

# EVOLUTION OF CONSTRUCTION PROCEDURES FOR METRO STATIONS IN BUENOS AIRES, ARGENTINA



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## ABSTRACT

Buenos Aires, Argentina, is expanding its metro network. Some 22 km of new tunnels and a number of metro stations have been constructed between 1998 and 2011, and three new lines including 20 km of tunnels are scheduled for construction in the near future. During these years, construction procedures for underground stations have achieved significant improvements that had a heavy impact on design, costs and speed of construction. Some of these improvements are described in this paper, along with a brief update of the characterization of Buenos Aires soils for NATM tunneling.

## RESUMEN

La ciudad de Buenos Aires, Argentina, expande su red de subterráneos. Se han construido 22 km de túneles y varias estaciones entre 1998 y 2011, y se planean tres líneas nuevas incluyendo 20 km de túneles adicionales para el futuro próximo. Durante estos años, los procedimientos constructivos para estaciones subterráneas han tenido mejoras significativas, con fuerte impacto en el diseño, en los costos y en la velocidad de construcción. Algunas de estas mejoras son descriptas en este artículo, junto con una breve actualización referida a la caracterización de suelos de Buenos Aires para tunelería NATM.

Keywords: NATM, tunnelling, construction procedures, numerical modelling, caverns

Palabras clave : NATM, tunelería, procedimientos constructivos, modelos numéricos, cavernas

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## INTRODUCTION

The City of Buenos Aires is extending its metro network as shown in Figure 1. Recently completed and ongoing projects are: Line A, extended 5 km, Line B, extended 5 km; Line E, extended 2 km; and new Line H, 5 km long. Some 20 km of new Lines F, G, I are scheduled for construction in the near future [1].

Landmarks of new construction procedures for tunnels are [2]: i) introduction of shotcrete, Line B, 1998 (Figure 2); ii) so called "belgian" tunneling method, Line H, 2000 (Figure 3); iii) full face excavation, Line B, 2004 (Figure 4).

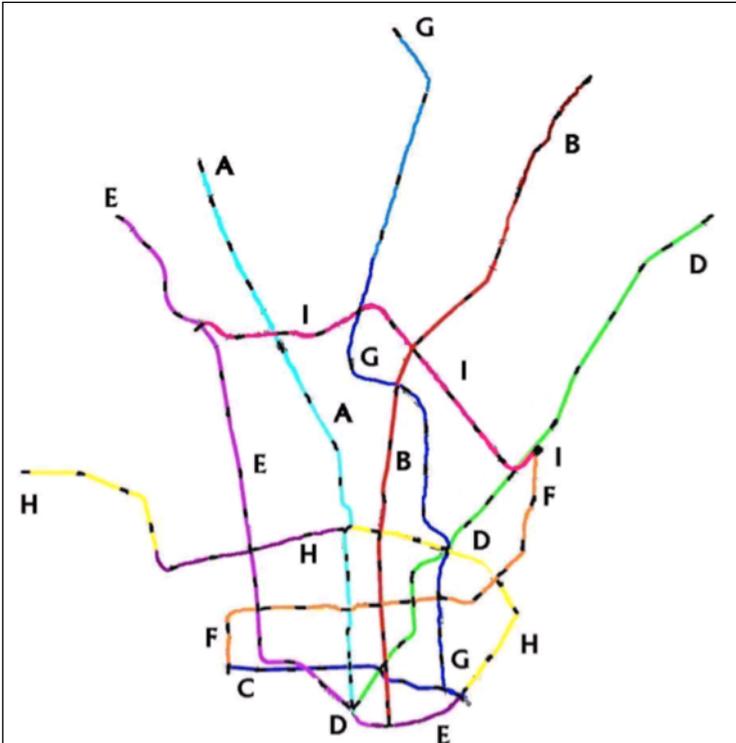


Figure 1. Metro network in Buenos Aires. Existing (A, B, C, D, E, H) and new projects (F, G, I).



Figure 2. German Method of tunneling and first use of shotcrete, Line B, 1998.

Geotechnical and structural analysis techniques evolved concurrently, from earth-load theory to state of the art computer simulation of construction procedures and calibration of constitutive models via back analysis of monitoring data [2][3][4][5][6][7]. Concurrently, research work has been carried out on the physical and mechanical characterization of Buenos Aires soils [8][9][10][11][12].



Figure 3. “Belgian” tunneling method, Line H, 2000.



Figure 4. Full face excavation, Line B, 2004.

Construction procedures for underground stations also showed significant improvements along these recent years. Landmarks are: i) use of shotcrete in Once Station, Line H, 2002; ii) full-face cavern excavation, Line H, 2006; iii) girder supported sequential excavation of invert, Line E, 2009.

The experience in the evolution of the construction procedures for tunnels has been described before (e.g. [2]). In this paper, the focus is oriented to the description of the evolution of the construction procedures for underground stations that took place in the last ten years in Buenos Aires.

## **CHARACTERIZATION OF BUENOS AIRES SOILS FOR TUNNELING**

### **Description**

Buenos Aires City soils have been described in other contributions [4][13][14][15][16][17][18]. Briefly, the Pampeano formation underlying Buenos Aires is a modified Loess, overconsolidated by dessication and cemented with calcium carbonate in nodule and matrix impregnation forms. Except for the upper three to six meters, penetration

resistance is systematically  $N_{SPT} > 20$  with some heavily cemented zones that exhibit very weak rock behavior with  $N_{SPT} > 50$  [16]. Soil mass, where cemented, is systematically fissured, yielding high secondary permeability. Thin non cohesive lenses are occasionally found interbedded with cemented material. While these lenses are extremely rare in the upper part of the formation, chances to hit them are increasing rapidly, as new tunnels need to be driven deeper due to higher restrictions in underground space.

### Shear strength and stiffness

Drained triaxial compression tests of undisturbed samples were recently performed at the University of Buenos Aires. Samples were recovered by direct pushing during the excavation of Corrientes Station in Line H, and tested at the very low confining pressures [8]. The results are shown in Table 1.

Table 1. Drained CTC test results, undisturbed samples of Pampeano soil,  $\sigma_c = 20$  kPa [8].

