Design and Construction of the Luz Subway Station for the São Paulo Subway

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1. Introduction

Luz Subway Station will be the northern terminal station for São Paulo Subway Line 4. It is in the final stage of construction. The multi-level station is located in the northern part of the São Paulo downtown area. The area is densely constructed and some historic nearby buildings had to be preserved to prevent damages caused by settlements. The station is connected by underground passenger walkways to the existing Line 1 subway Luz Station, in operation since the mid-seventies, and to the Luz railway station, constructed in the late nineteen hundreds, and recently refurbished and upgraded to a major suburban train station. The station is designed for a daily demand of 110,000 passengers. All the interconnections to existing stations are important underground constructions constrained to existing structures and a dense network of utility lines. The nearby existing Line 1 station determined the depth of the new excavation to about 40m, at the lowest elevation ever reached at the São Paulo Tertiary sedimentary basin.

In order to meet the high passenger demand, large volumes of underground space were required. Concourse, escalators, part of the platforms, technical and operational rooms are located in a 84-m long, 42-m wide open excavation consisting of three secant shafts. The reminder of the platform length is accommodated in 19.5-m wide, 252-m² shotcrete supported tunnels. The ground mass consists of water-bearing sand interbedded with stiff clay layers from the Resende Formation. The shotcrete-supported shaft had a non-structural slurry wall, which allowed dewatering to be limited to the lower aquifer, as required for shaft bottom and tunnel excavation stability. Description of the construction sequence design is described and ground movements measured during shaft and tunnel excavation are presented and analyzed.

2. Geological Aspects

The station was excavated in the domain of the São Paulo Sedimentary Basin. São Paulo Basin is a depression with colluvial, alluvial and lacustrine sediments filling of Lower Tertiary age (Paleogene), related with a past drainage network not much different from the present one, with a relatively rough paleotopography. The lower sediments, including conglomerates, sandstone and claystone, represent alluvial fans and deposits of a braided fluvial system, whereas the upper sediments, including similar lithotypes, are related to a meandering fluvial system [1].

The depression of tectonic origin is irregular and its development was strongly influenced by reactivation of weakness zones of the basement. Sandy sediments from the Resende Formation (yellow silty sands) occur at the construction site, interbedded with grey greenish stiff clay locally known as taguá. Sands from this area are predominantly fine to medium (81%) with localized horizons of gravel (about 1%). According to Rocha [2], average clay content is 10% and average fine content is about 17%, resulting in low cohesion and permeability in the range of 5 x 10-6m/s.
With respect to the tunnels, significant stratigraphic differences were observed in cross sections through the north and south portals. Resende Formation sands predominate in the central vault area and almost all over the side drifts at the south portal. At the north portal, sands occur at the roof, whereas stiff clay predominates in the side drifts, except for the invert arch region. These characteristics were responsible for differences in behavior during tunnel excavation.

3. Lay-Out Design

The main volume of the excavation consists of three secant cylindrical shafts. The internal diameters are 38.60m for the central shaft and 42.00m for the outer shafts, with 37.4m depth. Passenger circulation will take place mainly inside the shafts, which accommodate part of the platform. The remainder of the platforms will be located in two tunnels (North and South) excavated from the shafts. The tunnels, excavated according to NATM principles, have 254 m² cross section area, 19.51m width, 16.08m height and 18.50m overburden.

In addition to the shafts, important excavations are also the large walkways for passenger transfer to the existing Luz Metro Line 1 Station, to the CPTM Luz Suburban Train Station (18.3m wide for 22,000 passenger/hour), and the entrances from Casper Libero and Brigadeiro Tobias avenues. The CPTM passenger transfer walkway was excavated less those 3m above the previously excavated platform tunnels, and the construction sequence was carefully designed to minimize impact on the partially completed tunnel support and shaft structures.

The relative dimensions of the walkways are shown in Fig. 1, which shows the plan view at elevation 726.37m. A longitudinal section is shown in Fig. 2, including the running tunnel, platform tunnel and the 6-level shaft structure.

