Recent experiences with ground retaining systems in Buenos Aires, Argentina

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ABSTRACT. This paper presents a summary of the current construction procedures for urban excavations in Buenos Aires, Argentina. The geotechnical conditions are briefly described, and a few case histories are reported. These case histories include large excavations supported with post-tensioned anchors, excavations supported with piles, and diaphragm walls. Finally, the current engineering procedures are discussed and some recommendations for the advancement of the engineering of excavations is proposed.

INTRODUCTION

The city of Buenos Aires is the capital and largest city of Argentina, and its financial and commercial hub. Located on the shore of the River Plate, it is the fourth largest metropolis in America, with fifteen million people, home of about 25% of the GDP of Argentina. It hosts the largest port facility of Argentina, handling some 30 million tons annually. While the population of the city itself remained fairly stable around three million in the last few decades, an ever-growing conurbation area developed around, now covering an area of about 5000 km^2 (Figure 1). Not surprisingly, the city is home of a sustained construction activity which ranges from housing and commercial buildings, industrial facilities and major infrastructure projects.

Figure 1. Satellite image of Buenos Aires and conurbation area. By NASA - http://landsat-pds.s3.amazonaws.com/L8/225/084/LC82250842014353LGN00/index.html, Public Domain, https://commons.wikimedia.org/w/index.php?curid=39148887

Excavations in Buenos Aires are a routine construction activity. Shallow excavations, no deeper than eight meters or so, are performed with little engineering or supervision and generally perform very well, more because the ground is of very good quality than due to well designed and safe construction procedures. Deep excavations, 10 m to 30 m or so, pose additional challenges, because ground deformation in the neighbouring lots becomes more evident, and also because the risk of uplift and bottom failure due to artesian pressure grows with depth and becomes dominant for excavations ~18 m and deeper.

This paper presents a summary of the current construction procedures for urban excavations in Buenos Aires, Argentina. The geotechnical conditions are briefly described, and a few case histories are reported. These case histories include large excavations supported with post-tensioned anchors, excavations supported with piles, and diaphragm walls. Finally, the current engineering procedures are discussed and some recommendations for the advancement of the engineering of excavations is proposed.

GEOTECHNICAL CONDITIONS IN BUENOS AIRES CITY

Soils

Buenos Aires city is located in the Chaco-Pampeano Plains, a quaternary loess unit covering an extension of 1.000.000 km^2 in North-East Argentina. Pampeano soils contain silt and clay particles originated in volcanic activity in the Andes, transported by wind and water and deposited under calm water. Post-deposition unsaturation and precipitation of salts led to a stiff to hard deposit, heavily overconsolidated by desiccation and erratically cemented with calcium carbonate and magnesium oxides. Particular features of the formation are: i) desiccation fissures induce a high secondary permeability; ii) thin layers of non-cohesive loamy sands are found at depth 20m and below; iii) close to the bottom of the formation and right on top of Pliocene clean sands (Puelche sands), a poorly cemented sub-stratum of greenish clays acts as a hydraulic seal. Many publications describe the origin and characterization of the Pampeano formation (e.g. Bolognesi and Moretto 1957, 1961; Fidalgo et al 1975, Núñez 1986, Rinaldi et al 2007, Varde et al 2017).

On the margin of the La Plata River, Pampeano formation was partially eroded and covered by Holocene sandy silts and clays of the Postpampeano formation. Man-made fills have covered these soft soils at the coastline of the River Plate in the city of Buenos Aires. Figure 2 (Núñez 1986) shows a simplified sketch of the stratigraphic profile, Figure 3 shows two typical boreholes in the city center (Laría et al 2015). For further information of the Postpampeano formation, the reader is referred to papers by Leoni (2009), Rinaldi and Claria (2006), and Sfriso (1997).

The Pampeano formation is very favorable for deep excavations due to its high stiffness, high unconfined compressive strength, rapid drainage and good frictional behavior when drained (Núñez 2000). Effective friction angle is low bounded by the high-confinement friction angle $\phi' = 29°$ (Núñez 1986, Núñez and Micucci 1986) and can be as high as $\phi' = 37°$ at low confining pressure (Quaglia and Sfriso 2008). An effective cohesion intercept in the range $15\text{kPa} < c' < 50\text{kPa}$ is accounted for in practical engineering design. Average coefficient of subgrade reaction measured by plate load tests is $K \cong 500\,\mathrm{MN/m^3}$ in the upper six to eight meters and $K \cong 1200\,\mathrm{MN/m^3}$ below (Codevilla and Sfriso 2010), yielding a secant Young's modulus $E = 80|120\text{MPa}$ for the upper layer and $E = 220|280\text{MPa}$ below. These are typical design parameters for conventional excavations in Buenos Aires. For the most updated set of material parameters that can be used in the numerical modelling of excavations in the Pampeano Formation, the reader is referred to Vardé et al (2017).

