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# Desiccation control under a historical building founded over clayey soils: a case study

## Étude de cas : contrôle de la dessiccation sous un bâtiment historique fondé sur des sols argileux

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ABSTRACT: A case study involving desiccation control for the stabilization of a structurally affected, 80-year-old historical building in Bogota is presented and discussed. The building houses the school of arts of the Universidad Nacional de Colombia. Due to its historical and architectural components, it was declared a heritage asset for the country. The two-storey structure is founded with square footings over an organic clay deposit. In 2016 the building suffered severe and sudden crackings after an extremely dry period caused by the 2015-2016 ENSO. Forensic engineering studies found that the damages were caused by the volumetric contraction of the foundation soil due to changes in the water content. The presence of trees near the building aggravated the effects of the desiccation process. Different engineering solutions to control further changes in the water content were considered. The transient flow problem was modelled and used to assess solutions by considering risks to neighbouring buildings and overall implementation costs. The case study is found to be a relevant example of the engineering activities needed to face the upcoming challenges of climate change in urban environments.

RÉSUMÉ : Une étude de cas impliquant le contrôle de dessiccation est présentée et discutée pour la stabilisation d'un bâtiment historique de 80 ans, structurellement affecté, à Bogota. Le bâtiment, qui abrite l'école des arts de l'Universidad Nacional de Colombia, a été déclaré patrimoine du pays en raison de ses composantes historiques et architecturales. L'immeble de deux étages repose sur des semelles carrées sur argile organique. En 2016, après une période extrêmement sèche produit par le 2015-2016 ENSO, le bâtiment a subi des fissures sévères et soudaines. Des études géotechniques forensique ont été menées, et ont constaté que les dommages étaient causés par la contraction volumétrique du sol de fondation en raison d'une réduction de la teneur en eau. La présence d'arbres près du bâtiment a contribué à accroître les effets du processus de dessiccation. Des solutions d'ingénierie différente ont été envisagées pour contrôler des nouvelles modifications de la teneur en eau du sol. Le problème des flux transitoires a été modélisé et utilisé pour évaluer les solutions en tenant compte des risques pour les bâtiments voisins et des coûts généraux d'implémentation. L'étude de cas est un exemple pertinent des activités d'ingénierie nécessaires pour faire face aux défis à venir du changement climatique en milieu urbain.

KEYWORDS: Soil desiccation, forensic geotechnical engineering, transient flow, historical building, climate change.

## 1 INTRODUCTION.

Climate change and the continuous growth of populations around urban areas pose an important challenge for the management of historical buildings and heritage assets around the world. Historical buildings usually require periodical structural reinforcement and intervention to mend the damages they accumulate throughout their use and to improve their condition to reasonably comply with modern construction codes. This upkeeping must be done the rapid climate change and its impact on new and old infrastructure.

The "Bellas Artes" building is an 80-year-old historical building located on the Universidad Nacional de Colombia campus. It is the houses of the School of Arts. The building suffered significant structural damages during the 2015-2016 ENSO (El Niño–Southern Oscillation) period, leading to its closure in 2016. Given the structure's historical importance, engineering works were carried out to design its architectonic recovery and structural reinforcement. To this end, a detailed geotechnical characterization was conducted, and different possible reinforcement solutions were evaluated.

Special consideration was given to evaluating the desiccation phenomenon caused by the 2015-2016 ENSO and the risks posed by the increasing threat of climate change in the area. Different geotechnical solutions and analysis were considered involving budget costs, construction complexity, and technical effectiveness. The impermeabilization of the soil surface around the building was found to be the most efficient solution to avoid further damage due to seasonal volumetric changes in the soils under the foundation.

## 2 PROJECT DESCRIPTION

### 2.1 *Climate and geology*

Bogotá is located over a fluvio-lacustrine deposit on a high plateau at 2550 m above sea level formed by tectonic uplift. The soil deposit in the area can reach depths of more than 500 m, and its upper 80 m were consolidated during the last 250 000 years. The soil profile is composed mainly of fine-grained soils classified as high plasticity clays and silts (Caicedo et al., 2018). The slow sedimentation process of the deposits allowed the development of high proportions of organic matter in the materials. This is associated with facies originated under conditions of standing water and submerged vegetation (Torres et al. 2005). The water table in Bogotá is usually found near the surface during rainy seasons; however, the apparent overconsolidation and oxidizing environment in the first 7 m to 10 m suggest historical drops of the water level to those depths.