Test	$\omega$ %	c kPa	$\phi_{max}$ °	$E_{50}$ MPa	$E_{ur}$ MPa
T9	36.0	38.0	45.8	6.7	25.2
T10	40.9	43.3	37.4	12.8	24.6
T11	40.0	30.8	38.7	11.6	22.1
T12	38.8	37.7	36.5	12.4	25.3
T13	36.3	57.2	35.0	13.8	31.0
T14	36.5	22.4	45.1	14.5	32.2
T15	32.9	47.3	36.6	21.5	34.7
T16	40.5	24.4	35.0	9.3	22.7
T17	34.9	1.8	48.4	13.1	28.4
T18	35.7	21.7	42.6	12.3	28.8
T19	37.0	18.8	43.3	5.3	20.8

In Table 1,  $\omega$  is moisture content, c is effective cohesion,  $\phi_{max}$  is peak friction angle,  $E_{50}$  is the secant Young modulus at 50% shear mobilization and  $E_{ur}$  is the unload-reload young modulus. Parameters presented in Table 1 confirm previous results (e.g. [15][16]), showing the excellent mechanical properties of Pampeano soils.

### Underground construction in the Pampeano Formation

The Pampeano formation is very favourable for underground construction due to its high stiffness, reliable compressive strength, rapid drainage and good frictional behavior when drained.

Two particular characteristics of the formation must be accounted for in the design of underground projects [2][17]: i) the Pampeano formation is fissured and has lenses of quasi-granular behavior, forcing the installation of a primary support close to the face in order to avoid crown overexcavation; and ii) materials drain at a speed comparable to that of the construction. Due to these factors, the max allowable drift without support is about 2.5 meters. Up to this maximum, the unsupported drift has very little influence on the resulting settlements, as soil behavior remains quasi-elastic [4][6].

### CONSTRUCTION PROCEDURES FOR TUNNELS

Construction procedures evolved from german method (Figure 2) to “belgian” method (Figure 3) and have probably reached an optimal stage with full face excavation (Figure 4) (Sfriso 2008, 2010). These three methods, as adopted in Buenos Aires practice, are briefly outlined as follows:

German method of tunneling: Long, straight side walls with continuous footings are first casted in pilot tunnels. A circular crown is then excavated in slices 1.0 / 1.5 m long and supported with shotcrete & lightweight lattice girders. A cast-in-place secondary lining is afterwards added to the crown. Finally, the invert is made with cast-in-place concrete.

“Belgian” method of tunneling: This method is a (minor) modification of the Madrid method of tunneling. The upper half of the tunnel is excavated and supported using standard NATM techniques including shotcrete and lattice girders and a secondary plain concrete lining is casted short afterwards. After the cast-in-place concrete is cured, the bench is excavated and side walls are excavated and casted in a “batache” (i.e. tooth-like) configuration. Finally, a cast-in place invert is built.

Full face excavation: This is a standard NATM full face tunneling method with open invert. The tunnel is excavated full-face, supported by shotcrete & lattice girders, and resting on temporary continuous footing.

A secondary unreinforced cast-in-place lining is placed afterwards. In some cases, the secondary lining is formed by an unreinforced, thick shotcrete layer.

Figure 5 shows the cross section of a typical two lane, full face tunnel, as used in Line B and afterwards in lines H, A, E. A 15 cm unreinforced shotcrete layer and 1.0m spaced lightweight lattice girders account for the primary support of the tunnel, later supplemented with 30 – 40cm of cast-in-place unreinforced concrete.

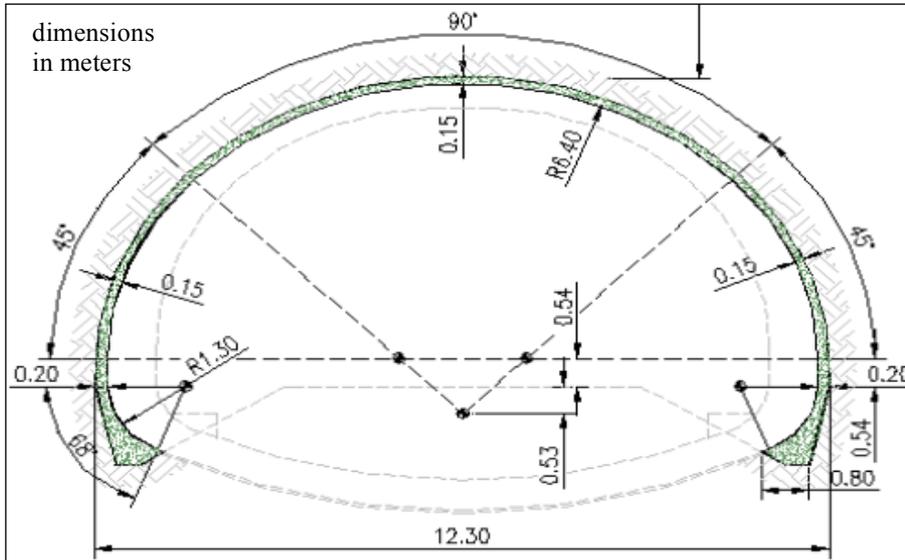


Figure 5. Cross section of a typical two lane, full face tunnel, lines B and H.

No closure of the structural ring is usually required for stability, and therefore advance rates of 2.5 m – 3.5 m per 12 hr shift are consistently achieved. After the tunnel is excavated, a cast in place invert is placed in 5 m – 6 m segments, allowing for the placement of the secondary lining in single poured 5 m segments. Figure 6 shows the two lane tunnel at Line B after placement of the invert.



Figure 6. Tunnel after placement of the invert, Line B.

## CONSTRUCTION PROCEDURES FOR STATIONS AND CAVERNS

Metro stations and caverns have been built using many techniques including: i) cut&cover slab-on-piles; ii) underground excavated main cavern & open pit excavated upper hall; and, iii) underground excavated main cavern & upper hall.

Cut&cover is – by far and large – the technique most employed and is always the obvious choice when feasible. Disturbance of urban life during construction, traffic disruption, noise and dust are among the drawbacks that yield cut&cover techniques not practical for dense urban locations.

This paper focuses on underground metro stations, cut&cover techniques shall not be addressed. In the following sections, the design and construction of four projects is briefly described to show the evolution of the construction and design procedures for underground caverns.

### Etcheverría and Villa Urquiza Stations, Line B, 2006 - 2008

These two stations belong to the extension of Line B. They were both designed and constructed during 2006 – 2008. Both have the section shown in Figure 7 and were built employing a german method of tunnelling. The construction procedure is sketched in Figure 8.