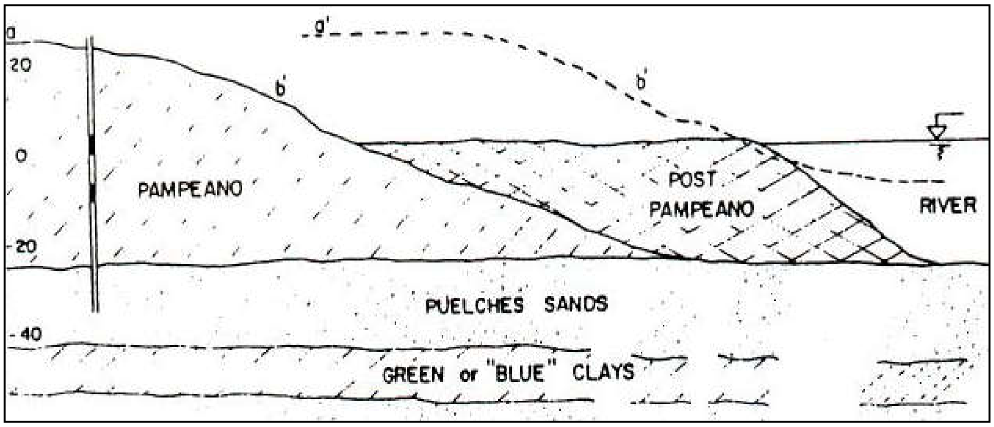

Figure 2. Stratigraphic profile of Buenos Aires City (Núñez 1986).

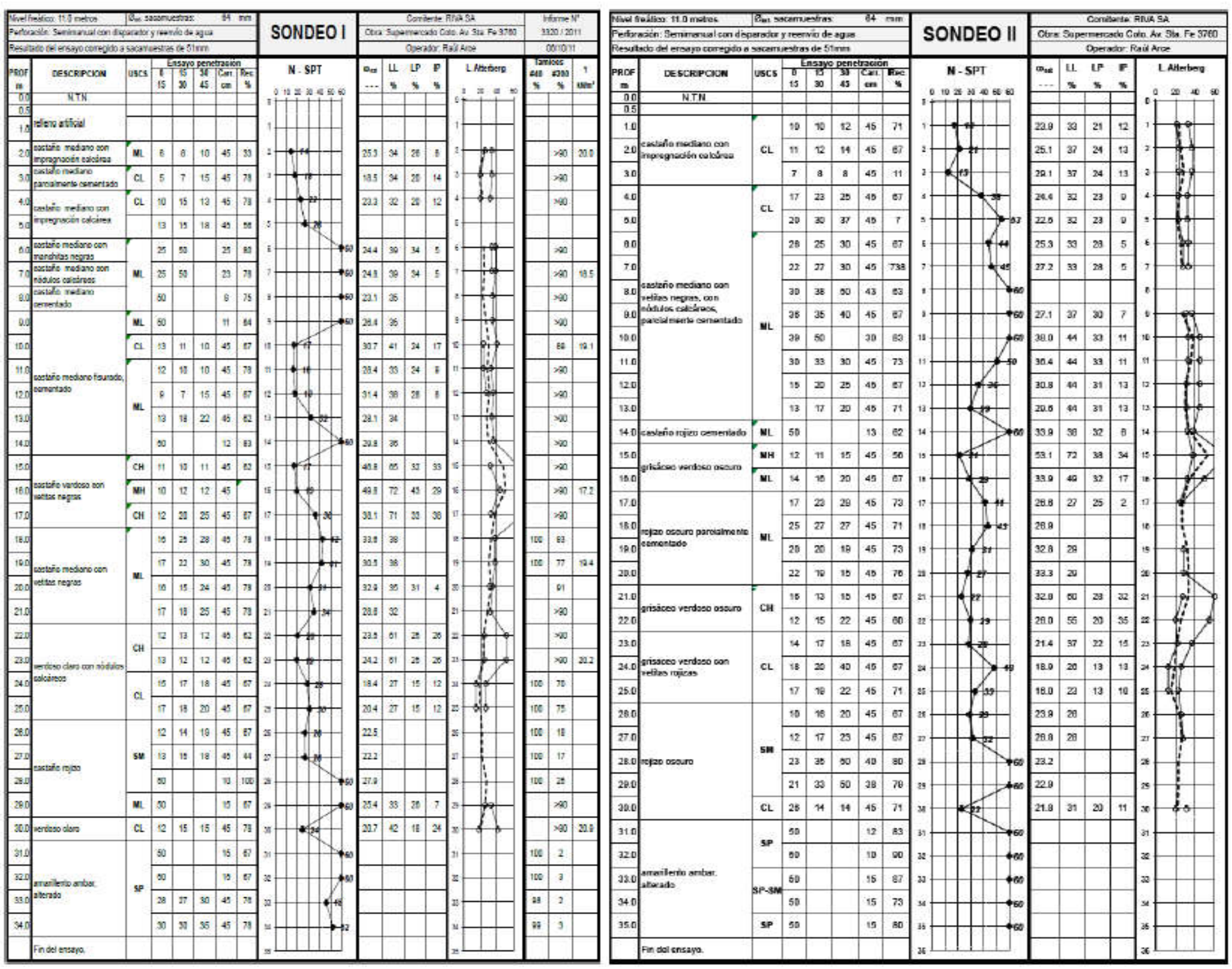

Figure 3. Two typical boreholes in Buenos Aires city center (Laría et al 2015).

Design of excavations in Buenos Aires

The Building Code of Buenos Aires requires that strutted excavations be designed with a minimum earth pressure which depends on ground conditions and excavation depth, as shown in Figure 4 (Moretto 1972).

