Segmental concrete tunnel lining design for two 6.9 m EPB TBM machines.

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ABSTRACT: Precast segmental linings for shield driven tunnels are designed as both initial ground support and final tunnel lining in modern projects. The parameters of tunnel lining such as dimensions, thickness and strength of materials are related not only to ground-lining interaction, but also to construction conditions. In current case, both conventional steel cage and steel fiber reinforcement were used in segmental concrete lining. The proximity of two 6.9 m EPB TBM machines and the local geology guided the choice of the type of reinforcement used. This paper presents unique technological aspects adopted in the ring design as well as the geological and the track way conditions that have led to some changes unforeseen in the original design.

1 INTRODUCTION

São Paulo is one of the biggest cities in the world, with around 20 Million people living in the city and in the suburban area. The city faces great mobility problems and, in recent years, the government has been investing great amounts on the city’s public transport. Figure 1 shows the location of the city of São Paulo.

The Line 5 Extension is the major government investment for public transport currently in progress in São Paulo/ Brazil. It will connect the south area of São Paulo to its central area. The whole extension has 11 kilometres of line, including 11 new stations and a new parking yard. The first stretch of the Line 5 extension consists of two single tunnels, each of which is almost 5 kilometres long. Both of these tunnels will be executed by two EPB TBM machines (Silva et al, 2013).

The two EPB machines will bore together more than 300,000 m³, and the expected average productivity is 15 m/day, per machine. The inner tunnel diameter is 6 m whereas the TBM outer diameter is 6.90 m. The propel cylinder is composed of 16 pairs of jacks that provide a total pushing strength of 60,800 kN. The cutting head potency reaches 1,600 kW and transfer a torque of up to 4,682 kNm.

Almost 6,000 concrete rings will structure the tunnel lining. These rings will be formed by 6 pre-cast segments and 1 key, reinforced in 70% of the tunnel with steel fibers and in the remaining stretch with steel frames. Its truncated cone shape allows 300 radius curves by changing the key piece location.
2 TUNNEL ALIGNMENT

The machines begin excavation from an access shaft built under Avenida Adolfo Pinheiro, near the Adolfo Pinheiro Station.

Immediately after departure, the machines leave the axis of the avenue and pass under an old theatre, toward Avenida Santo Amaro. In this stretch, the machines also go underneath the foundations of some close existing buildings, which required further studies in terms of loads on the rings. On the next page, Figure 2 shows a critical section in terms of tunnel proximity with building foundation.

Once on Avenida Santo Amaro, the machines will first reach the Alto da Boa Vista Station, and, in sequence, the Borba Gato and Brooklyn Stations. Along this stretch, the minimum coverage over the tunnel is close to 15 m, while the maximum is close to 25 m.

After Brooklyn Station, the machines cross an important avenue with heavy traffic which is under a valley. In this passage, the cover of the tunnel is close to 20 m, 8 of them consisting of very soft alluvial sediments.

After crossing, the ground cover increases rapidly, reaching a maximum coverage close to 30 m. Along this path, no special situations were considered on the rings design.

Before leaving the axis of Avenida Santo Amaro, the machines go through a conventional tunnel, designed to have track-switch equipment. A crossing through the Campo Belo Station is foreseen before the machines head toward the Bandeirantes Shaft, where the final breakthrough occurs.

Along this final stretch, the machines will cross blocks essentially occupied by small houses. There, two possible situations of interference with pile foundations are expected. Throughout the whole line, the distance between tunnel axes varies between 12 and 25 m.

3 GEOLOGY AND GEOTECHNICAL ASPECTS

Most works occur in sedimentary soil in the São Paulo basin, which can be basically divided into two main formations. The first formation, also known as the Resende Formation (Riccomini, 2004), is characterized by silty sands and silty clays, and occur below the second formation, known as the São Paulo Formation (Riccomini, 2004), which is characterized by sandy clays and clayey sands.

The Resende Formation is also characterized by overconsolidated clays, with some pronounced plane joints and very low permeability. In the region where tunnels were excavated, thin sandy layers occur with high water pressure.

In the region of São Paulo, the basement has gneiss-shape features with varying degrees of rock weathering. The saprolite and its derivative products are composed essentially of quartz, feldspar, illite and Muscovite. During the studies were recognized:

- Mature residual soil (the original rock structure is hardly recognizable);
- Young residual soil (the original rock structure is recognizable);
- Saprolite, altered rocks;
- Crystalline consisting of gneiss, little weathered on average, with very high change bands.