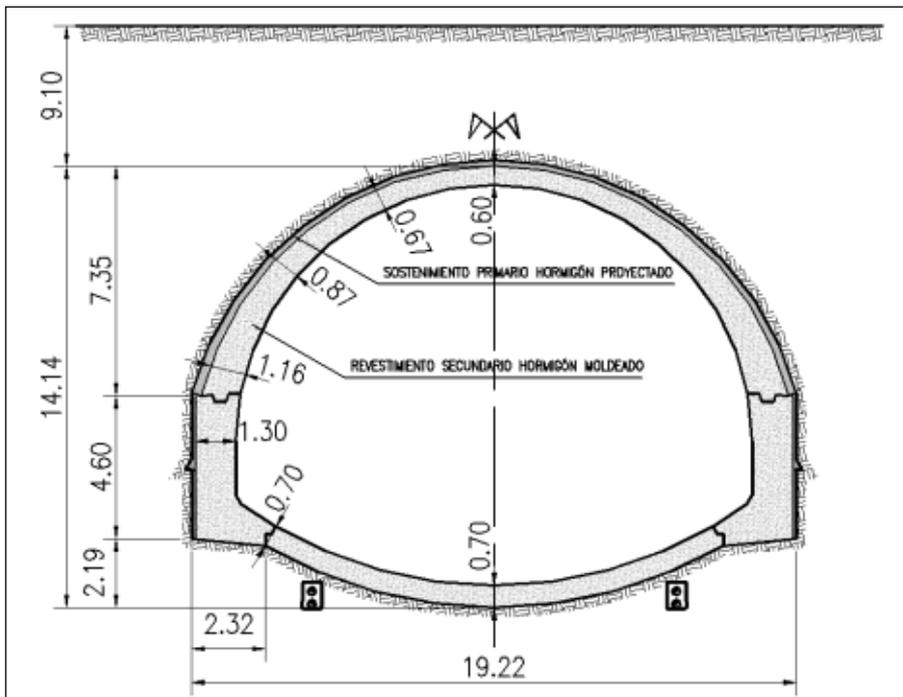


Figure 7. Etcheverría and Villa Urquiza Stations, cross section.

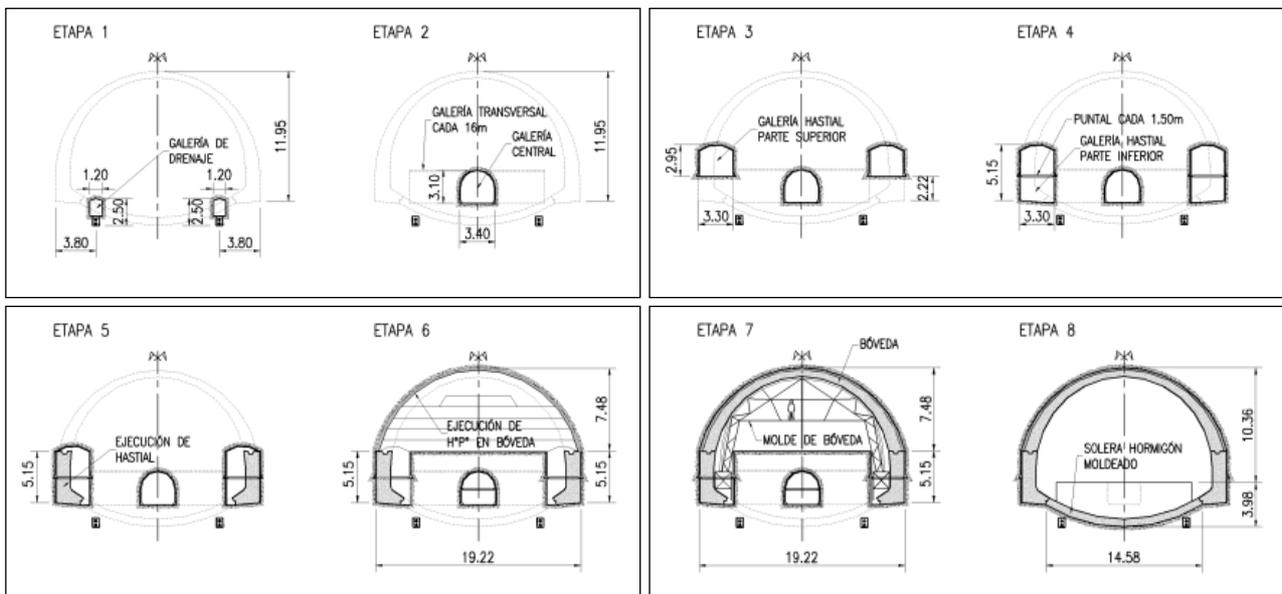


Figure 8. Etcheverría and Villa Urquiza Stations, construction procedure.

The predicted surface settlement after the complete excavation of the station was some 35mm. During construction of the first adits and pilot tunnels of Etcheverría Station (stages 1 to 3 in Figure 8) fissures were observed in the shotcrete lining of the adits, while the surface settlement exceeded 15mm, arising concern among the designers.

A numerical back-analysis of the first stages of the construction procedure employed showed that the behavior was predictable and was – in fact – a self inflicted damage. The network of pilot and access tunnels built to speed up the

cavern excavation reduced the confinement of the soil mass and produced the undesired behavior. The displacement map and the overstressing of the soil pillars is shown in Figure 9. Figure 10 shows the result of the computation of the factor of safety for an intermediate construction stage. A somewhat unexpected result is shown, namely that the soil body fails where the cavern has not yet been excavated. In this case, unconfinement produced by small access tunnels proved to be less safe than a full cavern excavation, yielding a low factor of safety 1.30. The pilot and access tunnels were fully lined and reinforced, and the construction was completed.