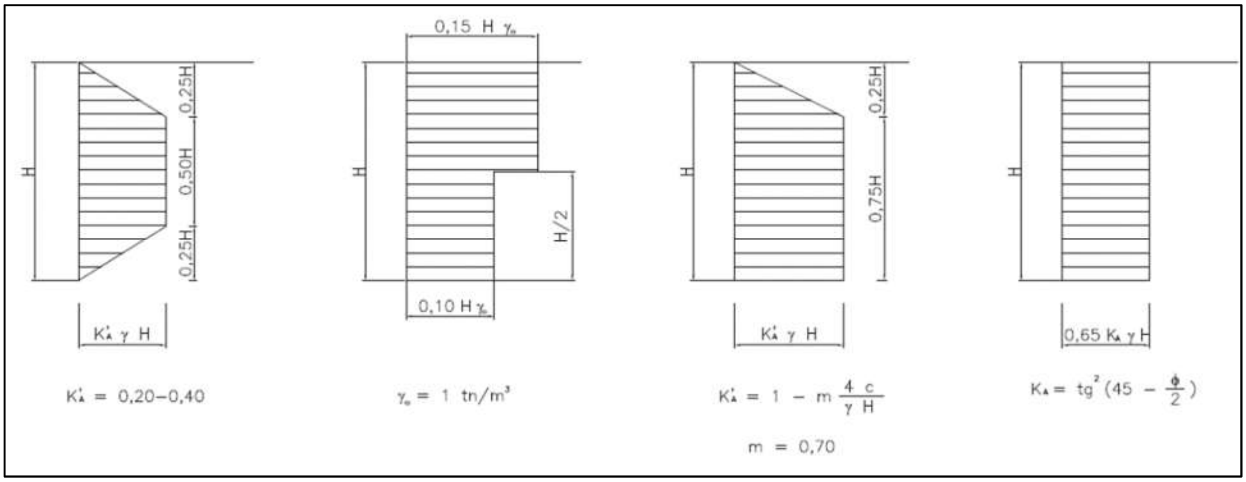

Figure 4. Code diagrams of minimum design earth pressures for strutted excavations
i) Stiff clays; ii) Pampeano Fm.; iii) Soft clays; iv) Sands (Moretto 1972).

Other provisions of the Code require the support of any excavation wider than 2.0 m (Moretto 1972). This restriction, which might be considered overly conservative by many, is intended to avoid any excavation including deep trenches being unsupported, because Pampeano soils are heavily fissured due to desiccation and are prone to fail with no warning when unsupported. A minimum support, much lower than what is usually employed in stiff clays suffices to guarantee stability and appropriate behavior (see Figure 4, second diagram).

The requirement of no excavation wider than 2.0 m be unsupported is almost 50 years old. The interpretation of this requirement evolved gradually in the period into a very popular procedure for advancing excavations that is readily apparent in Figure 5. The real-world version shown in Figure 6 also shows a magnificent opportunity for improving our construction procedures as well.

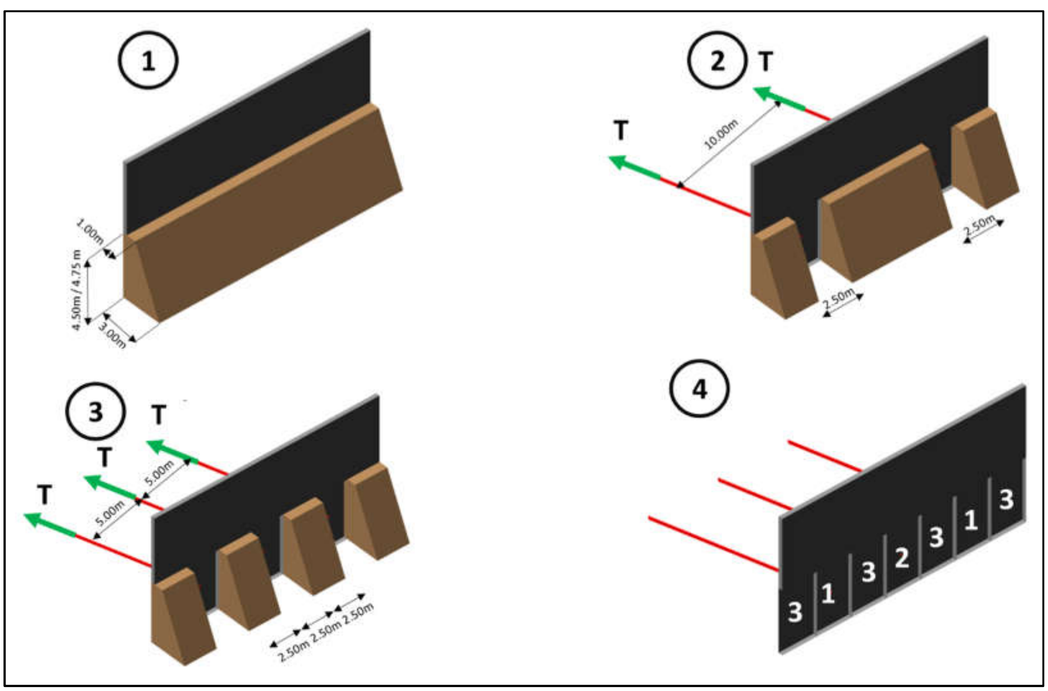

Figure 5. Typical construction procedures for large excavations in Buenos Aires. Ideal sketch.