Bogota´s mean temperature is 14 °C. It has total annual evapotranspiration between 800 mm and 1000 mm, and a yearly mean precipitation of 840 mm. Annually, rain intensity in the city follows a bimodal distribution, with higher amounts of rain from March to May and September to November. Dry seasons span from June to August and from December to January (IDEAM nd). However, the typical distribution of temperatures and precipitations is affected by different climate phenomenons with more extended return periods, such as the ENSO.

The ENSO has two kinds of anomalies known as "El Niño" and "La Niña". During "El Niño", mean temperatures increase, and the mean precipitations are reduced. On the other hand, during "La Niña", the behaviour is opposite with reduced mean temperatures and higher rainfall. The city's Institute of Risk Management and Climate Change (IDIGER) classifies the intensity of the "El Niño" anomaly as weak, moderate, or strong according to variations in the surface temperature of the eastern Pacific Ocean. Since 1979, three strong "El Niño" anomalies were recorded: the first one from May 1982 to August 1983, the second from May 1997 to May 1998 and the third from October 2015 to July 2016 (IDIGER 2019). The 2015 strong ENSO was the shortest one but followed a two-month period classified as moderate.

The 2015-2016 ENSO is regarded as one of the more intense climate phenomena to have occurred in Colombia in the last century. According to the CTN (CTN ERFEN 2016) this ENSO caused several damages to infrastructure and cost more than USD 420 Million in prevention and emergency attention. In Bogota, hydrometeorological stations recorded temperatures above 20°C in 2016 following annual precipitation around 600 mm in 2015. From November 2015 to February 2016, the monthly rainfall fell to less than 20 % of the decennial mean. During this period, evapotranspiration potential became more significant than the recorded rainfall. Those severe climate conditions caused a drop in the water table level in the soil deposit of Bogotá. This drop was accentuated in areas covered by grass and vegetation.

### 2.2 *Structural characteristics*

The main campus of the Universidad Nacional de Colombia is located around the geographical centre of Bogotá city, where the lacustrine deposit has about 180 m depth (Reina-Leal et al., 2018). The campus is a large area covered by grasses and vegetation and holds a representative collection of Colombian architecture in the last century. Fifteen university buildings are considered heritage assets, and the whole campus has a historical value. Most structures have up to three storeys and are founded over the overconsolidated clay using shallow foundations at depths between 1.0 and 2.0 m.

The "Bellas Artes" building was constructed between 1936 and 1940, during the first construction stage of the university campus. The structure was declared to be a heritage asset in 1996 and is considered the cradle of modern Colombian architecture.

The original design of the building only included a two-storey linear structure founded on rectangular footings 1.4 m to 2.0 m wide located 1.5 m deep (① in Figure 1). The footings were designed to be independent, with no beams connecting the foundation at ground level. However, two lateral structures founded with strip footings 1.0 m deep were added during construction (② in Figure 1). The three structures are supported on rigid concrete frames, and the three modules are structurally independent with only architectural connections. Before 2016, there had been insufficient maintenance of the structural components and hydraulic systems of the building.

The building faces the NE direction and, since the 1950s, it has had trees and vegetation to the W and concrete walkways to the NE. Plants around the building consist of eucalyptus trees planted in the second half of the XX century and pastures. By 2015, the trees had grown to be more than 15 m tall and were distanced close to 10 m from the foundation. Green areas around the building did not have an irrigation system.

### 2.3 *Soil properties*

Geophysical surveying, seven trial pits, and three boreholes were conducted under the footings and in the surrounding areas of the building.

A seismic reflection survey, together with CCAMS (Cross-Correlation Analysis of Multi-channel Surface waves) experiments, were conducted to obtain 1D and 2D Vp (P-wave velocity) and Vs (S-wave velocity) profiles around the building. GPR (Ground-Penetrating Radar) testing and the trial pits allowed the identification of the dimensions of the foundation elements, as well as the properties of the soils located directly below the footings. The boreholes reached a maximum depth of 30 m and obtained undisturbed soil samples for laboratory testing. An open inspection tube piezometer was installed in one of the boreholes, and it was used to monitor the water table. Water levels were found at a maximum depth of 3.0 m during normal dry climate conditions and near the surface during rainy seasons.

