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Large Caverns for Metro Stations in Buenos Aires

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ABSTRACT: Buenos Aires Metro Line H, in Argentina runs N-S, at the west side of the city's downtown area. An extension of the line started in 2011. A TBM tunnel and one cut&cover station will be built southbound in estuary soft holocene soils; a NATM tunnel and three cavern stations are being built northbound in stiff cemented silts and clays. The experience accumulated in the last fifteen years has allowed for continuous advancements in the construction methodologies used for tunnels and underground caverns in stiff soils. Nowadays, the Line H northbound caverns - approximately 135m long and with a +200m^2 face - are being excavated full face with excellent performance, far better than previous experiences where more conservative, staggered excavation procedures were employed. In this paper, the evolution of the NATM techniques in Buenos Aires´s big metro caverns is reviewed; the advanges and disadvantages of the changes in procedures are discussed and different optimization alternatives awaiting to be developed are described.

Keywords: NATM tunnels, caverns, construction procedures.

1 INTRODUCTION

Extension of Line H is an interesting challenge: C2 northbound extension consists in four new caverns and 2km of two lane NATM tunnels, while the southbound A0/A1 extension faces very poor geotechnical conditions that require the use of a TBM (Figure 1).

Northbound, engineering challenges stand for the optimization of already very efficient construction procedures. Big caverns that required eighteen months for excavation in 2005 and eight months in 2007 are now being built in only five months. Southbound, engineering challenges are more related to feasibility. A two-lane TBM is just too big to fit in the available space, and bottom stability of the access shafts is marginal; costs can easily escape from control in such adverse conditions.

In this paper, the project is introduced, the geological and geotechnical conditions is described, the evolution of the NATM techniques in Buenos Aires´s big metro caverns is reviewed and some of the most significative challenges encountered are discussed.

2 BUENOS AIRES SOILS

Buenos Aires City soils have been described in other contributions (Bolognesi 1975, Fidalgo et al 1975, Núñez 1986, Codevilla & Sfriso 2011). Briefly, the Pampeano formation un-derlying Buenos Aires downtown area is a modified Loess, overconsolidated by dessication and cemented with calcium carbonate in nodule and matrix impregnation forms. Except for the heaved upper three to six meters, penetration resistance is systematically $N_{SPT} > 20$ with some heavily cemented zones that exhibit very weak rock behavior and $N_{SPT} > 50$.

Particular features of the formation are: i) fissures induce a high secondary permeability; ii) thin layers of non cohesive loamy sands can be found at depths 20m and below; iii) close to the bottom of the formation and right on top of pliocene clean sands, a poorly cemented non fissured sub-stratum of greenish clays acts as an hydraulic seal. Pampeano soils are good for underground construction due to high stiffness, reliable compressive strength, rapid drainage and good frictional behavior when drained.

Figure 1. Extension of Line H, Buenos Aires Metro.

The max allowable unsupported drift is about 2.5m due to crown instability of the fissured soil mass (Sfriso 2006, Núñez 2007). Table 1 lists a typical set of material parameters used for the design of underground excavations (Sfriso et al 2008, Codevilla & Sfriso 2011).

Table 1. Design material pars, Pampeano Formation.

Parameter	Units	0m-8m	8m-30m	30m-40m
c_u	kPa	50-100	110-220	40-120
ϕ_u	°	10-20	0-10	0
c'	kPa	10-25	25-50	15-30
ϕ'	°	30-32	30-34	29-32
ψ	°	0-3	0-6	0-3
E_{50}	MPa	60-100	70-150	60-90
E_{ur}	MPa	150-250	180-300	140-220
m	-	0.0-0.4	0.0-0.4	0.0-0.4
ν	-	0.20-0.30	0.20-0.30	0.20-0.30
R_f	-	0.80-0.90	0.80-0.90	0.80-0.90

3 EVOLUTION OF TUNNELLING PROCEDURES IN BUENOS AIRES

Figure 2 shows the excavation of the first Metro Line A in 1912.