Figure 6. Typical construction procedures for large excavations in Buenos Aires. Real world.

CASE HISTORIES OF GROUND RETAINING SYSTEMS IN BUENOS AIRES

Anchored concrete walls: Vista Tower

The Vista Tower excavation was 19.60 m deep, located close to the Scalabrini Ortiz metro station, surrounded by buildings up to 14 storeys and supported by up to seven rows of passive and active anchors and cast in place concrete walls. Post-tensioned anchors were 150 mm in diameter, had five Grade 270 15.2 mm strands and a locking load of 700 kN. Passive anchors were 150 mm dia and reinforced with three rebars dia 25 mm. The length of the various anchor rows is shown in Table 1. This excavation was a case leading to the approval of the so called "law on anchors" which allowed contractors to use temporary anchors drilled in the ground of neighbour properties.

Table 1. Total|grouted length of ground anchors (in meters) (Laría et al 2015).

Depth:	17.0m	15.5m	17.5m	19.6m	Type
Line 1	19.0 | 9.0	19.0 / 9.0	19.0 / 9.0	21.0 | 9.0	5 strands
Line 2	17.0 | 9.0	18.0 | 9.0	17.0 | 9.0	20.0 | 9.0	5 strands
Line 3	16.0 | 9.0	16.0 | 9.0	16.0 | 9.0	19.0 | 9.0	5 strands
Line 4	16.0 | 9.0	10.0(1)	5.0(1)	17.0 | 9.0	5 strands
Line 5	7.0(1)	-	-	10.0(1)	3 rebars
Line 6	-	-	-	10.0(1)	3 rebars
Line 7	-	-	-	8.0(1)	3 rebars

(1) passive anchors

In general, the excavation performed very well. Main issues related to construction were: i) the failure of several anchors from the upper two rows; ii) challenges with the use of the final concrete wall as temporary support; and iii) ground deformation inducing minor damage in the surrounding constructions. These issues are briefly commented below.

Failure of anchors from the upper two rows: Several ground anchors from the upper two rows failed to resist the stressing load and exhibited sustained creep leading to rejection of the anchors. In some cases, a clean, naked strand was pulled out of the anchor with little effort. The problem was attributed to the fact that the low-heat, slow-hydrating cement used for the main foundations was also being employed for the production of the infilling paste; and that the water/cement ratio was not controlled with enough care. After changing the cement and the procedure for producing the cement paste, the rejection rate of anchors failed to an almost negligible value.

Final wall employed as temporary support: The final basement wall was just 30 cm thick. The architectural design made no allowance for the placement of a temporary shotcrete wall and it was also decided not to invade the neighbour property, not even with small anchor plates. Therefore, the 30 cm thick final cast-in-situ wall was employed as a temporary support as well. This decision came along with a large number of challenges, delays and costs.

The construction employed was (Figure 7): i) excavation in limited spans; ii) installing of the anchors; iii) casting of the anchor plates; iv) post-tensioning of anchors; v) casting of the final wall; vi) repeat in remaining spans and levels.

Ground deformation and damage of surrounding buildings: Deformations induced by the excavation were small for a project this size, in the range of 5 to 8 mm (Figure 8) (Laría et al 2015). They however induced minor cosmetic damage to neighbour buildings. It looks like this level of deformation cannot be avoided with practical methods. Back analyses showed that doubling the amount of ground anchors, for instance, would only reduce the deformation by about 30%.

Figure 7. Construction sequence of the anchor plates as part of the final wall (Laría 2015).

Pile-supported excavations: Vista Tower street side

In the same project, the street side was only six meters away from Scalabrini Ortiz metro station, and the excavation was 18.5m deep. The solution adopted employed piles 0.6m dia, 23m long, supported by three rows of active anchors. As evident in Figure 9, the piles were needed to carry the vertical component of the load added by the first row of anchors (Laría et al 2015).

The solution proved itself to be very convenient from the point of view of performance, cost and ease of excavation. The performance was actually very good: the maximum displacement of the wall was 7.0 mm at the top and up to 5.0mm at the first row of anchors, a similar displacement to that of the other walls which required seven rows of anchors instead of just three.