4. Dewatering System

Major shaft and open-face tunnel excavations were carried out in cohesionless sand as described in item 2. In addition to the raveling ground characteristic, the combination of perched water levels with high piezometric heads required a dewatering system. However, the combination of excavation at great depth with the occurrence of compressible alluvial deposits at the surface imposed limits to prevent settlement damage to near buildings. Experience with other similar works [3] have shown that significant settlement may occur at distances up to hundreds of meters from the dewatering operation, which could be disastrous in such a densely occupied area. The dewatering system, designed for the purposes of shaft bottom and tunnel face excavation stability, was restricted to the lower aquifer and left the upper water level untouched. The presence of clay layers was providential for this purpose. High-rise, historic and heritage buildings exist at close distance to the construction site. In particular, two 19th century hotels were located at ~30 m from the excavation and had to be preserved.
Only the lower sand layer was drained by means of seventy deep wells spaced at 5.0m. The 44.2-m deep wells were equipped with vertical submersible 10-cm diameter turbine pumps, and consisted of 0.30m diameter perforated tube and 0.15m diameter filter tube. The ring space was filled with well-graded sand. For monitoring purposes, 36 stand-pipe piezometers were installed. The wells were designed to work primarily under gravitational conditions. However, they were designed for possible vacuum application, depending on the performance observed in piezometer readings.

Previous experiences of excavations in the neighborhood for both Lines 1 and 4 showed some difficulty to dewater the intermediate sand layers. So, additional local horizontal drains with vacuum were also included in the design for the tunnel excavation stage. Total discharge of 75m³/h was measured at the beginning of operation and 54m³/h after stabilization. The performance of the system was satisfactory.

5. Excavation Methods

5.1 Shafts

The need for construction simplification and safety with respect to the preliminary design was the most important motivation for the modifications introduced in the final design. In the preliminary design stage, a single 40-m diameter shaft had been adopted with a diaphragm wall. Escalators were accommodated in several inclined large cross section tunnels to be excavated outside the shaft perimeter in saturated sand. The 3-secant shaft concept adopted eliminated the need for those tunnels and decreased the length of the large span platform tunnels. Overall construction risk and schedule were decreased.

The combination of thick sand layers and high water pressure required a non-structural diaphragm wall to be installed before the excavation and shotcreting operations.

The design of the shafts followed well succeeded experience of other shotcrete supported shafts. Axisymmetric non-linear finite element models simulating all the excavation and support installation stages were used for design. Exhaustive studies and analyses were carried out before design. Special emphasis was given to the evaluation of possible scale effects, which could compromise previous experiences in smaller shafts. As a matter of fact this shaft was unprecedented in designs for the São Paulo Metro both in terms of dimensions and adverse geotechnical and hydrogeological conditions.

In combination with the dewatering system described in the previous item, the non-structural slurry diaphragm wall (0.80m thick, characteristic strength fck = 4MPa) along the excavation perimeter contributed for the stability during excavation. Pre-drilled holes between panels were adopted in order to decrease vertical deviation.

Excavation started at the central shaft with 1-m round staged in 8 sectors. After excavation, welded mesh reinforced shotcrete was installed as structural temporary support. Shotcrete thickness increased with depth, varying from 0.07 to 0.50m.

After completion of the excavation and shotcrete support, a PVC waterproofing membrane and protecting geotextile were installed, followed by conventional reinforced concrete (fck =35MPa) final lining structure and transversal beams. Due to the structural separation between primary shotcrete and final concrete lining, design criteria by the São Paulo Subway Company established that no contribution from the primary shotcrete support should be taken into consideration for long-term safety. Final lining thickness considering full water pressure ranged from 0.50 to 1.40m.

After completion of the central shaft permanent structure, the extreme shafts were excavated following the same sequence.
In order to avoid unbalanced loading to the central shaft structure, difference in excavation depth at the two shafts was limited to 3.0m. Excavation stages are shown in Fig. 3. Excavation and final lining construction for the three shafts were completed in 18 months.

Displacements caused by the excavation were monitored by means of inclinometers, shaft convergence, surface and deep settlement readings. The excavation process was followed by a team of professional from both construction and design, responsible for permanently evaluating safety conditions based on ground mass direct observation and instrumentation results. No incident was observed.

5.2 Tunnels

Tunnel excavation design was carried out according to previous experiences on shotcrete supported tunnels excavated in similar sands and stiff clays. Detailed finite element method simulation of all excavation stages was providential for construction sequence design. Large dimensions of the cross sections shown in Fig. 4 required excavation staging as shown in Fig. 5. Final dimensions were based on safety requirements and operational limitations of excavation equipment available. Support structure consisted of light steel lattice girders, welded steel mesh at the invert arch and 0.45m thick shotcrete. After a PVC waterproofing membrane, 0.70m thick conventional concrete lining was installed. Similarly to shafts, no structural contribution from primary shotcrete could be considered for long-term safety, also according to São Paulo Subway Company design criteria.