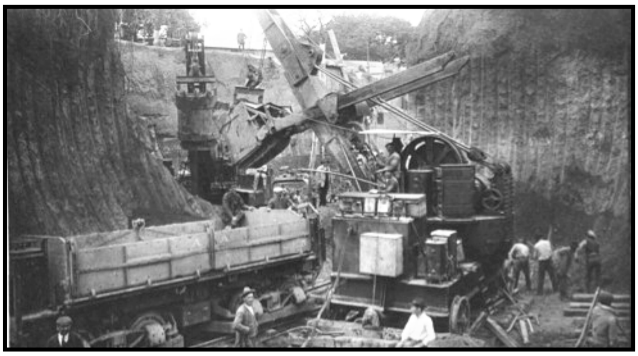

Figure 2. Open pit excavation of Line A in 1912.

The use of shotcrete as primary support and the subsequent evolution of tunnelling procedures started in 1998 and is reported elsewhere (Sfriso 2006, 2007, 2008). For big caverns, construction procedures remained conservative for longer time. Echeverria and Villa Urquiza stations were executed using the german method and required up to 18 months for completion of excavation. Auxiliary transverse galleries sparkled the plastification of intermediate pillars, induced surface settlements ~35 mm and required temporary propping (Figure 3).

Figure 3. Temporary propping of auxiliary galleries to reduce surface settlements, Echeverría Station.

The experience served to change to full face excavation at Corrientes Station. The cavern has ~18.9m x 14.1m (220 m^2) under only 9.0m of overburden. Excavation was completed in 7 months with surface settlements below 20mm. The case is fully reported in Sfriso (2007, 2008), and Sfriso & Laiún (2012).

Another milestone is the garage-workshop at Line A, the first tunnel executed with one pass lining method (Figure 4). The primary support has 0.90m side-wall and 0.35m in the crown. The construction procedure is similar to that used in the Corrientes station. The Metro Authority required a waterproof tunnel, and therefore a membrane spray was applied to the inner face and covered by a thin shotcrete (Sfriso & Laiún 2012).

Figure 4. First one-pass lining at garage-workshop in Line A.

The solution adopted for the garage-workshop at Line B was different. The main contractor chose to use a temporary shotcrete invert (Figure 5). The extra cost for the adopted solution was compensated by the higher speed of construction compared to the cast-in-place concrete used at Line A and Corrientes Station. This cavern, 460m long and 200m^2 face, was excavated in seven months at four simultaneous faces, achieving advances of 8m to 10m per week for the full cycle.

Figure 5. All-shotcrete solution for garage-workshop in Line B.

Urban growth favours regions of good soil quality; when these regions are exhausted, growth continues at marginal areas. That is the case of the River Plate coastline in Buenos Aires, where the Line E extension was excecuted recently. This line is located at the eroded eastmost portion of the Pampeano Formation; it crosses man-made fills and thin layers of non cohesive sandy soils turns more usual. Significant challenges were faced during the excavation of the Correo Central Station due to bottom instability (Sfriso & Laiún 2012). The solution used in this case consisted in short invert advances 2.2m long and inmediate girder/shotrcrete support (Figure 7).

4 EXTENSIÓN OF LINE H (2011-2013)

4.1 *Description*

The C2 section of Line H consists in four stations linked together by three sections of two-lane tunnels with a total length of 2050m. The first three stations, Córdoba, Santa Fe and Las Heras, are 135m long caverns with a cross section of ~220m^2. The last station, Plaza Francia, has been deferred to 2017 and might change to an open pit excavation. The project includes a transversal stope located near Cordoba Station to accommodate an electrical substation.

4.2 *Excavation faces*

Three ramps (Figure 6) provide access to the tunnel faces. The ramps start at road level through an open trench shored with piles and go underground where the overburden is 2.5meters.