The soil profile was divided into five materials: a stiff grey clay with oxidation veins from 0.0 m to 6.5 m (M1), a firm to soft grey clay with oxidation veins from 6.5 m to 8.5 m (M2), a soft organic clay from 8.5 m to 22.5 m (M3), a peat layer from 22.5 m to 24.8 m (M4), and a firm brown clay from 24.8 m to the explored depth (M5). Physical soil properties such as liquid limit (LL), plasticity index (PI), gravimetric water content (w) and unit weight (γ) are summarized in Table 1. Mechanical properties such as undrained shear strength (Su), void ratio ($e_o$), virgin compression index (Cc) and hydraulic conductivity ($k$) are summarized in Table 2. All tests were performed according to ASTM standards.

Table 1. Physical properties for the materials of the soil profile.

| Material | *LL* *(%)* | *PI* *(%)* | *w* *(%)* | *γ* *(kN/m³)* |
|---|---|---|---|---|
| M1 – CH | 63 | 38 | 30 | 17.6 |
| M2 – CH | 76 | 48 | 80 | 15.7 |
| M3 – CH | 131 | 93 | 115 | 13.1 |
| M4 – OH | 157 | 138 | 250 | 11.0 |
| M5 – CH | 118 | 84 | 90 | 15.4 |

Table 2. Mechanical properties for the materials of the soil profile.

| Material | *Su* *(kPa)* | $e_0$ | *Cc* | *k* *(m/s)* |
|---|---|---|---|---|
| M1 – CH | 100 | 0.94 | 0.20 | $5.55 \times 10^{-10}$ |
| M2 – CH | 35 | 2.18 | 0.65 | $1.47 \times 10^{-10}$ |
| M3 – CH | 17 | 3.12 | 0.70 | $1.59 \times 10^{-10}$ |
| M4 – OH | 17 | 6.79 | 3.23 | $4.50 \times 10^{-11}$ |
| M5 – CH | 50 | 2.37 | 1.40 | $5.80 \times 10^{-11}$ |

In the first 22.5 m, the consistency of the soil does not improve with depth. There is a significant reduction in the undrained shear strength of the material in the first 10 m. This is caused by the continuous decrease in the overconsolidation ratio of the upper meters of the soil profile. There is also a significant increase in the compressibility of the materials between 10 m and 25 m. This reduction of resistance and the increase of compressibility with depth, have direct implications in the reinforcement of the foundation and dessication analysis as will be shown later.

Soil Water Retention Curves (SWRC) were obtained from filter paper testing on two soil samples recovered near the footings. The obtained SWRC were fitted to the equation proposed by Fredlund and Xing (1994), and their fitting parameters are presented in Table 3. Both curves are relatively similar and lead to the assumption of a homogeneous SWRC across M1. The SWRC shows a very high air entry point of about

4.5 MPa. Under the 3.0 m variation of the water table measured with the piezometer, this value suggests that the soil remained fully saturated during dry periods developing significant negative pore-water pressures. Thus, the effective stress principle can be applied under negative pressure conditions and can be used to evaluate the resistance and compressibility of the soils below the foundation.

Table 3. Fitting parameters of the SWRC according to Fredlund and Xing (1994) proposal. Units in SI.

| Parameter | *Pit 2* | *Pit 3* |
|---|---|---|
| Saturated gravimetric water content | 37.5 | 36.3 |
| Suction in the residual water content | 26796 | 19724 |
| Curve fitting parameter a | 5051 | 4362 |
| Curve fitting parameter n | 1.21 | 1.24 |
| Curve fitting parameter m | 2.24 | 1.78 |

## 3 DAMAGE HISTORY AND FOUNDATION ASSESSMENT

After the start of the 2015-2016 ENSO period, the building developed fissures in the masonry walls and around the ground floor windows. Damages became more severe towards the beginning of 2016 when the building started to move towards the West. Fissures widened, and window frames began to bulge inwards and became visibly affected. Damages reached a critical point when a sudden and wide crack appeared in the architectural joint between the central and northern structures. The crack extended across both storeys and posed a severe risk of wall collapse to the building inhabitants (see Figure 1a).