Large volumes of sand intercepted by the excavation were treated with horizontal jet grouting for stability reasons. Besides that, frontal jet grouted bulkheads were created at 10m intervals in order to prevent longitudinal flow. Dewatering wells were installed alongside the tunnels, and because of geometrical limitations imposed by the running tunnels, no wells could be installed in a frontal section.

Construction started by the side drifts with 0.80m excavation rounds. Minimum distance between excavation faces of the two drifts was 10.0m. After completion of the side drifts, double lines of jet grouted columns (\( \phi = 0.80m \) diameter) were installed at their toes as shown in Fig. 5. The purposes of these columns were twofold: (1) improving the sand layer foundation conditions for the large span arch after top heading excavation, and (2) sealing the sand layer against flow of water not collected by the dewatering system, and stabilization of the sand wall during bench excavation.

After completion of the upper part of the cross section, the first stage of bench excavation took place, simultaneous to side drift shell demolition, followed by shotcreting of the temporary invert.
arch in 1.60m rounds. After this, final bench was excavated and the final invert arch was shotcreted. The excavation round length was 2.10m.

6. Behavior During Excavation

Contrary to conservative expectations at the design stage mainly due to the large dimensions of the excavation, the construction went through in a generally favorable condition, except for minor incidents unrelated to ground mass stability. For example, an unknown steel pile, probably abandoned during construction of Line 1 station 30 years earlier, compromised the sealing capacity of the diaphragm wall during shaft excavation. The problem was easily overcome with local jet grouting. Other problems were due to inevitable minor infiltrations.

With respect to settlements, a general comment is that about 10% of the final values are due to dewatering. Settlements due to ground treatment are in the range of 2.0% of the final values. Jet grouting treatment and systematic excavation face nailing also contributed to decreasing ground movements around the tunnels.

Fig. 6 shows the results of central shaft convergence measured at three different elevations along three directions. Maximum displacement was less than 40mm, representing less than 1/1000 of the diameter. Displacements decrease with depth because of the positive contribution from the non-excavated bottom. A concrete ring at surface elevation prevented the overall maximum displacement to occur there.

The 25-m long tunnels are too short as compared to their 19.5m excavation span. Usually, settlements start to be measured about two tunnel diameters before and stabilize about 2 diameters behind the excavation face. In relatively short tunnels it is expected that full settlement expected for a long tunnel does not occur, and that maximum settlement takes place about tunnel mid-length. In addition, the positive contribution from the completed shaft final structure decreased settlement at the portals.

Fig. 7 presents the longitudinal distribution of deep and surface settlement devices installed along tunnel axes. The general trend of maximum values at mid-length of the tunnels is observed, except for deep settlements at chainage 15068m of the south tunnel. The local minimum is due to the proximity of the instrument to one of the stiff jet grouted bulkheads described in section 5.2 to prevent the hydrogeological hazard more pronounced in the south tunnel. Worst geological conditions in that tunnel described in item 2 are also reflected in greater settlements than in the north tunnel.

At Hotel Federal, one of the historic buildings, settlement of the pillar located 6m from the shaft excavation edge, settlement due to dewatering and excavations reached 51mm. Maximum differential specific settlement was 1:522.
The evolution of those settlements with time is shown in Fig. 8 (deep settlement) and 9 (surface settlement). For the south tunnel, maximum deep and surface settlements were less than 60 and 50mm, respectively. For the north tunnel, those values are 30 and 25mm. No damage was observed at any nearby building or utility line.

Due to utility lines and other urban interferences, a number of settlement devices could not be installed and complete settlement troughs could not be measured at most cross sections. However the positive effect of the side drifts during the 15-m central span excavation can be observed in Fig. 10 (deep settlement) and 11 (surface settlement). At chainage 15083m, south tunnel, deep settlement at the center is even lower than those above side drifts. The positive contribution of pre-existing tunnels to decrease settlements has been previously reported [4].
7. Conclusions

The excavation of the major Luz Station for the São Paulo Subway was successfully completed. The excavation consisted of a 79m long, 40m wide, 38m deep shotcrete supported shaft and 19.41m wide platform tunnels. In spite of adverse geological conditions characterized by about 40m depth with thick sand layers below high water table, surface settlement was limited to 50mm above the most unfavorable tunnel and 25mm above the other one. High-rise and historical buildings at the surface were not affected by construction and no damage was observed.

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9. References