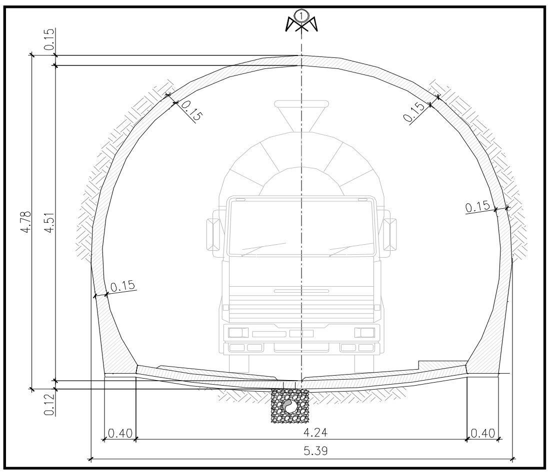

Figure 6. Typical ramp cross section.

Figure 7. Correo Central station. NATM invert.

4.3 *Tunnels*

The typical tunnel section is 10m wide, with a 55m^2 cross section and 9.0m to 14.0m overburden, fully below the water table; as such, soil must be systematically drained in advance to simplify excavation works and marine removal.

The excavation methodology consists in full-face heading, 15cm thick plain shotcrete with girders and “elephant feets”. Excavation and soil removal is performed using conventional excavators, while the fine profiling is done by hand using jackhammers.

The use of reticulated metal truss embedded in the shotcrete and spaced according to the excavation advance is the normal practice for tunnels in subways. The advance lengths usually adopted depend on the geothechnical quality and the hydrogeological condition that prevail at the working face and may vary between 1.0m and 2.5 meters.

It is required that a final concrete lining be installed. This is not a geotechnical requirement but an owner’s decision based on serviceability and durability considerations. Specifications require that this final lining be built using cast-in-place plain concrete. Shotcrete is rarely accepted for secondary linings; when employed, it is placed manually, as robots have not been systematically used for Metro projects.

4.4 *Caverns*

After the good experience at Corrientes Station, the contractor was adviced and decided to repeat the same construction procedure for the three caverns in this project.

The construction methodology consists in a NATM full-face excavation using two backhoe equipments located at two benches, producing two independent working faces, but keeping the closure of the structural ring within one diameter of the tunnel face. The procedure is described by Sfriso (2007, 2010). The complete cycle allows for 6m to 8m advance per week. The cross-section, construction procedure and pictures are shown in Figures 8 to 11.

The particular challenge of the three caverns of sector C2 when compared to Corrientes Station is that the geotechnical conditions are less favourable. In the particular case of Las Heras Station, placed at a cliff, it has a highly variable overburden with a minimum of only 5 meters for a 19m wide cavern.

The primary lining is made of shotcrete 0.30m to 0.45m thick, 20kg/m girders and rebars at the side-walls. Between the primary lining and the final concrete lining a 4mm thick Masterseal 345 sprayed membrane is applied. This membrane was used before in the Corrientes Station and the Line A warehouse-garage with aceptable success.