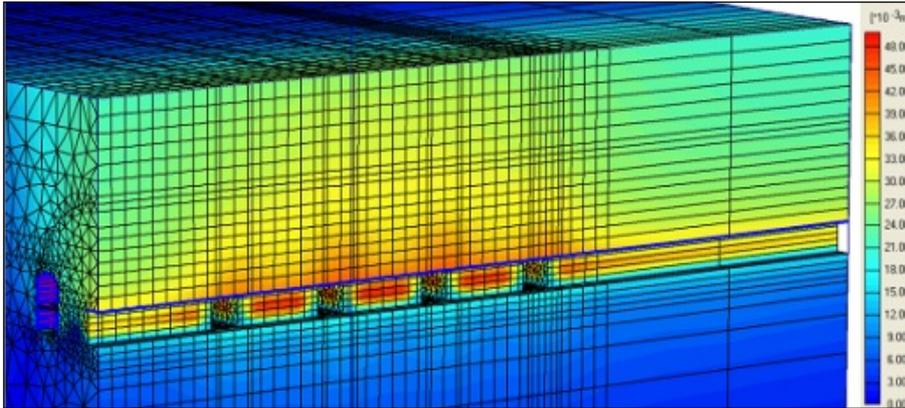


Figure 9. Displacement map after stage 4 (Figure 8).

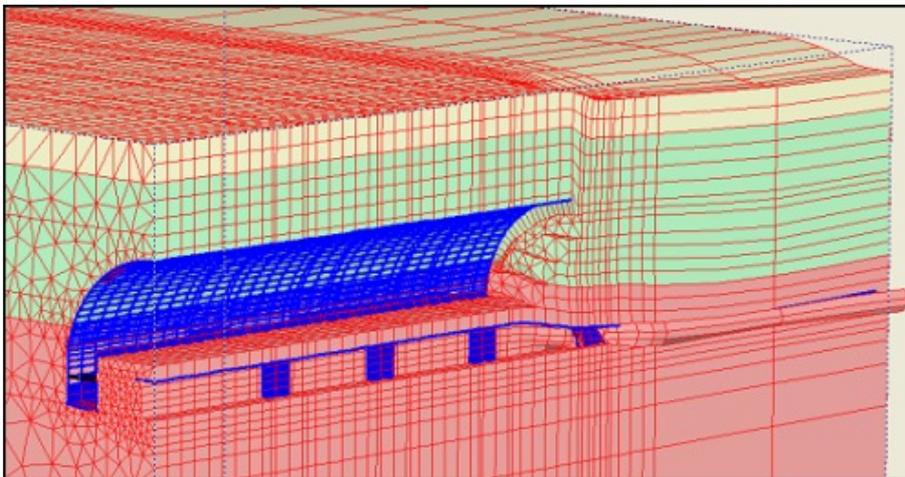


Figure 10. Failure analysis for an intermediate construction stage (stage 6, Figure 8). Failure occurs in the unexcavated area. The factor of safety was 1.30.

After this first experience in Etcheverría Station, the construction procedure for Villa Urquiza Station was changed to reduce the number and size of adits and access tunnels. In Villa Urquiza Station, surface settlements after stage 4 were about one third of those of Etcheverría Station.

### **Corrientes Station, Line H, 2007 - 2008**

To date, the flagship of underground construction is Corrientes Station (Figure 11). It is an underground cavern 14.1m high, 18.9m wide and 135m long. On top of the main cavern, a 6 m high access hall was excavated after completion of the secondary lining of the main cavern. The construction procedure is shown in Figure 12 and Figure 13. The primary lining of Corrientes Station was formed by 20 – 40 cm mesh reinforced shotcrete placed in two layers, and 1.0 m spaced lightweight lattice girders. This construction procedure allowed for a reduction of the duration of the excavation of 50% to six months, a major achievement for a NATM station excavated in soil. The extraordinary optimization achieved in the geotechnical design of Corrientes Station is apparent in Figure 11, where the primary and secondary linings are shown. The relative thickness of the two linings is self-explanatory.

Figure 14 shows an interesting detail in the excavation of bench #2 (Figure 11). The backhoe excavator is positioned transversal to the axis of the cavern, and the bench is only excavated at both ends. This particular detail allowed for the use of a single excavator for both benches #1 and #2. Benches #3 and #4 were excavated using a second backhoe excavation standing on the cast in place invert. After startup and fine tuning of the procedure, one 6m long invert segment was consistently casted each five days of construction. The shifts were 12hr only, as it was considered not necessary to maintain a 24hr operation due to the time savings obtained with this construction procedure.

Figure 15 shows a rear view of Corrientes Station during construction. The picture was taken from bench #1 when the excavation was about 80% complete. By that time, the construction of the secondary lining and interior structures was advancing fast. Notice the platforms already built at the far end. The early construction of the platforms allowed to use them to run the formwork used for the cavern crown.

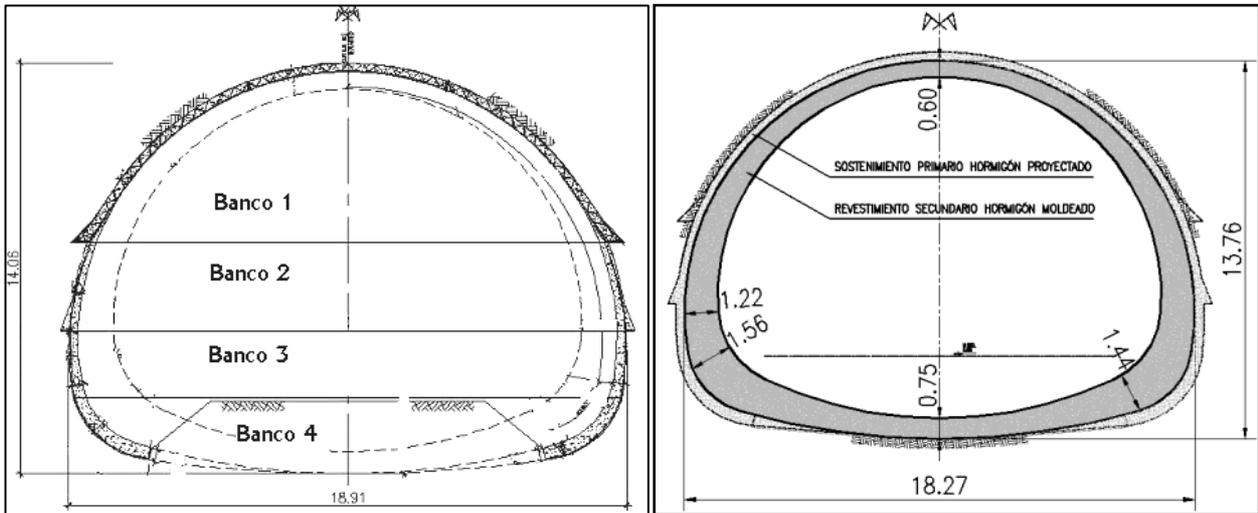


Figure 11. Corrientes Station, cross section. Primary and secondary linings.

