Important Jet Grouting Applications at the Subway Line 4 in São Paulo, Brazil

G. Guattari¹,², A. Koshima¹, J.R.Lopes¹,², M.R.Pieroni¹,²
¹Novatecnas Consolidações e Construções S.A, São Paulo, Brasil; ²Terrajato Lda - Praça Francisco Sá Carneiro, 2 - 1º Floor - 1000-159 Lisboa Portugal

1. BACKGROUND

The Line 4 of the Subway of the City of São Paulo (SP), Brazil, also known as Yellow Line, is 12.8 km in length and possesses 11 stations. Six stations will be commissioned immediately, whereas the remaining stations are expected to be operating in two years. Initial subway operation tests for Line 4 are scheduled for January 2010.

Yellow Line Consortium (CVA) composed of five principal Brazilian contractors (Odebrecht, Andrade Gutierrez, Camargo Correa, Queiroz Galvão and OAS) was responsible for the construction of the Line 4 which lasted four years. Alston and Siemens were also part of the Consortium to implement the subway system. This project has introduced two significant innovations to the Brazilian engineering. First, the Metropolitan of São Paulo (Metrô – SP) adopted the use of turnkey contract for the first time in Brazil. Second, an EPB shield with an unprecedented large diameter of 9.5 m was employed in Brazil to excavate the tunnel into the Tertiary Sedimentary Basin of SP [1]. The shield used for excavation of double track tunnel advanced from Faria Lima Subway Station towards João Teodoro shaft located beyond Luz Station, totaling about 6.4 km of tunnel. Furthermore, the shield was dragged through five subway stations and one train parking tunnel with three tracks and 500 m in length previously excavated.

The main characteristics of Line 4 are its integration with the surface metropolitan railway system of the State of São Paulo (CPTM) at two subway stations, Pinheiros and Luz. In addition, Line 4 is integrated with three other existing subway lines 1, 2 and 3, which serve approximately 3 million users daily Figure 1 illustrates a schematic view of the existing subway system in the City of São Paulo, two integrated CPTM lines and the new subway stations along Line 4.

Figure 1(Schematic Plan View)

2. SITE SUBSURFACE CONDITIONS

Figure 2 shows 6.4 km of the tunnel route between the Faria Lima Station and the João Teodoro shaft excavated in the Tertiary Sedimentary Basin of São Paulo using the EPB shield. The figure
also indicates that the geological transition of the Tertiary deposits with the Pre-Cambrian bedrock is located around the Faria Lima Station. In this segment, the tunnel crossed through two well-known geological units within the Tertiary deposits, which are São Paulo and Resende Formations. The São Paulo Formation is found on high elevations, approximately between Oscar Freire Station and Higienópolis Station crossing the Paulista ridge. The Resende Formation is located between the Faria Lima Station and the Oscar Freire Station towards the suburbs and between the Higienópolis Station and the Luz Station towards downtown (Figure 2). Both formations exhibit interdigitated layers of clay and sand. In general, the Resende Formation is more resistant and pre-consolidated than the São Paulo Formation, for instance, leading to the development of greenish hard clays locally known as “Taguá”. The layers of fine to coarse sand with gravel typically present small fines fraction, as found at the Luz Station next to the Crystalline Basement where they are known as “basal sand”. The sandy strata in the São Paulo Formation possess fines fraction larger than in the Resende Formation resulting in a longer stand-up time. The clays in the upper and intermediate strata are widespread and impermeable, creating perched groundwater tables.

The remaining tunnel segment was implemented in Pre-Cambrian bedrock composed of gneiss and granite. The subsurface profile along 4.4 km of the tunnel route consisted of all material types derived from varying degrees of weathering, including sound rock, weathered rock, saprolite and residual soil. The soil-like materials are predominantly saturated micaceous silty soils, with sand and some clay, with variable SPT N-values typically increasing with depth, from 10 blows per foot to refusal. The weathered rock and saprolite preserve all geological features of the original parent rock, including schistosity, discontinuities and mineral composition, with peculiarities in the degrees of weathering consistent with the tropical environment, with emphasis on several kaolin spots [2]. This Pre-Cambrian bedrock was found to be extremely heterogeneous and unpredictable on its behavior during excavation, disclosing short stand-up time and large deformation. The groundwater presented an unfavorable behavior during the excavation of double track tunnel; although the tunnel was deep, with cover of about 20 m above the crown. Significant drawdown of the groundwater table was observed during excavation causing large settlements which ultimately stabilized with time. The geological contact between the soil-like and rock-like materials was gradual, erratic and serrated, conditions which required careful construction procedures and localized ground treatments as needed.