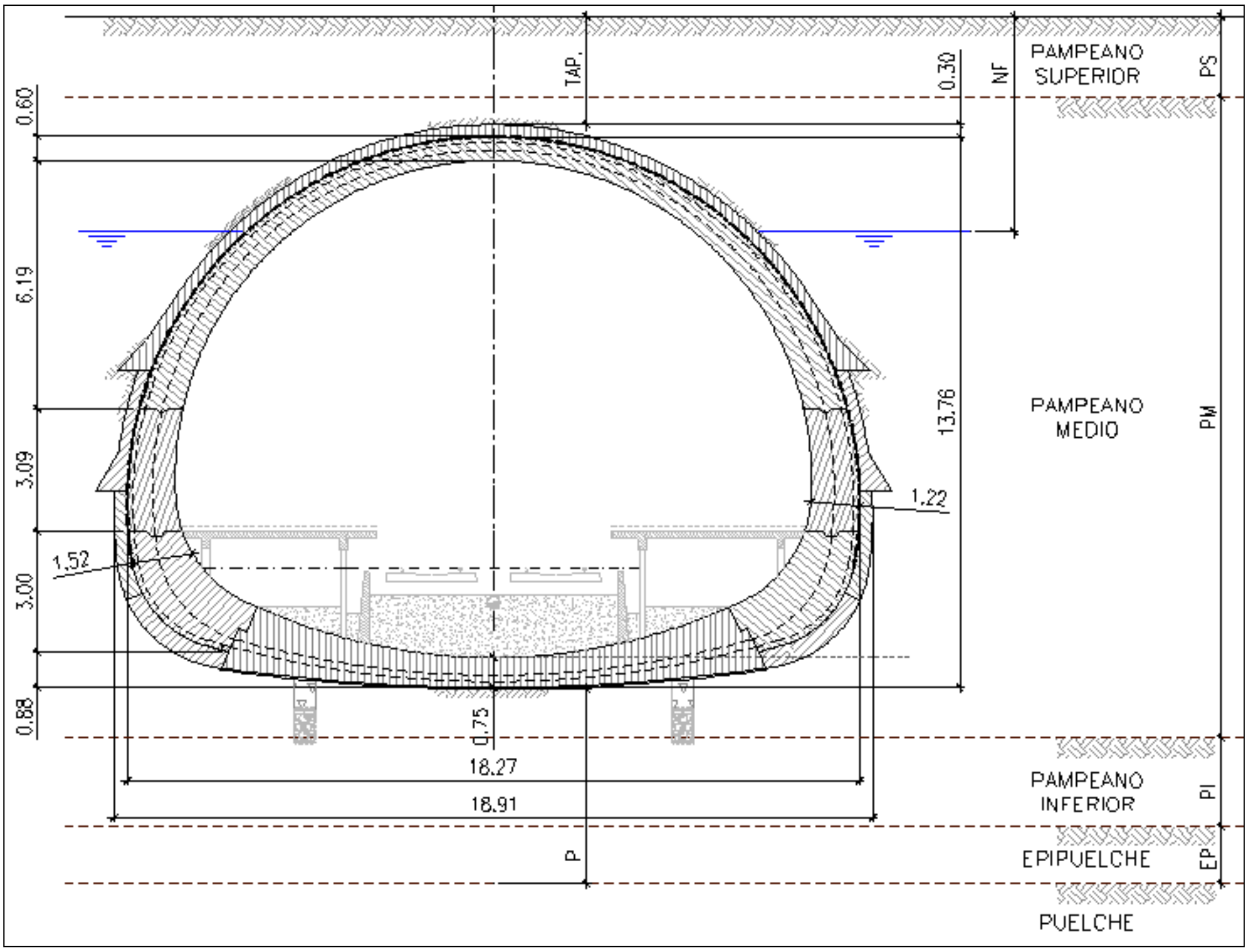

Figure 8. Cross section of Las Heras, Santa Fé and Córdoba stations.