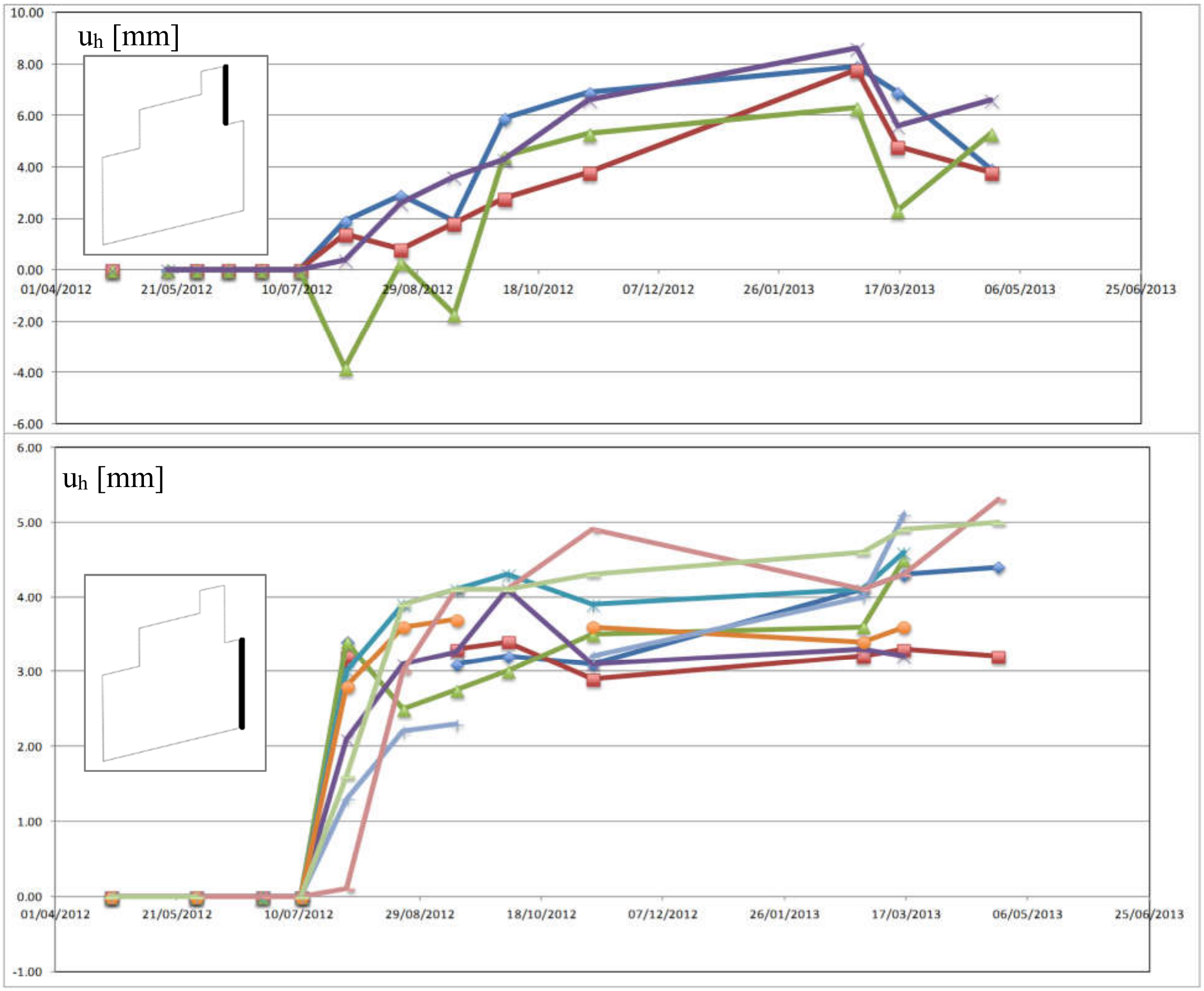

Figure 8. Horizontal displacements of selected control points at the crest of the wall.

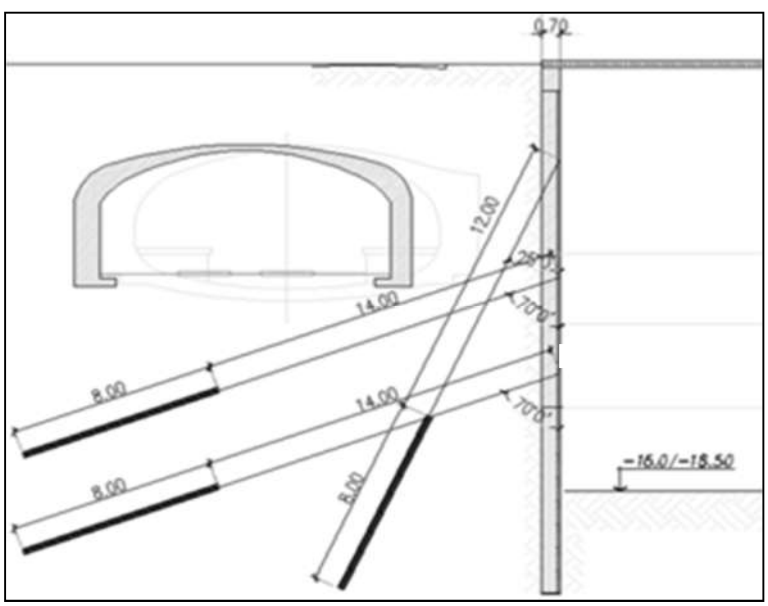

Figure 9. Solution adopted for street side of Vista Tower.

The pre-excavation support provided by the piles allowed for a much faster excavation. Figure 10 shows an already completed excavation of the front wall, while the remaining walls are well behind 50% of completion. Despite the advantages provided by the pile-supported excavation and the wide communication to the industry that took place, few projects built after Vista Tower actually employed piles or other pre-excavation technology for supporting deep excavations, the main reason being the “lost underground space” due to the thickness of the wall embedding the piles.

Figure 10. Pile-supported excavation, street side of Vista Tower.

Uplift stability during construction: L’Avenue

L’Avenue Libertador is a tower located at the toe of the cliff shown in Figure 2, that is to say, where the ground surface is eight to ten meters closer to the aquifer referred as “Puelches sands”. In this 18.5 m deep excavation, the support of the lateral ground was carried out using a combination of diaphragm walls and sequential excavation and is not presented here.

The most interesting feature of this project -which is under construction at the time this paper is issued- is the proximity between the bottom of the excavation and the Puelches sand. Referred to ground level, the bottom of the excavation is -18.5 m, the Puelche sands are is about -25.0 m, the phreatic level is about -4.0 m and the piezometer head of the aquifer is about -3.0 m. In other words, 6.5 m of a clay plug must resist 15.5 m of unbalanced uplift pressure. Excavating the whole surface was not feasible, as it would have led to immediate bottom instability. The procedure adopted instead consists in splitting the area in five regions and excavating them in a controlled sequence. Stability of each portion of the excavation was achieved by the contribution of the self-weight of the ground and the downwards load contributed by piles and barrettes (Figure 11).

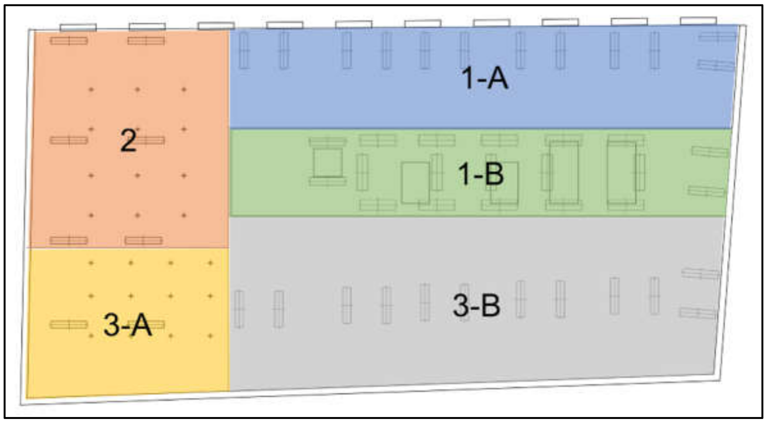

Figure 11. Division of the excavation area to prevent bottom uplift failure.

The whole area was excavated to a depth of 14.0 m, safe from the point of view of uplift forces. From then on, the excavation sequence is the one shown in Figure 11. The deepest region is 1-B, 7.63 m wide and 37.80 m long, the only one to be commented here. A simple schematic diagram of acting forces is shown in Figure 12.

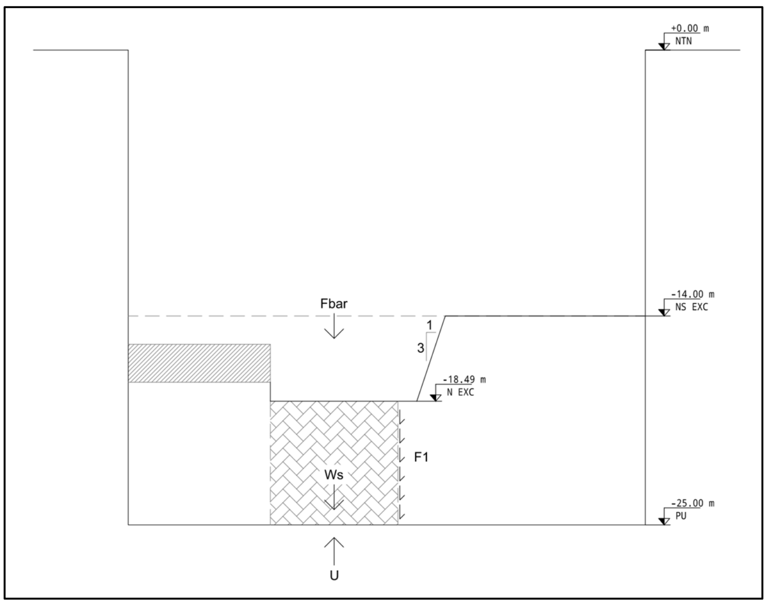

Figure 12. Forces acting on the soil plug in region 1-B.

The factored de-stabilizing force is $U = 36.3\text{MN}$. Stabilizing forces are $W_s = 13.2\text{MN}$, $F_{bar} = 25.9\text{MN}$ and $F_1 = 13.0MN$, where F_{bar} is the total load contributed by the barrettes. The sum of the factored stabilizing foreces is $R = 52.2MN$, and therefore overall stability was guaranteed.

This simple math set aside, the fact is that during the final stages of the excavation, a few spots of clear water were observed. In a few hours, small sand particles accumulated in the vicinity of the spots. It was all evident that, while overall stability was a non-issue, the risk of piping, erosion and progressive distress of the excavation could not be ruled out. It was decided to build a gravel bed, 40 cm thick and covered by geotextiles, to allow for the free drainage of incoming water but to prevent further migration of particles. This pre-emptive measure sufficed to stop the incipient piping process and allowed for completion of the excavation without further problems (Figure 13).

Figure 13. Excavation of sector 1-B, L'Avenue project.

WHAT COMES NEXT (IN BUENOS AIRES)

Modernizing sequential excavations

There is actually no need for using the cumbersome sequence shown in Figure 5. A sequential excavation, customary in other parts of the world, can be easily adopted in Buenos Aires. The author participated in a few cases where a sequential excavation was adopted, avoiding the use of those soil buttresses shown in Figure 6 and that bring the feel and like of the middle ages to 21st century construction sites.

One such case is the "Al Río" project in Rosario, an excavation 9.6 m deep and about 10.000 m2 in area, supported by passive ground anchors and shotcrete and excavated in long -but shallow-spans. Figure 14 shows an overall view of the excavation, while Figure 15 shows one of the spans, waiting to be covered by shotcrete.

Figure 14. Overall view of the excavation of the Al Río project in Rosario, Argentina. Note the wall supported with shotcrete and ground anchors, and the buttressed portion to be excavated.

Figure 15. Detail of one excavation stage. Note the carving and mesh reinforcement for the anchor plates, and the ground surface waiting for the shotcrete to be placed.

Incorporating uncertainty to the design

The design of anchor-supported excavations employing deterministic finite-element models is now routine engineering in major urban developments. The concept of risk and the use of non-deterministic design methods, however, have been recently brought to the attention of the Argentinian geotechnical engineering community because of the adoption of LRFD procedures by structural engineers. Us geotechnical engineers claim that risk is somewhat controlled by our "cautious estimate of input parameters" but usually provide little support to this statement.

Ledesma et al (2019) present the case study of the Al Rio excavation employing probabilistic analyses. The simulation of the construction process, a standard excavation in five benches, yielded a minimum factor of safety $FoS = 1.40$ at the last stage. Crest displacements of the wall are $U_x = 2.6mm$ (horizontal, to the left in Figure 16) and $U_y = 1.5mm$ (vertical, downwards). Loads in the anchors are shown in Table 2.

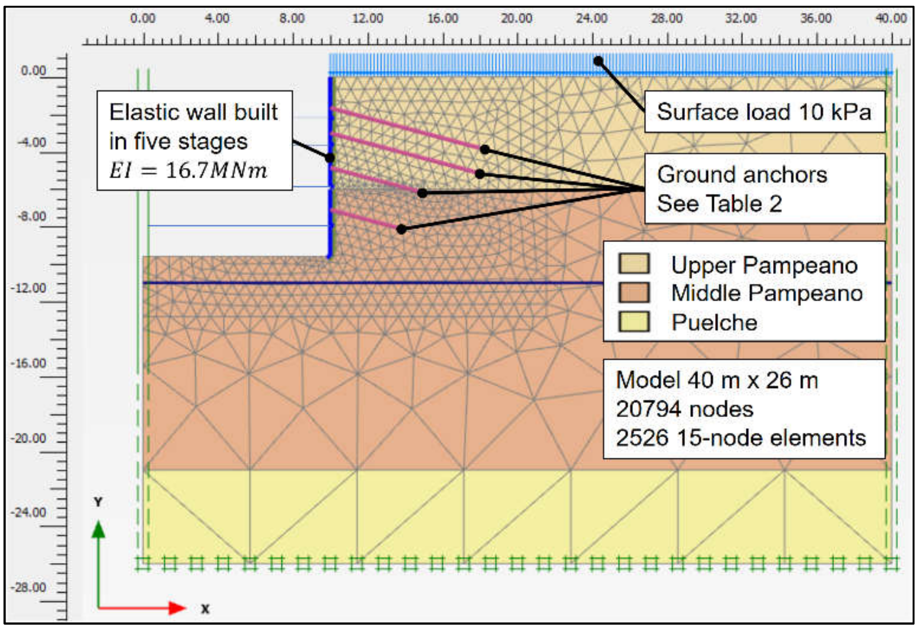

Figure 16. Geometry and finite element mesh.

Table 2. Characteristics of the ground support system.

Row	Length	Inclination	Spacing	Yield load	Max. Load
	m	º	m	kN	kN
1	7.0	15	2.5	290	290
2	7.0	15	2.5	504	504
3	6.0	15	2.5	497	497
4	4.0	15	2.5	378	378

A probabilistic analysis was performed using the Taylor Series Method (TSM) and the Point Estimate Method (PEM). TSM is based on a Taylor series expansion of the target function considering only two moments (mean μ and standard deviation σ). PEM combines all parameters evaluated at $\mu_i \pm \sigma_i$ (Baecher and Christian 2005, Phoon and Ching 2014, Gibson 2011). What follows is a brief excerpt of the results. The reader is referred to Ledesma et al (2019) for further details of the model.

Table 3 shows the probability of failure for both PEM and TSM for three limit states, namely ULS limit state, defined when $FoS < 1.0$, and the SLS limit states, defined as displacements in excess of 10 mm. Figure 17 shows the probability distribution and cumulative probability function of U_y using PEM. Both uncorrelated and loosely correlated strength parameters were employed in the analysis.

Table 3. Probability of failure for the three target functions (Ledesma et al 2019).

Method	$\rho_{\phi\|c}$	$P[FoS < 1.0]$		$P[U_x > 10mm]$		$P[U_y > 10mm]$	
		normal	lognormal	normal	lognormal	normal	lognormal
PEM	0.0	7E-03	2E-03	1E-07	8E-04	7E-09	2E-03
	-0.5	2E-02	1E-02	2E-04	8E-03	2E-05	7E-03
TSM	0.0	2E-02	1E-02	7E-10	6E-04	2E-10	2E-03
	-0.5	8E-03	3E-03	8E-12	2E-04	6E-13	1E-03