With the appearance of the crack, the building moved considerably, and its inclination towards the north became evident (Figure 1b). Window frames on the ground floor were crushed (Figure 1c), and the activities inside the building had to be shut down until further notice. The closure of the building brought severe inconvenience to the university's art school, and the damages to the historical building caught the attention of the national press.

A plan to reinforce and recover the building was put into motion, and its activities began in early 2016. The building was evaluated from structural and geotechnical perspectives, while topographical surveys were carried out from February 2016 to August 2017. Building movements were tracked with respect to baseline levels measured in the first month. Inclinations measured showed that the building was moving as three individual structures, each of which followed different directions. The central and south ones had visible leanings towards the W, and the northernmost one moved towards the east. In all cases, movements occurred towards the neighbouring eucalyptus trees located in these directions. Successive surveys showed that movements continued, and the building responded to changes in its surroundings.

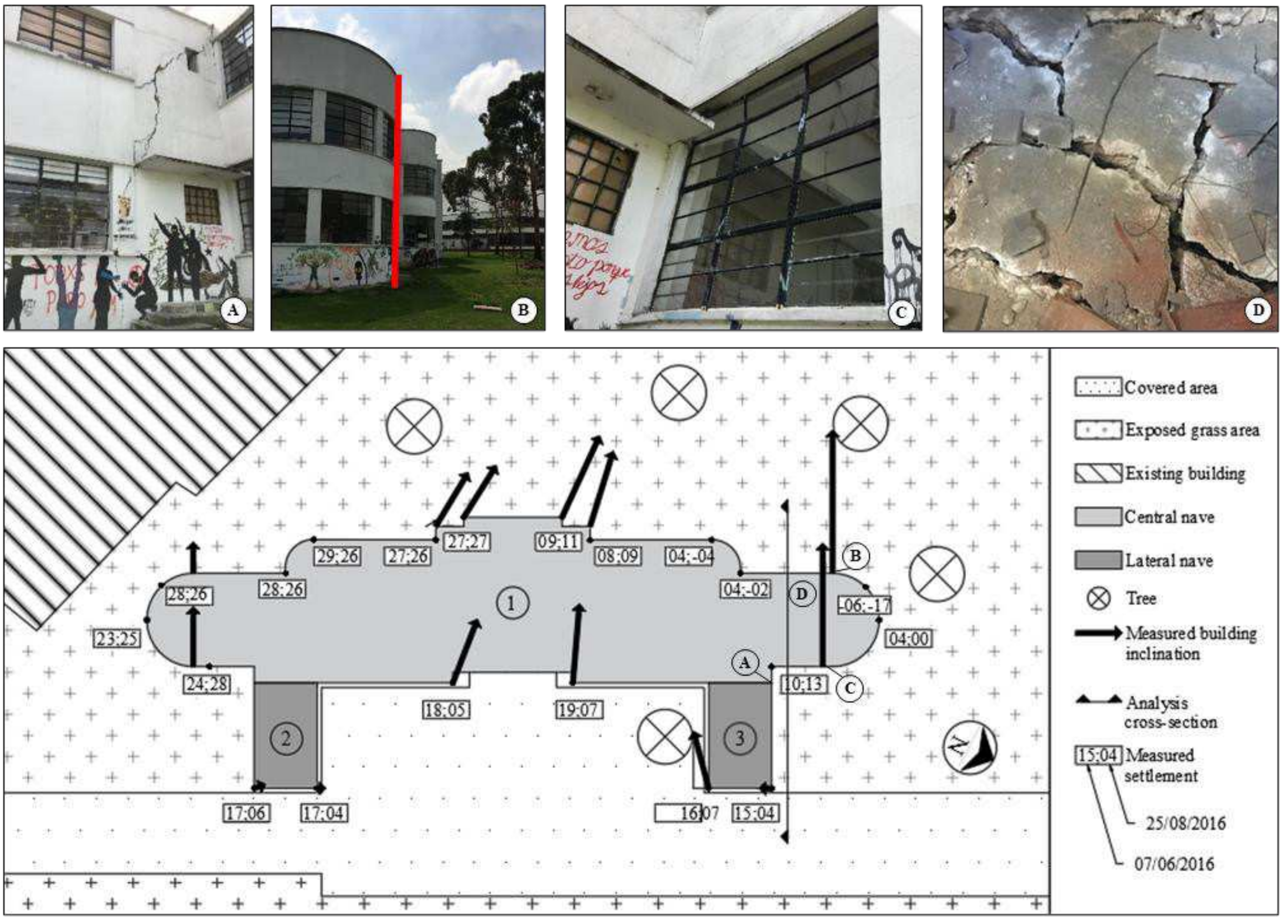

Figure 1. Schematic of the "Bellas Artes" building with topographic measurements, structural damages, and surrounding areas.

Geotechnical exploration of the structure used trial pits and GPR readings to review the state of the footings. Concrete elements under the building were found in good condition, and its dimensions were in good agreement with the ones in the available blueprints. The static and seismic load-bearing safety factors of every support were calculated. All footings were found to have safety factors well above 3.0 and 1.5, respectively. On the settlement side, the hydraulic conductivity values of the soil profile implied that the primary consolidation settlement had already concluded. Both findings suggested that the structural loading did not cause the movements of the building. Instead, they seemed to be related to other surrounding factorsThe trees around the building were assessed, and their width and bark showed that they were mature specimens. They had fully developed root systems and were highly avid of water, as is common in eucalyptus trees. Blight (2009) described the effects of eucalyptus trees and showed they could cause significant descents of the water table and affect nearby structures. This effect can be attributed to the increased transpiration that occurs through their leaves.

The trial pits showed that the soil under the floorboards of the building was severely desiccated. Tension cracks in the material were measured and found to be deeper towards the NW side of the building, in the area with higher movements (Figure 1d). Thus, the hypothesis that settlements had been caused by volumetric contraction of the soil under the footings was proposed. In August of 2016, a topographic survey indicated that the building had recovered part of its inclination after the advent of the rainy season and cutting eucalyptus trees. This evidence strengthened the volumetric change hypothesis.