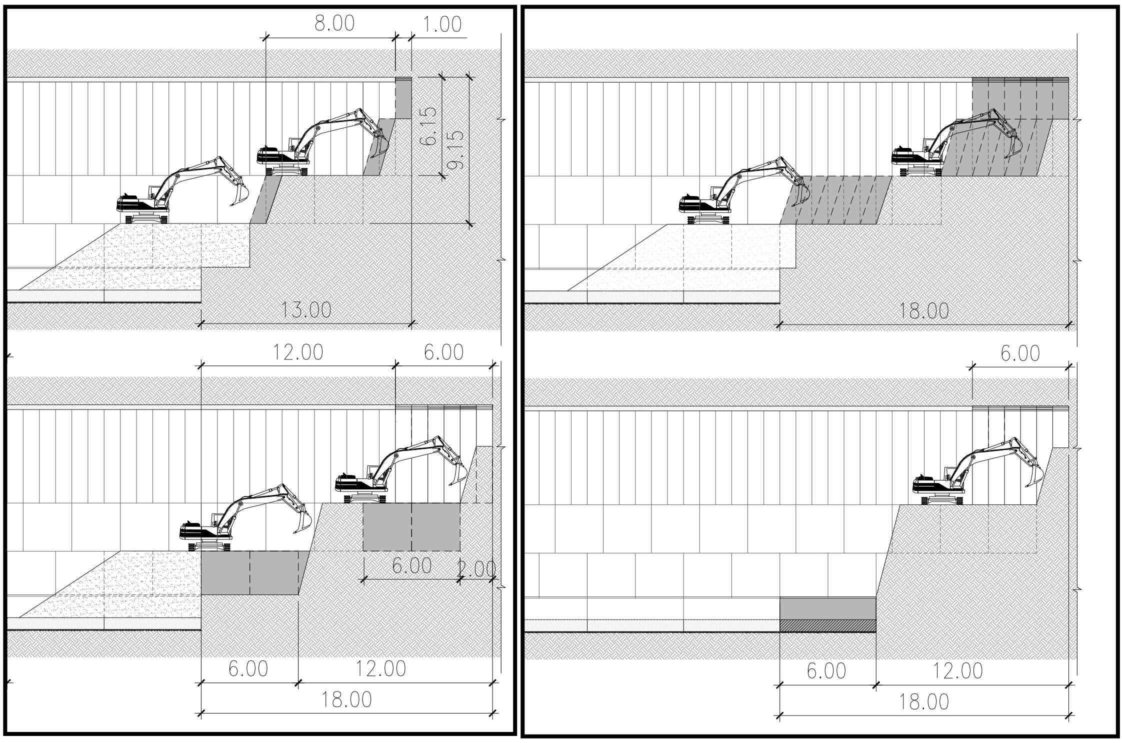

Figure 9. Longitudinal sketches of construction stages, Las Heras, Santa Fé and Córdoba stations.