Recent studies, i.e. Cecilio Jr. (2009) and Futai et al (2012), have shown that these materials are very heterogeneous. The latter emphasize the small amount of data and information available regarding these materials.

Also, uniaxial compressive tests carried out in weathered gneiss showed that strength can easily vary from 5 to 60 MPa according to the content of biotite. On those tests, mostly strength parameters can be assigned to the discontinuities and not to the rock mass itself.

Such information warns of the possibility of unpredictable behaviour of these materials, which can induce asymmetric loads on the lining, leading to a conservative final design.

Local alluvial deposits range from silt clays to pure sands with grains, predominantly quartz and feldspar. Organic materials are often presented in those layers. These sediments stay superficially and with an average thickness of 6 to 8 meters. These layers occur in local areas associated with channels and river crossings.

Figure 3 shows a simplified geological section along tunnel alignment.
4 TUNNEL LINING DESIGN

4.1 Lining geometry

The segmental line has an inner diameter of 6.0 m whereas the outer diameter is 6.6 m. Its medium length is 1500 mm, with a conicity of 42 mm to allow a minimum curve radius of 300 m.

It is designed with 5 trapezoidal segments plus key segment, which allows for having three thrust cylinder pairs per each segment and one pair in the key segment.

The maximum segment weight is 45 kN while the total ring weight is 222 kN. Figure 4 shows an overview of the tunnel lining. Figure 5 shows a scheme of the ring assemblage.
4.2 Structural Design

Structural design was developed in order to ensure not only the final tunnel security but also to ensure segment integrity during the stages of manufacturing, storage, transport, assembling, machine advance and grouting.

The studies lead to three ring types of precast segments. Two types have steel rebar reinforcement. One of them is designed for crossing under building foundations, whereas the second was designed for stretches with a short distance between tunnels. The third precast type has only steel fiber reinforcement.

Concrete final strength was designed to have a strength of 45 MPa under compression. For the early ages, a compression strength of 10 MPa for demolding and 15 MPa for storage was specified.
For the steel fiber reinforcement ring, a final mean tensile strength of 3.8 MPa was specified, along with 1.4 MPa for demolding and 1.8 MPa for storage. For services analysis, a post-cracking residual flexural strength of 0.7 MPa was specified. Those parameters were achieved using fibers with an aspect ratio (l/d) equal to 80 (60 mm of length and 0.75 mm in diameter), hooked ends, and glued in bundles.

The rings are designed for shield front pressures up to 6 bar and 7 bar during backfill grouting. The maximum thrust force expected is 60,000 kN, being considered a maximum thrust cylinder eccentricity equal to 20 mm in the design.

4.3 Inserts and Accessories

Radial joints were conceived to be trapezoidal and to have guide rods. Only one line of bolts was designed in order to assure assembling in some special cases, such as machine departure in opened pits.

Circumferential joints were designed to have dowels with maximum pull out resistance equal to 100 kN. Shear resistance is also equal to 100 kN. Figure 6 shows a schematic view of the dowel used.

Watertightness is ensured with anchored EPDM gaskets along the whole perimeter. These gaskets are designed to resist more than 40 bar of water pressure under perfect gasket contact. Assuming an offset of 15 mm and a gap of 5 mm, the system ensures tightness for water pressure up to 10 bar. Along the whole stretch, a maximum of 40 m of water pressure, or 4 bars is expected. Figure 7 shows some design details of the guide rod and anchored gasket specified in the lining design.

Finally, wooden pads were foreseen in circumferential joints to avoid contact damage between segments during ring assembling.

4.4 Experimental laboratory test

In order to verify the effectiveness of the designed solution a research program was developed by performing experimental tests on full scale specimens.

A bending test is being carried out in order to analyse the flexural performance of fiber reinforcement elements and even the ordinary reinforced ones. A point load test is being developed for verifying structural performance during the construction phase. A similar procedure was presented by Moccichino et al (2010), as shown in Figure 8. To date, the whole structure has gone through a calibration process, although no results have been produced.
5 FINAL REMARKS

Every segment that is produced is assigned a unique reference identification code by the factory’s automated control system. This code can be used to identify all the specific components contained within each segment, as well as detailed information on vibration and curing. This procedure allows for segment identification in the tunnel, as the same barcode can be scanned at the point of installation. It can also be used to build a final 3D model for every segment positioned.

Tunnelling begins on November/2013. Until then, approximately 750 segmental rings are expected to be produced. Figure 9 shows an overview of some of the rings already produced.

REFERENCES

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