The Tertiary deposits and Pre-Cambrian bedrock developed significant groundwater pressures of 2 to 4 bars at the tunnel level; for instance, these conditions required a maximum face pressure on the order of 5 bars at the Luz Station. Moreover, in localized segments along the tunnel route, lines of thalwegs and paleovalleys were intercepted. For instance, Quaternary alluvial deposits were found covering the Brazil shaft site, whereas saturated gravel with coarse sand deposited in a paleovalley filled with water was encountered at Bianor access of Butantã Station.

Figure 2 (Geological Profile)
3. CHARACTERISTICS AND DESIGN CONCEPTS OF GROUND TREATMENT

The types and design concepts of the ground treatment were specific to each site as functions of the excavation method, i.e., EPB shield tunneling in the Tertiary-age deposits and NATM in the Pre-Cambrian bedrock. Nonetheless, all proposed types of ground treatment were performed from inside the tunnel because of the intensive use of land surface.

3.1. Design of ground treatment for the tunnel segment excavated in Tertiary deposits using EPB shield

The types of ground treatment were designed for the following conditions:
• Departure and arrival of the shield in subway stations. The need to insert the shield cylinder into the ground through the launching portal from inside the station required excavation of the initial segment without face pressure. Meanwhile, there was a need to eliminate the face pressure at the arrival of shield in the station. The typical solution was to treat the entire sandy stratum investigated using secant columns of horizontal jet grouting (HJG) with a diameter of 50 cm. At the launching portal, an additional measure was taken by implementing a 2-m-thick frontal wall at the end of ground treatment using HJG columns of 70 cm in diameter performed from the treatment face. In this case, the drilling length for the 360-degree HJG and for the 2-m-thick wall was 18 m [3]. This typical solution was adopted for the Higienópolis and Luz Stations where 360-degree HJG was used, and for the ventilation tunnels Brazil and Rio Branco.
• Connection of NATM ventilation tunnel with the shield tunnel. The ventilation tunnels were systematically excavated upon the passage of shield. The ventilation tunnels were generally short and were always started from the launching construction shaft after the shield passage. This condition required an internal reinforcement of the shield tunnel at the connection with the ventilation tunnel using a ring made of lean concrete. This reinforcement was built prior to the HJG, and was supposed to surround the segmented shield rings and seal the frontal wall when excavated in sandy layer (for instance, Rio Branco shaft).
• Subway stations excavated as caverns using NATM prior to the passage of shield for maintenance and dragging of shield. These stations in soil with 230 m² in section area were excavated in stages. First, two side-drifts, one on each side of the cavern, were excavated; second, excavation of the crown was performed in two stages; and third the lower section of the cavern was excavated to develop the final section of the station. In each intermediate stage, a temporary inverted arch was implemented. In more clayey soils, subject to detachment and fall of unstable soil blocks, either injected tubular forepoles or forepoles with continuous bulb were used. The ground treatment with HJG was applied to unstable sandy layers in order to provide an adequate excavation of side drifts and crown as needed. The HGJ was also one of the solutions adopted for nailing to reinforce the ground immediately ahead of the face. Exceptionally, at two stations (Higienópolis and Luz), the ground was reinforced at the foundations of the steel ribs in saturated sands where load transfer would occur. The ground reinforcement would also serve as containment for excavation of the lower section. To implement this concept, sub-vertical jet grouting was applied from the side drifts prior to the excavation of crown.
• Access tunnels to the stations excavated by NATM from large construction shafts incorporated to the stations. HJG of 50 cm in diameter was systematically adopted to protect the excavations in saturated sand layers, in conjunction with tubular forepoles used in clayey layers subject to detachment and downfall of soil blocks. This treatment concept became a standard practice and was extended to all tunnel segments with similar site conditions, including the segment in Pre-Cambrian bedrock. The typical advance of a HJG consisted of drilling holes of 12 m in length and constructing columns of 9 m in length, leaving the initial 3 m without injection to provide a cylindrical excavation of 7.2 m in length per advance. The typical indice for the construction of a HJG column or a forepole was on the order of one hour and 15 minutes, excluding rock drilling. The excavated tunnel geometry using steel pipes forepoles was similar, in which PVC pipes were installed within the initial 3 m and connected to steel pipes which would be cut during excavation.
• Connection and access tunnels excavated by NATM for pedestrians use between the new and the existing station. Used the similar treatment described above.
Tunnels for train parking consisted of three tracks and about 500 m in length, located between José Eusébio shaft and Paulista Station and excavated by NATM in São Paulo Formation. Used the similar treatment described above.