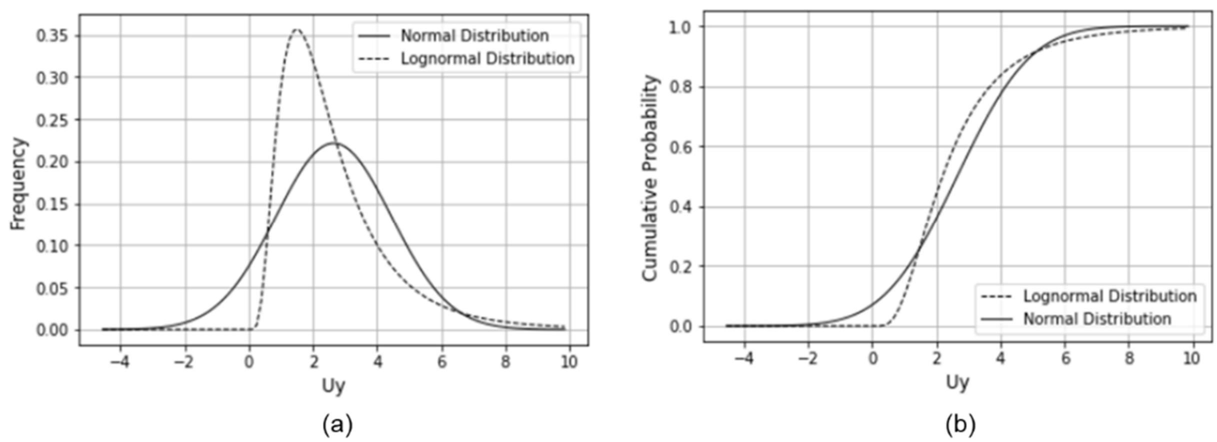

Figure 17. Distribution of probability (a) and cumulative probability (b) of the vertical displacement U_y for uncorrelated cohesion and friction angle using PEM (Ledesma et al 2019).

Probabilistic analyses allow for easily determining which parameter contributes more to the geotechnical risk of a given project. For instance, Figure 18 shows the contribution to uncertainty of key parameters in the Al Río case.

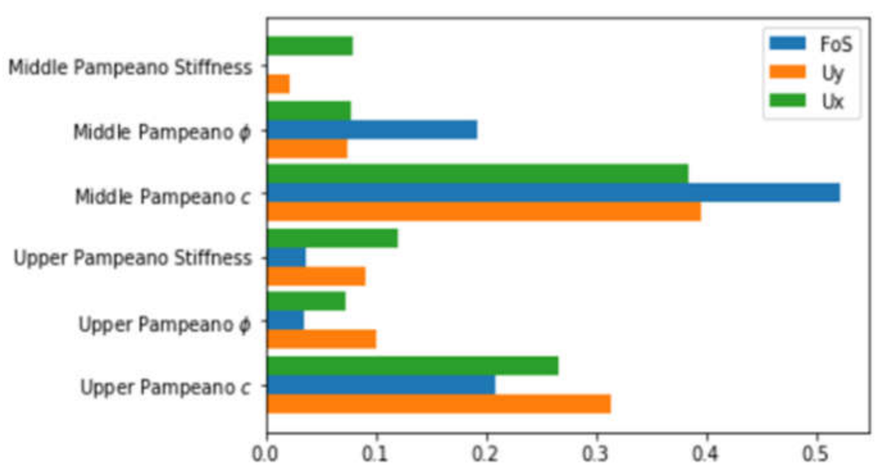

Figure 18. Sensitivity score of input parameters for different target functions: FoS, U_y and U_x.

It is expected that reliability analyses of support systems for urban excavation will become routine practice in Buenos Aires, at least for major excavation projects. If, as expected, a risk and reliability approach to design gains popularity, it will in turn induce better practices for ground investigation, design, and construction, as has happened in other industries and also in geotechnical engineering in other parts of the world.

SUMMARY AND CONCLUSIONS

This paper presents a brief description of the current construction procedures for urban excavations in Buenos Aires, Argentina. It has been shown that the Pampeano formation is very favorable for deep excavations due to its high stiffness, high unconfined compressive strength, rapid drainage and good frictional behavior when drained. The Building Code of Buenos Aires requires, however, that strutted excavations be designed with a minimum earth pressure. The code requirement of no excavation wider than 2.0 m be unsupported derived in the use of soil buttresses that have been abandoned already in many other places in the world.

The Vista Tower case history was a leading case for the adoption of temporary anchors in urban construction. In general, the excavation performed very well, but a few opportunities for improvement were identified and described here. This case history showed that pile-supported excavations can be actually more convenient than support systems that rely on anchors only. Architects and land developers, however, must accept the loss of some underground space due to the increased thickness of the retaining walls.

L'Avenue case history, where piping and incipient erosion was controlled by an ad-hoc countermeasure, shows the challenges of making an excavation too close to the Puelche sands and the value of close monitoring in reducing geotechnical risks.

The examples show that there is room for improvement in the design and construction procedures of deep excavations in Buenos Aires. There is no need to continue using soil buttresses, sequential excavations of modern age can be adopted instead. During the learning curve -probably a few years- staff should be specifically trained to understand the advantages and challenges of the new construction sequence, and adequate supervision should be mandatory in these cases. One case history, the "Al Río" project, proves that the procedure is feasible and convenient.

The design of anchor-supported excavations employing deterministic finite-element models, now routine practice, should lead its way to risk-based approaches. One pilot example was presented in this paper, showing the enhanced value of statistical procedures in advancing the design practice of urban excavations. If, as expected, a risk and reliability approach to design gains popularity, it will in turn induce better practices for ground investigation, design, and construction, as has happened in other industries and also in geotechnical engineering in other parts of the world.

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