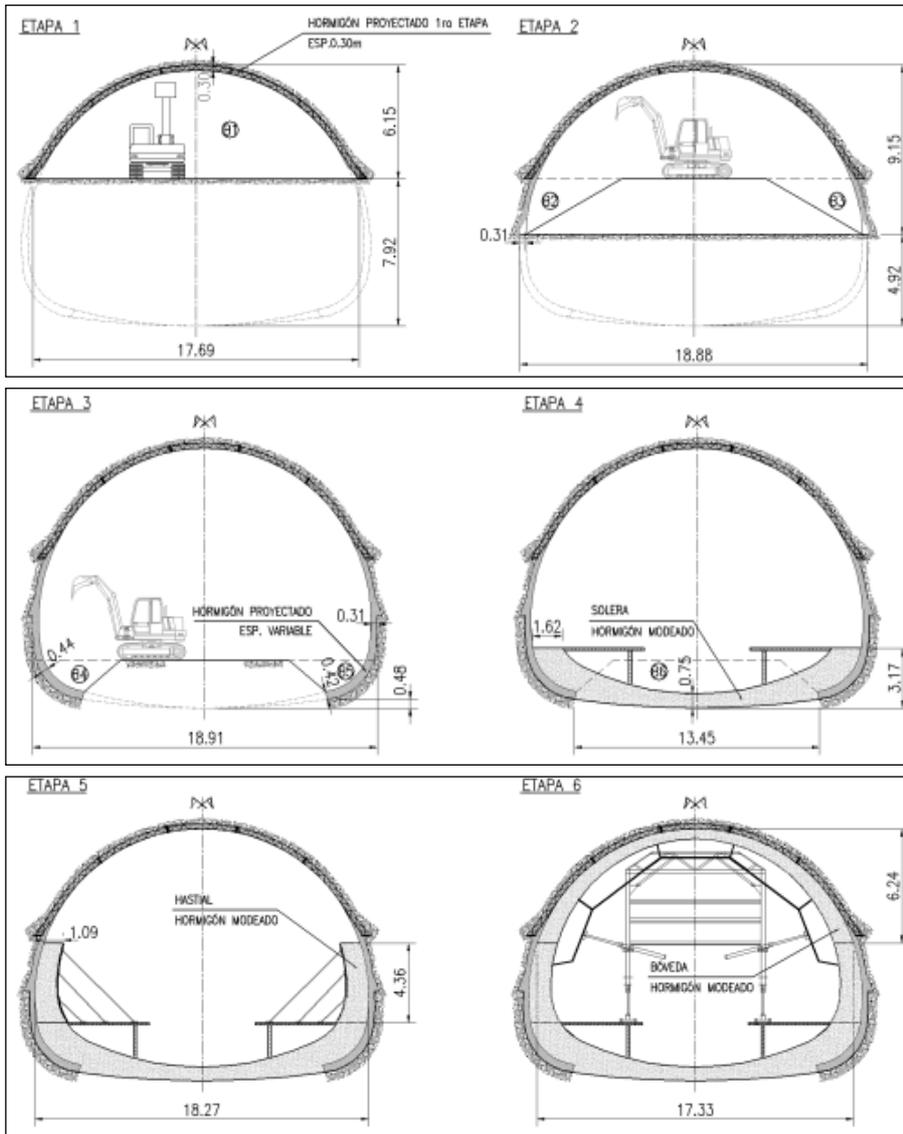


Figure 12. Corrientes Station, cross section. Construction procedure.