3.2. Design of ground treatment for the tunnel segment excavated by NATM in Pre-Cambrian gneissic and granitic bedrock

The tunneling by NATM allowed the start of eight independent excavation fronts once the notice to proceed was issued by the Metrô - SP. The Design Consortium, retained by the Yellow Line Consortium upon selection of the NATM, attempted to optimize the design and deepen the tunnel grade as much as geometrically allowed; this was to drive the tunnel through the rock and more competent foundation materials and minimize the need for ground treatment. Nevertheless, it happened that the ground generally required more treatment than initially estimated, including some segments in saprolite. The weathered rock and sound rock with low cover were locally treated with forepoles for blasting. Moreover, the irregular top of bedrock conformed to a serrated fashion, as characterized by the project investigations; such subsurface profile required a careful construction observation until achieving a complete penetration into the sound rock with adequate cover, in a safe manner. The type of treatment ranged from horizontal jet grouting, forepoling with continuous bulb (made of small diameter columns reinforced with steel pipes), and injected steel pipe forepoling with or without use of packers to fill the hole. Furthermore, injection with packers using standard cement and fine cement (not the subject of this paper) was locally adopted in an attempt to provide recompression of weathered rock mass and saprolite. Nailing into the ground immediately ahead of the face using HJG, or PVC or fiberglass bars, was also intensively applied; this was to maintain the stability at and in front of the tunnel face and reduce ground extrusion, and, therefore, to minimize ground and surface deformations. In some segments, there was also a need for ground reinforcement to provide sufficient bearing capacity for the foundations of steel ribs prior to the excavation of crown. An intensive use of long horizontal drains with vacuum pressure was also required to provide subsurface drainage. Another relevant characteristic of this segment was the development of significant settlement until its stabilization, despite all cautious measures taken towards construction safety.

The ground was found to be highly sensitive to dewatering, indicating generalized movements well before the influence of stress relief from tunnel excavation. Furthermore, the ground indicated to be overly susceptible to drilling and installation of jet grouting columns, despite using cement with high initial strength and a drilling sequence that provided substantial spacing between adjacent holes. The ground was also sensitive to the excavation of the upper half section, even though a temporary invert next to the excavation face and a soil buttress were provided. In addition, similar ground behavior was observed during the excavation of the lower tunnel section, with a delayed stabilization which occurred at significant distance (more than four tunnel diameters). Despite large cover above the tunnel, no beneficial arching effect was developed above the crown, as indicated by similar settlements observed at the crown and at the ground surface.

4. IMPORTANT APPLICATIONS OF JET GROUTING IN THE PROJECT

4.1. Some cases in Tertiary deposits:

4.1.1. Higienópolis Station

Figure 3 illustrates the layout of the station. The construction access to the station was made possible once the first shaft of the two secant shafts was completed, and by an access tunnel with 43m in length and excavated section of 160m$^2$, with 14m in height and 15m in width. The station was composed of two segments of caverns, one towards Paulista Avenue and the other towards República Square with 135m in length and excavated section of 230m$^2$, with 16m in height and 20m in width.

The cavern presented a cover on the order of 23m, and was topographically located on the hillside of the Paulista ridge, accommodating to the natural slope inclination. The subsurface profile indicated that the station was located at the transition between the São Paulo and Resende Formations, with the occurrence of a more clayey layer at the crown and predominance of sandy soils in the remaining cavern section.
The conceptual design called for the use of forepoles with continuous bulb in clayey layers and HJG in more sandy layers. The portal of the access tunnel was excavated in stages, including the upper crown excavation and several additional phases to excavate the lower section. As previously described, the cavern for the station was excavated using two side drifts, two stages of crown excavation and excavation of the lower section (Figure 4). The excavation work faced great difficulties with large loss of sandy soil due to groundwater infiltration, leading to large surface settlements (topographic contribution for preferential groundwater recharge). Although long horizontal drains were used, deep wells performed from the ground surface, from the inverts of side drifts, and from the temporary invert arc of the upper crown section were necessary. In addition, ground reinforcement at the foundations of steel ribs was required from the side drifts using jet grouting columns of 80 cm in diameter to consolidate the ground prior to the opening of crown and for face containment during the excavation of lower section.