Therefore, the clay volume change of the shallow soil profile caused by a loss in water content gave a coherent explanation to the observed structural damages and movements of the building. The sudden and severe cracking of the exterior walls could be explained as being caused by the desiccation event that followed the 2015-2016 ENSO period. The intensity of the desiccation process was different for each face of the building. The existing structures and pedestrian road protected the soil to the E and S, while the W and N fronts were exposed to high rates of water evaporation. With the low hydraulic conductivity of the material, pore pressures could not homogenize rapidly, and the effect resulted in a significant stress differential within the soil. Given that the clay is highly compressible, this gave rise to differential settlements.

The effects of suction were aggravated by three factors: (i) the presenc of non-native arboreal species close to the building foundation causing a lowering of the water table levels, (ii) the existence of leakage from the hydraulic systems of the building that allowed to maintain a higher water table level around point (C) in Figure 1 and (iii) the lack of irrigation in surrounding areas. Considering those effects, the spatial occurrence of desiccation-induced suctions matched the building movements and provided a logical explanation for the damages.

## 4 DESICCATION CONTROL ANALYSIS

The building reinforcement proceeded with a plan to mitigate further movements by addressing future desiccation events and the identified aggravating factors. The eucalyptus trees around the building were removed, and the hydraulic systems were scheduled for reconstruction during the structural reinforcement.

Foundation reinforcement with micropiles was evaluated as a way of preventing movements caused by changes in water content. However, considering that the building has many columns and the soil is highly compressible and soft between 10 m and 25 m, the reinforcement of the foundation would require piles. This is necessary to achieve significant load-bearing capacities complying with the allowable differential settlements for a historical building. Construction of these elements would require excavations in many points of the building and the demolition of valuable architectural components such as walls and floors that had to be conserved. Thus, structural reinforcement of the foundation using micropiles resulted inefficient to comply with the project's needs.

Instead of dealing with the effects of desiccation by reinforcing the footings, solutions to mitigate its causes (i.e. change in water content) were explored. Two methods were considered: the installation of an impermeable sheet pile wall and the impermeabilization of the soil surface. Both alternatives were evaluated using a transient flow finite element simulation using RocScience Slide®.