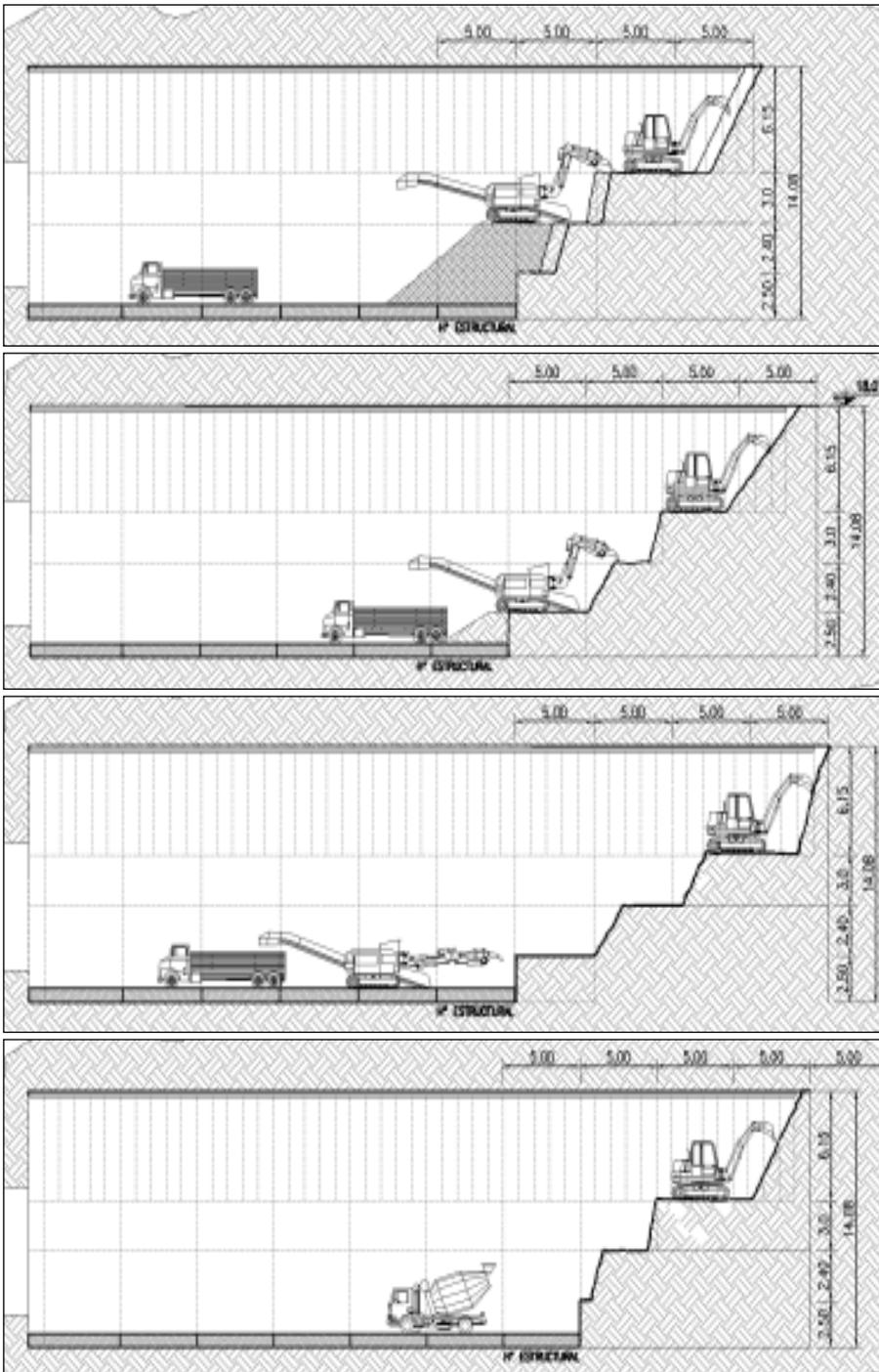


Figure 13. Corrientes Station, longitudinal section. Construction procedure.



Figure 14. Excavation of bench #2, Corrientes Station. Notice the position of the upper backhoe excavator.



Figure 15. Corrientes Station. Construction of secondary lining as seen from the upper bench (position of the camera).

### Warehouse Cavern, Line A, 2010 - 2011

The warehouse cavern in Line A is a somewhat unusual and controversial design for a NATM underground construction. The cavern is a 4-lane tunnel at one end of Line A, designed to work as a warehouse and parking place. In this particular project, it was decided to employ a one-pass approach. The resulting section is shown in Figure 16.

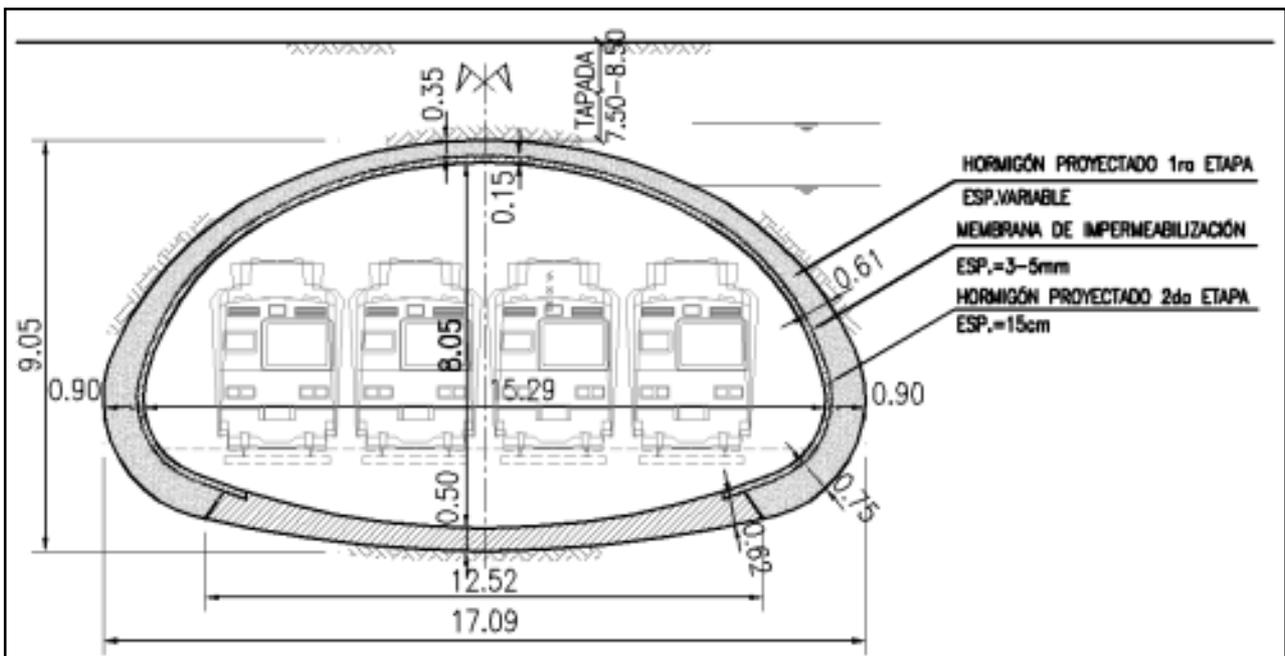


Figure 16. Warehouse Cavern, Line A. Cross section.

The construction procedure employed is based on the one employed at Corrientes Station. The main difference between the two is the fact that in Warehouse Cavern, Line A, the primary lining was thick, up to 90cm at the equator of the cavern. The construction procedure is shown in Figure 17.