4.1.2. Luz Station

Figure 5 presents the layout of the station. Three large secant shafts (42 m in diameter and 45 m in depth each shaft) were excavated to provide a composite shaft with a plan length of 80 m, which was incorporated to the station. A cavern segment of 25 m in length was added to each end of the composite shaft to complete the excavation of the station. Diaphragm walls of 80 cm in thickness, using mix type “coulis”, were constructed to serve as a retention system for the shafts. Dewatering was provided by several deep wells with submerged pumps installed at depths exceeding 50 m. The central shaft was excavated first and shotcreted, then it was lined with concrete and internally braced to allow simultaneous excavation of the adjacent shafts [4]. At a depth adequate for the implementation of ground treatment for the tunnel portal, the shaft excavation was interrupted to perform the HJG at the crown, side drifts, foundations of steel ribs and nailing into the ground immediately ahead of face. Once the excavations of the adjacent shafts were concluded, sealing was carried out and a concrete retaining system was constructed. Afterwards, excavation of the side drifts for the cavern was started to allow ground reinforcement for the foundations of steel ribs using sub-vertical jet grouting columns, as described for the Higienópolis Station.

4.1.3. República Station

This station is different from the others because it was designed and constructed between 1977 and 1983, during the construction of the existing Line 3 to allow future connection with Line 4. The bid documents predicted a single connection using a NATM tunnel to conform to the existing station. However, the CVA decided for a design modification to excavate a double track tunnel using the shield to reach the station due to numerous logistical difficulties encountered to perform
the work as initially planned. Among many problems, countless subsurface interferences were identified, which would ultimately cause adverse effects to the utility users. The existing site conditions would preclude construction works, including the excavation of two large shafts, one to remove the shield and the other to launch the shield for additional tunnel excavation. Therefore, the existing station was structurally modified to allow the shield to be dragged through it, requiring removal of columns, load transfers, demolition and excavation of a tunnel segment in NATM to allow launching of the shield to excavate the tunnel segment between República Station and João Teodoro shaft.

Since the slabs of the existing station were suited for a single tunnel, there was a need to implement ground treatment with industrious and ingenious geometry to be able to perform HJG from inside the station. Despite the use of land surface, it was possible to construct a minimal block of vertical and sub-vertical jet grouting of 80 cm in diameter. The block was approximately 3-m thickness located next to the wall of the station to form a treatment area with unusual geometry until it was able to start with a standard geometry for HJG (Figure 6).

4.1.4. Rio Branco Ventilation Tunnel
A standard solution was used for ventilation tunnels along the segment excavated by the shield. This solution was implemented in five ventilation tunnels, including Cunha Gago, Brasil, Incor, Roosevelt and Rio Branco. The tunnel portal was always developed from a shaft strategically located, while the ventilation tunnel and emergency exit (VEE) was excavated until reaching the double track shield tunnel. The ground treatment using HJG required a special construction care to consolidate the ground next to the shield tunnel. This care was necessary to minimize potential faulty adhesion between the treatment envelope and the liner of shield tunnel, or to control possible overpressure of HJG on the liner of shield tunnel( Figure 7).

4.2. Some Cases in Pre-Cambrian Bedrock
4.2.1. Morumbi Station
The range of treatment options in the Pre-Cambrian bedrock was generally plentiful. For saturated micaceous silty and sandy residual soil, the column diameter was larger than 50 cm, while for saprolite, the column diameter was highly variable and dependent on the degree of weathering of the principal minerals and its behavior when undergoing intensive jetting. In this project, the use of a hybrid solution composed of jet grouting and injected steel pipe forepoles, termed by the authors as forepoling with continuous bulb, was preferred. This type of forepoling was deemed to possess technical quality and installation time more suited for the project than the injected steel pipe forepoling with packers. The self-drilling injected forepoling systems could be compared in case there was a significant difficulty in the installation of steel pipes into the holes. Since such situation occurred in the same treated section, the decision for the treatment solution to be adopted was left to the on-site construction team.

Where hard rock was typically found, rotary-percussion drilling equipped with hammer was implemented and the ground treatment was changed to the steel pipe forepoling with packers. For ground which typically needed recompression by means of cement grout injection, several injection stages using packers were adopted, which was the case of Morumbi Station. To reduce the amount of water infiltration and hydrostatic pressure on the final liner of the cavern, an intensive injection program using fine cement was conducted. And, to optimize the construction schedule in this station, the side drift towards the Caxingui shaft located almost at the end of the footprint of the station was adjusted to allow continued excavation of the double track tunnel. This
adjustment was similar to the excavation procedure that had been used in the opposite direction from the Caxingui shaft.

4.2.2. Double-track tunnel in NATM from Caxingui ventilation and emergency exit (VEE) shaft

From the access tunnel to the Caxingui (VEE) shaft, two fronts of excavations were opened. One towards the Morumbi Station with about 850 m in length, and the other towards Tres Poderes VEE with an approximate length of 170 m until reaching a zone of mylonitized geological fault. From the fault, the tunnel continued into a rock mass with good quality.