An initial water table 0.5 m deep was considered. During the following month, a linear drop to 5.0 m was imposed, and this level was maintained for 12 months. The water level below the border of the building was tracked monthly, and its values were used to make decisions concerning each possible structure. For the sheet pile wall, lengths of 5.0 m, 6.0 m and 7.0 m were evaluated. For the surface impermeabilization, covered distances of 10.0 m, 12.5 m and 15.0 m from the building face were analyzed. Figure 2 and Figure 3 show the pore pressures obtained after one year for a 7.0 m deep sheet pile and covered area of 15.0 m, respectively. Table 4 summarizes the expected descent of the water table under the building for the different structures considered.

The compressibility properties of the soil profile were used to relate suction levels to settlement values. The water table descent had to be contained to less than 0.40 m after twelve months to keep future movements of the building under 2 cm. Solutions complying with these criteria included using a 7.0 m length sheet pile or covering an area distanced 15.0 m around the building. The selection of a final solution came down to the costs and installation requirements of both alternatives. The sheet pile solution offered the advantage of requiring intervention along a smaller area; however, the driving needed for the installation could cause vibrations and potentially affect the building and other surrounding structures. The surface impermeabilization did not require specialized machinery or processes but impacted a large area around the building and required the movement of a considerable volume of soil.

Table 4. Expected drop of the water level under the building for different structures

| Structure | *Expected descent (m)* | |
|---|---|---|
| | *6 months* | *12 months* |
| 5.0 m Sheet Pile | 1.01 | 1.29 |
| 6.0 m Sheet Pile | 0.29 | 0.47 |
| 7.0 m Sheet Pile | 0.09 | 0.21 |
| 10.0 m Covered Area | 0.62 | 0.86 |
| 12.5 m Covered Area | 0.41 | 0.59 |
| 15.0 m Covered Area | 0.24 | 0.40 |

The architecture team in charge of the renovation project proposed the development of areas for students on the NW side of the structure. Such construction meant that the impermeabilization alternative could be easily implemented under the new zones proposed, which amounted to significant economic and technical advantages. These advantages led to the selection of the 15 m impermeabilization as the optimal solution for the building. The administration of the university insisted on the conservation of green areas that are characteristic of the campus, and thus, the protection proposed had to allow for gardening arrangements. Figure 4 shows a scheme of the final solution adopted.

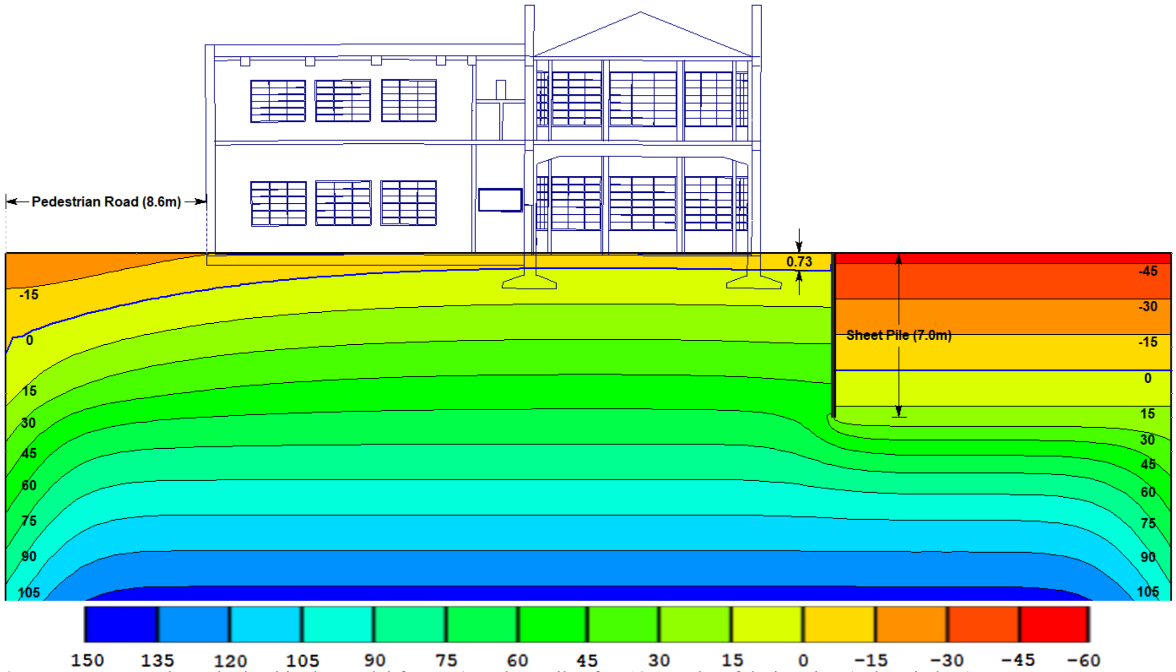


Figure 2. Pore pressure values obtained in the model for a 7.0 m sheet pile after 12 months of desiccation (values in kPa).

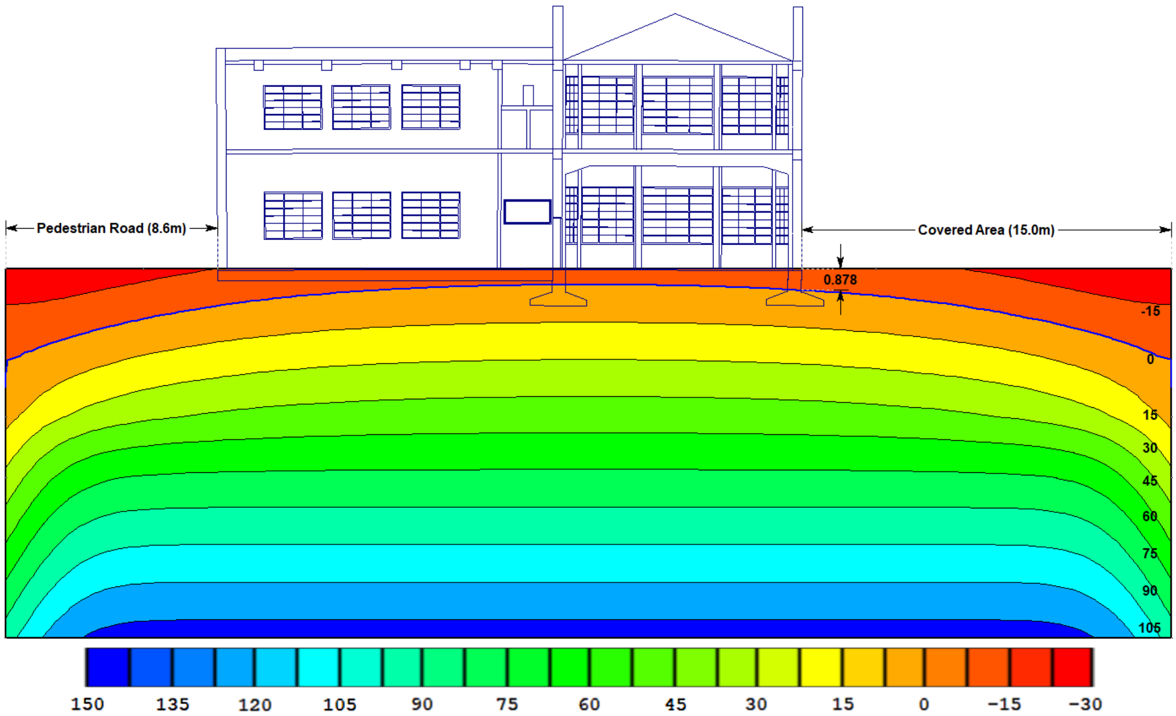


Figure 3. Pore pressure values obtained in the model for a covered area of 15.0 m after 12 months of desiccation (values in kPa).