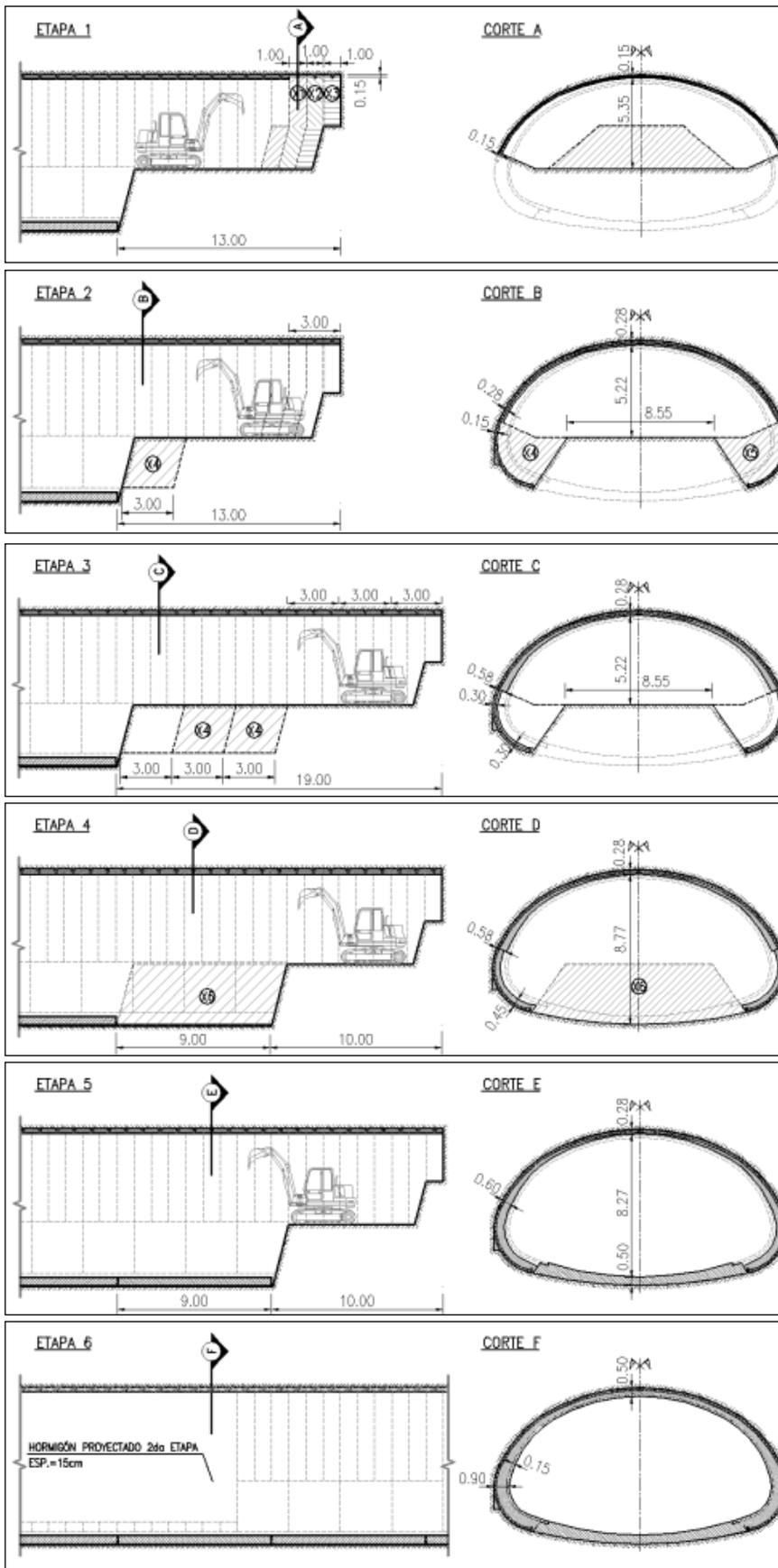


Figure 17. Warehouse Cavern, Line A. Construction procedure.

The requirement by the Metro Authority was to produce a “dry” tunnel, a difficult challenge for a shotcreted large cavern built using one-pass techniques. It was decided to employ a projected membrane, covered by a thin 15cm layer of shotcrete, as shown in Figure 16. Figures 18 and 19 show different stages of the construction of the cavern, from face excavation to project completed. Figure 20 shows the numerical model. Notice the shallow overburden.



Figure 18. Warehouse cavern, Line A. Face and bench excavations.



Figure 19. Warehouse cavern, Line A. Construction of invert and final view.

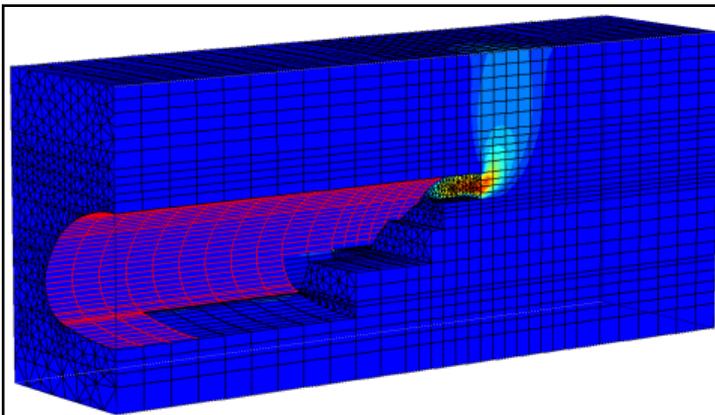


Figure 20. Warehouse cavern, Line A. 3D model employed for face stability analyses. Notice the shallow overburden of the cavern.

### Correo Central Station, Line E, 2010 – 2011

Correo Central Station is a cut&cover station belonging to Line E (Figure 21). Its construction procedure shall not be described here because it is beyond the scope of the paper. However, the project is included because the excavation of this station posed a new challenge due to the high uplift pressures acting on the invert and from a sand layer located short below the bottom of the excavation.

Most of the underground projects before Correo Central Station were excavated in the Upper and Middle Pampeano sub-formations [2]. At Correo Central Station, an underground excavation came close to the base level of the Pampeano Formation, past the contact between Middle and Lower Pampeano sub-formations [2]. At this deep level, the Pampeano Formation has never been exposed to atmosphere, it is greenish instead of brownish, has less cementation and is, in general, of significantly poorer quality for underground excavation [18]. The contact between the two substrata of Pampeano Formation is distinct and can be readily identified (Figure 22). Some six meters below the contact shown in Figure 22, the Pampeano Formation ends and the soil changes to a water-bearing coarse sand.

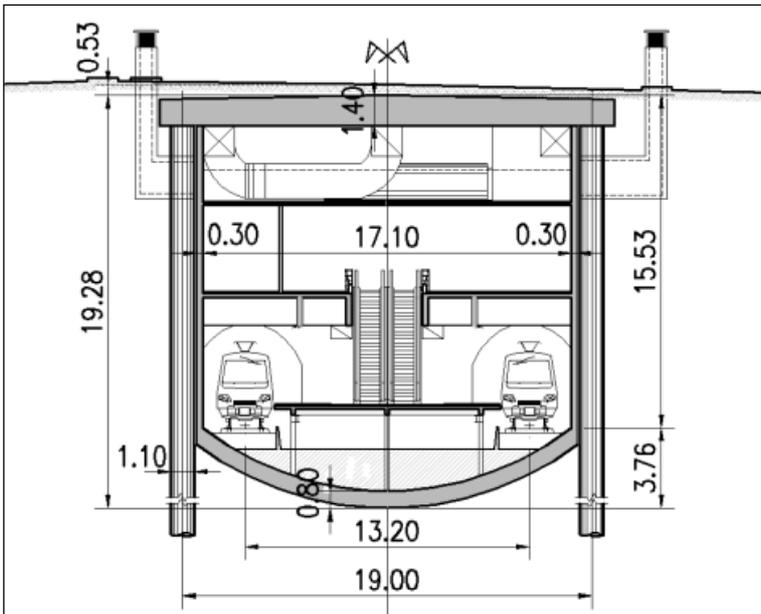


Figure 21. Correo Central Station. Cross section.