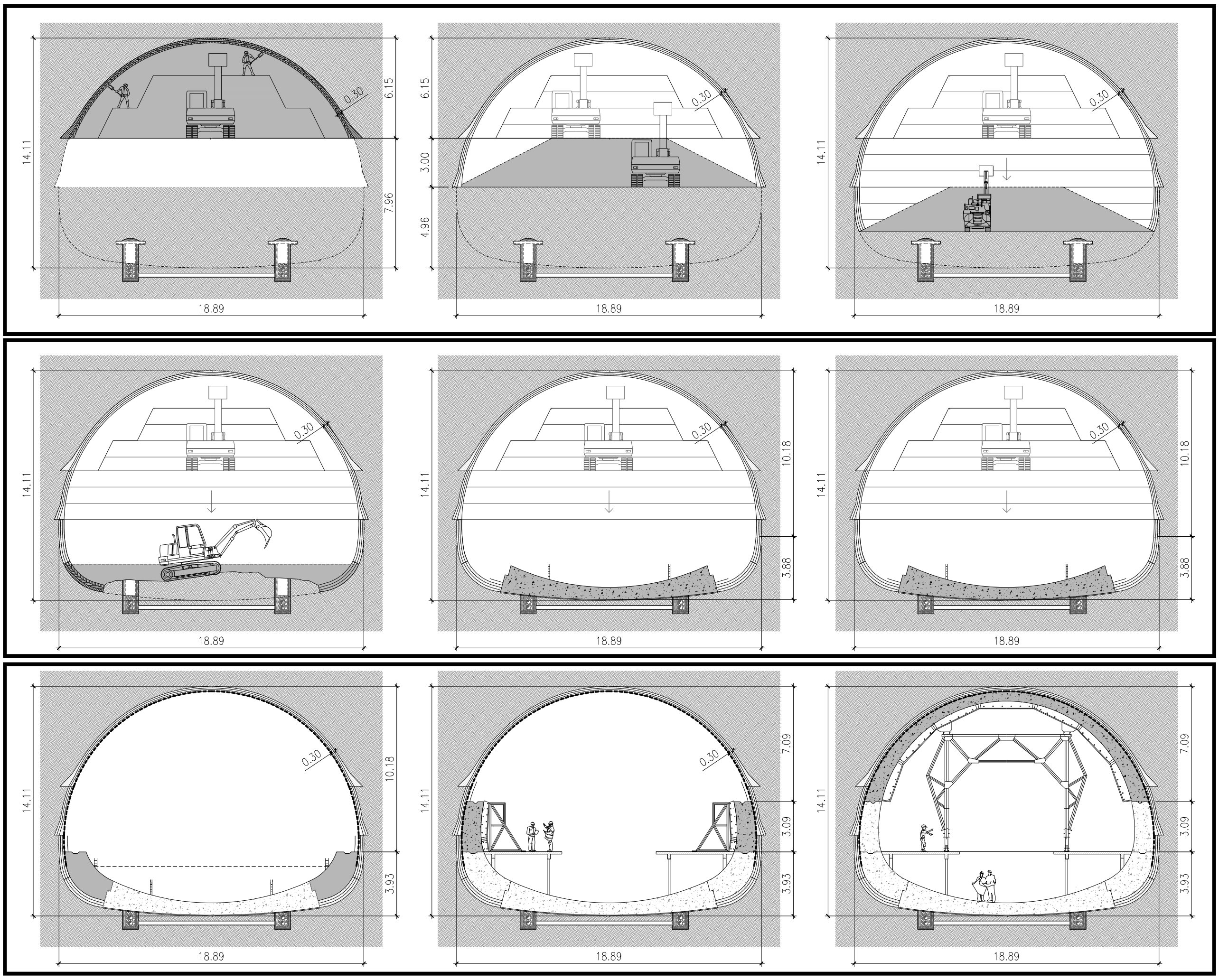

Figure 10. Las Heras, Santa Fé, Córdoba stations. Construction stages.

Figure 11. Construction stages of the caverns.

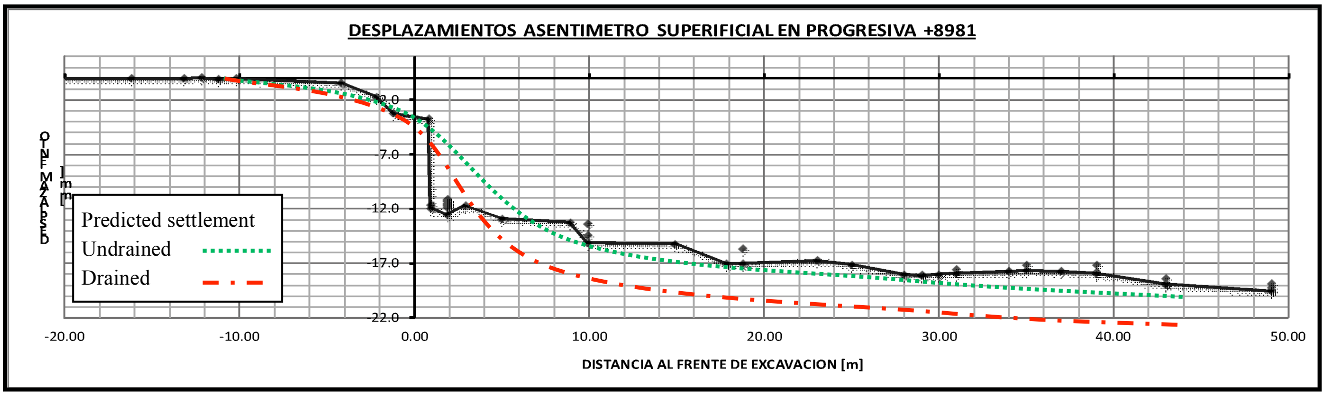

Figure 12. Las Heras station. Settlement vs distance to excavation face. Shallow monitoring point at Pr +8981.