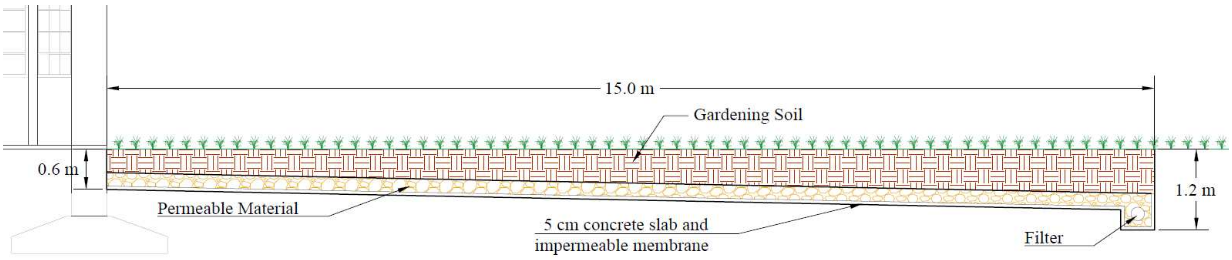


Figure 4. Schematic view of the impermeabilization adopted as the final solution.

Evapotranspiration within the soil will be controlled using a 5 cm concrete slab placed over a 1.5 mm thick geomembrane. The system will be built underground to allow for the placement of low height vegetation. By doing so, water storage within the gardening soil is permitted, preventing rapid evacuation towards the sewerage. The concrete slab was designed with a 2 % inclination to allow for water drainage to go away from the building. The final solution is in line with soft engineering principles where the water is allowed to follow a cycle more similar to the naturally occurring infiltration.

The impermeabilization was accompanied by the construction of concrete beams connecting the footings of the foundation. Connecting beams were designed to be capable of managing moderate differential settlements without adverse effects for the architectural components. This ensured that the building would have adequate geotechnical behaviour in the years to come

## 5 CONCLUSIONS

A case study of the structural reinforcement of the 80-year-old "Bellas Artes" historical building in Colombia was presented and discussed. The building is founded on square footings 1.5 m deep and suffered various structural damages during the severe 2015-2016 ENSO period that led to its closure in 2016. Structural damages occurred suddenly despite that the foundation had adequate factors of safety and the consolidation settlements had already concluded.

Forensic engineering activities found evidence of soil contraction due to the reduction of the water content in the most superficial soil layers. SWRC measured on soil samples taken directly under the foundation showed that the material could develop high negative pore-water pressures without desaturating. Volume change of the clay caused by desiccation, and aggravated by nearby eucalyptus trees, served as a viable explanation for the sudden movements experienced by the building.

Different alternatives for the geotechnical reinforcement of the structure were evaluated. Conventional intervention to the foundation using micropiles was considered. However, the number of columns in the building and the poor resistance of the soil between 10 m to 25 m meant that micropile reinforcement would require many elements founded at considerable depths. Construction activities required to install them could severely impact valuable architectural components. This fact led to the neglecting of the micropiling approach.

Instead of controlling the effects of desiccation by reinforcing the foundation of the building, two alternatives to mitigate its causes (i.e. change in water content) were proposed: a sheet pile wall and an impermeable area covered around the building. Both were analyzed using a transient flow finite element model to predict the water table drop after a one-year-long desiccation period. The models were used to select an adequate sheet pile length or width of the protected area. A 7 m deep sheet pile wall or a 15 m wide covered area were found to be suitable alternatives to limit the future movements of the building to less than 2 cm.

The architecture team of the project considered the construction of new urban areas on the exposed faces of the building. Thus, the 15 m covered area was found to be the optimal alternative to prevent future movements of the building. The final solution was designed to be constructed underground to preserve grassland areas characteristic of the university campus and allow for gardening activities around the building. Connecting beams capable of withstanding moderate differential settlements accompanied the protection of the surrounding soil from desiccation. These measures followed the cut down of eucalyptus trees near the structure and the reparation of hydraulic systems.

The "Bellas Artes" reinforcement project is an excellent example of structural interventions required by the advent of severe climate periods. This kind of engineering projects is expected to become more common as climate change develops and causes extreme rainfall and dry periods in Latin America. The case shows the importance of considering future climate conditions in the foundation design for new and old infrastructure. Historical buildings and cultural assets are especially prone to suffering damages during extreme climate conditions. Thus, procedures for their structural reinforcement and maintenance that consider local climate conditions are required.

The alternative for reinforcement presented can be considered a soft engineering solution adapted to different return periods of extreme climate conditions. Furthermore, infiltration is allowed on the surface, making it a more environmentally friendly solution than a conventional impermeable concrete walkway.

## 6 ACKNOWLEDGEMENTS

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