Figure 22. Contact between Middle and Lower Pampeano Formations.

The construction procedure for the excavation of the invert required careful analysis due to this challenging geotechnical conditions. The result is shown in Figure 23. First, a safe level for general excavation was determined. From that safe level a short, segmental-like excavation was employed and lattice girders were installed together with a shotcrete layer to produce a primary closure. A membrane was then placed, before the construction of the final cast in place invert. Figure 24 shows details of the construction.

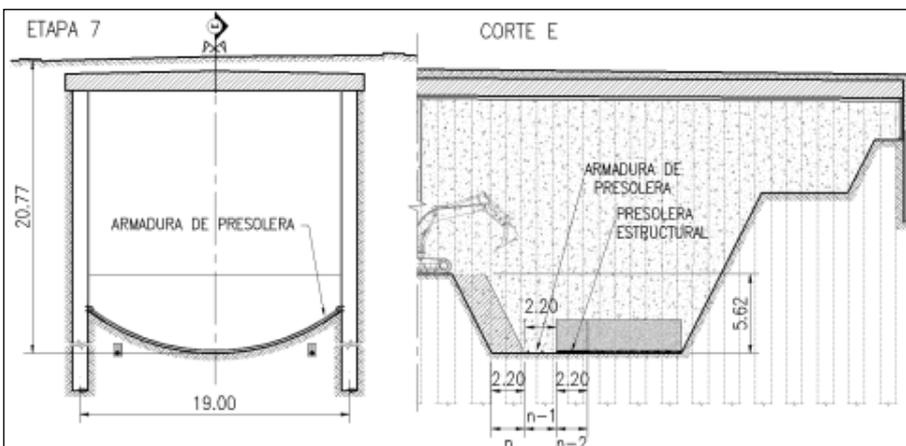


Figure 23. Construction procedure for the invert of Correo Central Station.

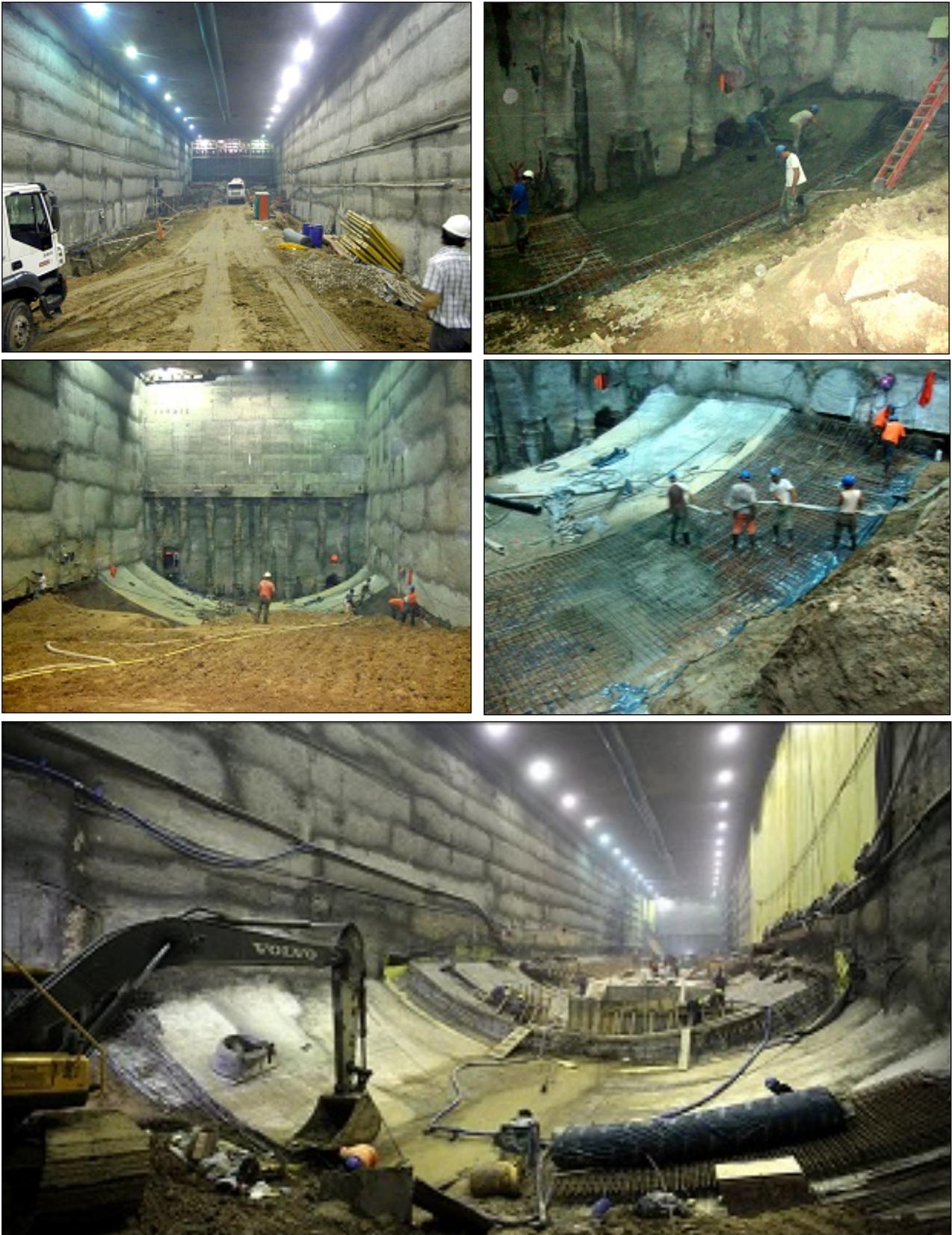


Figure 24. Different stages of the construction of the invert, Correo Central Station.

## CONCLUSIONS

Following the development of construction procedures for tunnels, construction procedures for underground stations in Buenos Aires also experienced significant improvement during the last decade. The major advancements were the introduction of shotcrete, the employment of full-face tunnelling for caverns and one-pass support. These advancements were briefly described in this paper.

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