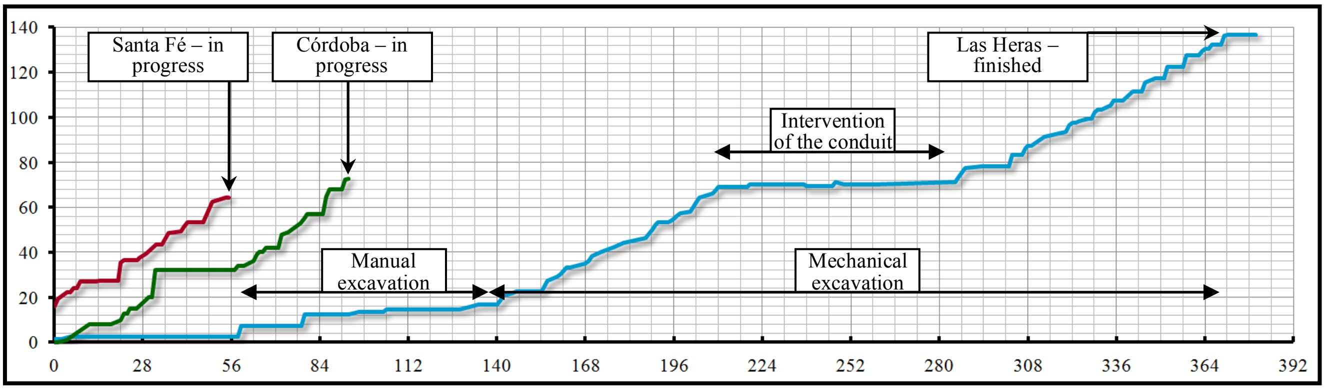

Figure 13. Accumulated distance to the face of the main excavation [m] vs. time [days].

As in the tunnels, soil excavation is done by two high capacity backhoe excavators; digging and shaping of the bench is manually executed using pneumatic hammers.

Round length depends on the ground conditions, ubt is usually restricted to one meter by the Metro Authority. The temporary shotcrete lining is manualy sprayed in two stages to complete the design thickess 30cm to 45cm.

As a result of the urgency to meet deadlines and speed up the cavern execution, an additional excavation front was opened at each station and accessed through shafts. These additional faces were used to excavate manually, by top-heading method, the crown of the tunnel and execute the temporary lining, building 1.4m footings. Those excavated top sections are found encountered afterwards by the main mechanical excavation front.

4.5 *Behavior*

Figure 12 shows the measured settlement of the caverns, showing a maximum value ot 21mm. The estimations obtained from a 3D finite elements model using Plaxis were in the range 18.5mm to 22.5mm for drained and undrained conditions respectively. This is an excellent agreement between measured and computed settlements. Unfortunately, not much instru-mentation is placed in the caverns, and therefore it is not easy to state that this matching also applies to other ground behavior indicators such as tilting, ground stresses or structural loading of linings.

Figure 13 shows the evolution of the main excavation faces for each station. It's observed that the average advance rate for the final sections its reaches 8m per week.

In Las Heras station there were some delays caused by the interference of a main sewer pipe situated near the cavern's crown. The duct was deteriorated and had to be repaired after an atypical strong rainfall that generated water pressure and broke it, forcing to stop excavation works. It can be observed 10m to 15m step advances produced by the secondary faces. This change of procedure generated an inefficiency on the excavation performance and delayed the construction. It is a leason learned: advice against opening secondary fronts.

5 CONCLUDING REMARKS

In this paper the Buenos Aires Metro Line H extension project is introduced, the geological and geothecnical context in which it is placed is described, the evolution of the NATM techniques in Buenos Aires´s big metro caverns is reviewed, and different engineering challenges are briefly discussed.

The development of big cavern construction occured during the last ten years in Buenos Aires city allowed for a sustained progress and a continuous develpoment of excavation and support construction methodologies. It has been training ground for the design teams, constructors and for the supervision authorities as well.

The simultaneous excavation of the three caverns – Córdoba, Santa Fe and Las Heras stations – as described in this paper allowed for a consolidation, in a practically definitive way, of the full face NATM excavation techniques as the most economic, safe and efficient excavation methodology for Buenos Aires big caverns.

The current advance of the excavation works, which is close to 70% for section C2, shows nowadays the deadeline of 2015 as challenging but attainable. Modern and safer construction procedures, the reduction of concrete thickness, the use of shotcrete as secondary linings and it´s possible integration to the primary liner in a composite structure, the use of robots for the application of shotcrete and, finally, the implementation of more reliable monitoring techniques, are still some awaiting points which need to be developed in the close future.

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