evaluating the effectiveness of the leveling solution prior to its execution, rendering adequate results when compared to the final condition of the building. The jack-assisted leveling procedure leads to successful correction of the building's tilt (from floor plan slopes of 1.21% and 0.37% to plan slopes of 0.04% and 0.36% in the east-west and north-south directions, respectively) by performing an intervention to a limited group of piles, and therefore reducing the costs of the leveling solution. From the experience of the executed leveling maneuver, and the numerical model conducted, the following lessons may be drawn:

1. The leveling process presented herein may be considered as a feasible solution for differential settlements that generate a tilt of the building as a rigid body, since settlements may be corrected with a lower cost than a more invasive intervention, or even the demolition of the entire building.
2. The implementation of this leveling procedure was possible due to the presence of the 1.5 m-thick transition slab at ground level, which allowed the rotation of the entire structure as a rigid body as the movement of the group of piles

was conducted.

3. The computational model conducted in this study predicted, with a reasonable proximity, the effectiveness of the leveling solution. However, the results of the numerical model are highly dependent on the available information and assumptions about the soil conditions.
4. To the credit of the owner of the project and the consulting team involved in the leveling process of the structure, the building continued its remaining construction process, and is now in service.

7. ACKNOWLEDGEMENTS

The authors gratefully acknowledge the unconditional support of the project owner CUSEZAR, and the entire consulting team involved in this achievement. Special thanks are extended to Mr. Armando Palomino, structural engineer of the building and co-author of this paper, who proposed the successful leveling solution.

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