The ground treatment, which advanced in stages of 7.2 m each, typically consisted of secant columns of HJG in the crown, and forepoling with continuous bulb when the ground was more resistant. It also included external long horizontal drainages surrounding the excavation and columns of HJG for nailing of the ground in the immediate front of the face. The tunnel in this segment was excavated in stages, including the excavation of the half section at crown with temporary invert arch and the excavation of the lower section to conform to the final tunnel section.

4.2.3. Bianor Pedestrian access tunnel in NATM towards Butantã Station

Although short, this tunnel of approximately 30 m in length with a cover of 4 m, and with various interferences between the ground surface and the crown, turned out to be one of the major problems in the project. Coincidently, the tunnel route intercepted a paleovalley filled with gravel and coarse sand with 7 to 10 m in thickness and completely filled with water, and sitting on “Taguá”. The tunnel crossed underneath a boulevard with intensive vehicular traffic which could not be cost-effectively relocated to a temporary detour road during construction. To allow an adequate tunnel excavation, the ground treatment was implemented in the upper half section using the HJG with vertical wall of jet grouting at frontal end of treatment. This method successfully replaced the previously abandoned ground treatment which consisted of driving steel pipes of 30 m in length. To excavate the lower tunnel section, ground treatment using jet grouting columns inclined towards the direction of excavation advance was adopted (Figure 8).

![Figure 8 (Sections - Bianor)](image)

5. FINAL CONSIDERATIONS

The ground treatment necessary for tunnel excavations is strongly associated with the construction method and properties of the surrounding materials.

A typical example is the excavation of a double track subway tunnel of 6.4 km in length in the Tertiary Sedimentary Basin of SP using an EPB shield of 9.5 m in diameter for the first time in Brazil. A maximum tunneling rate of 31.5 m per day was recorded, with an average value of 21 m per day.

For shield operation dictated by specific site conditions, use of jet grouting was crucial for the successful ground treatment required prior to the passage of the shield. Examples of such conditions included excavation in the region next to the existing structures which could displace due to the counter pressure applied to the ground, excavation in unstable ground at the launching portal where face pressurization could not be applied, and excavation in unstable ground at the receiving portal where face pressure had to be removed.
Moreover, the jet grouting principally in the horizontal direction was essential for excavations in saturated sandy soils of the Tertiary deposits using the NATM. Such excavations included caverns of 230 m² in section area for the subway stations, access tunnels to subway stations, connection tunnels between the new and existing stations, ventilation tunnels connected to the shield tunnel and ventilation and emergency exit for pedestrians.

In the remaining segment of subway tunnel totaling 4.4 km, use of the traditional NATM was selected to advance through extremely varying ground conditions in the Pre-Cambrian gneissic and granitic Basement. The tunnel advanced through residual soil, saprolite, weathered rock, and sound rock. The residual soil was described as saturated micaceous silt with sand, with SPT N-values typically increasing with depth from 10 blows per foot to refusal.

The NATM tunnel allowed several excavation fronts simultaneously which could be started immediately after the notice to proceed, as opposed to the shield tunneling which would require a waiting period to manufacture, transport and assemble the shield machine.

The authors believe that efficient tunneling progress was achieved by using personnel and equipment which were capable of undertaking a large amount of ground treatment in a variety of site conditions, including constrained areas in the side drifts to large areas in the crown of a NATM cavern for the stations. The ground treatment consisted of nailing the ground in front of the face, and when necessary implementing the frontal thin wall at the end of the 360-degree treatment area to provide stabilization for the excavation in cohesionless material with water flow. Reinforcement, consolidation, and containment of the region below the steel ribs for the excavation of the lower section of the cavern, installation of the invert arch, and drainage were part of the ground treatment as well. Overall, 23 sites along the 10.8 km of the subway tunnel were treated during the four years of construction, totaling over 260,000 m of drilling (12 percent in rock or concrete), and 205,000 m among horizontal jet grouting (77 percent of ground treatment), vertical jet grouting, forepoling, ground nailing and long horizontal drainage. The time required for the installation of horizontal jet grouting (HJG) and forepoling, excluding rock drilling, averaged 75 minutes which allowed NATM tunnel advances of 35 to 45 m per month.

6. ACKNOWLEDGEMENTS

The authors and Novatecna wish to acknowledge the METRÔ-SP Subway and the Yellow Line Consortium (CVA) for the permission to publish this paper. Novatecna is deeply indebted to the CVA for the trust and opportunity to undertake the most critical and challenging construction tasks in this project. The authors are grateful to Novatecna’s field personnel for the unconditional commitment to complete the jet grouting work with quality, safety and on schedule. Nelson Kawamura reviewed the English version of this paper.

7. REFERENCES - Articles in Congress:


