The construction of the tunnel Kennedy in Santiago de Chile. A major challenge of an urban tunnel in soils

J. Kuster & R. Núñez
Costanera Norte, Santiago de Chile, Chile

E. Chávez, JM. Galera & D. Santos
Subterra Ingeniería, Madrid, Spain

ABSTRACT: Costanera Norte is an urban expressway concessionary in Santiago de Chile connecting its Western and Eastern sides. To enhance this connectivity several measures were necessary, including four new tunnels. The most singular one is 'Tunnel Kennedy', that has a length of 1,166 m with two sections (4 and 5 lanes), 17.45m and 20.95m wide, and 11.8m height. The tunnel was excavated in alluvial gravels, partially under the water table. The main challenges were: its section over $250 m^2$, the ground conditions (requiring SEM), its urban environment and low overburden (10 to 16m). The support consists in a 3cm sealing, HEB steel arches spaced 1.0m and 27cm shotcrete. Systematically buttress and occasional canopy tubes have been used. A concrete lining (20cm to 40 cm, depending on the water column), was added, and a third layer 10cm with polypropylene fibers for fire protection. The excavation took place from October 2014 to February, 2017.

1 TUNNEL DESCRIPTION

The tunnel is located in the NE of Santiago de Chile, close to the financial centre of the city. The whole tunnel alignment is parallel to the current Kennedy Avenue, mostly below a golf course called "Los Leones". Figure 1 shows the location of the tunnel.

Figure 1. Location and layout. Kennedy Tunnel.

The access to both portals is solved by mean of two trench structures composed by piles, crossbeams and slabs. At the beginning portal, the road configuration at the surface has evolved, from a roundabout to a bridge and several connections with high complexity.

The typical cross section of the tunnel provides four lanes, 3.5 m wide each one, and two shoulders of 0.75 m respectively. Below the pavement a maintenance gallery is provided. The inner dimensions with respect to the lining are 17.45 m wide and 11.30 m height.

At the beginning of the tunnel, there is a connection lane so for around 50 m, a special section of five lanes have been constructed. For this section, the inner dimensions are 21.0 m width and 11.8 m height. An additional section was also envisaged, which was called “4.5 lanes”, designed in order to soften the transition between the sections of five and four lanes. Figure 2 shows the geometrical definition of the two existing sections of the tunnel.

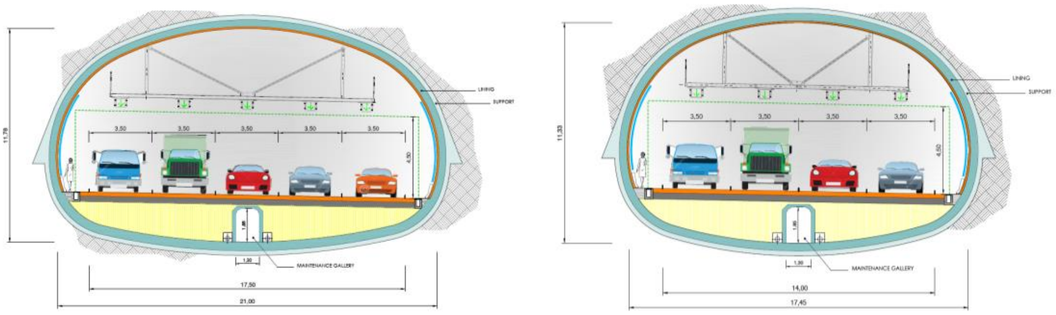

Figure 2. Functional sections (4-lanes and 5-lanes). Kennedy Tunnel.

As mentioned before, three emergency exits have been constructed for the evacuation plan of the tunnel. The first one is located close to the access structures at the portal. The second and third ones were solved by shafts of 8,3 m diameter from surface and pedestrian gallery connections.

2 GEOLOGICAL AND GEOTECHNICAL CHARACTERISTICS

The entire tunnel has been excavated in the well-known alluvial materials composed by gravels and pebbles of the second and first deposition of the Mapocho River.

In the lower part of the tunnel, the presence of weathered andesites and lutites of Abanico Formation, was expected between Km 1,046 and Km 1,050 in the invert of the tunnel section. However, just some andesite blocks have been excavated

In terms of the soil parameters, Table 1 shows strength and deformational parameters considered for the support calculations.

Table 1 Strength and deformational parameters of the soil in the Kennedy Tunnel.

SOIL PARAMETERS	GEOTECHNICAL UNIT		
	ANTHROPIC FILL	2nd DEPOSITION	1st DEPOSITION
γ (kN/m^3)	17,0	22,5	22,5
Cmax (kPa)	10	25	35
φm (°)	33	45	48
Ec (kPa)	20.000	42.000xZ0,5(Z<17) (*)	42.000xZ0,55(Z<17) 55.000xZ0,53(Z>17)
v	0,30	0,25	0,25
Ψ (°)	0	12	12
K_0	0,43	0,70	0,9-0,0533X(Z-6)(6<Z<18) 0,26 (Z>18)

Z = Depth with respect to level ground measured in meters
(*) In gravels a minimum value of Ec=100.000 kPa is considered to a depth of 5 m

The water table is located at 623 MASL. Accordingly, it is placed above the tunnel from its beginning until approximately Dm 1350. The water table passes through the tunnel from the level of the top section to the level of the invert in the Dm 1800. From this point, it continues below the level of the invert until to the end of the tunnel.

Figure 3 includes a synthetic geological longitudinal section of the tunnel in which the water table has also been highlighted.

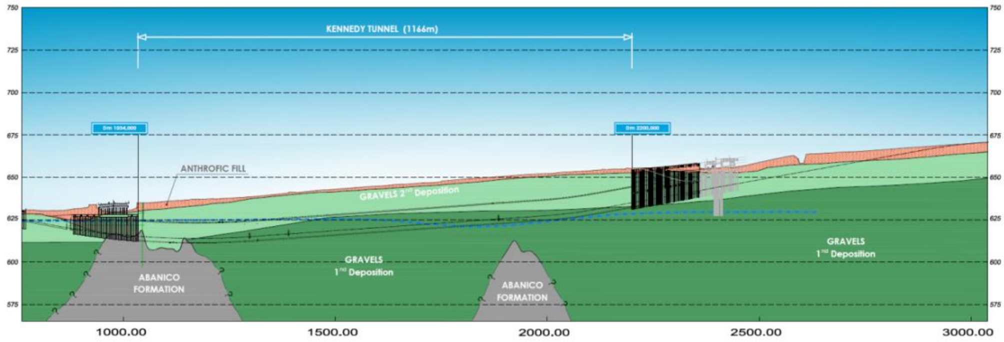

Figure 3. Geological section of the tunnel.

During the tunnel construction, the water table was really encountered at 615 MASL, eight meters below the foreseen height. At the top heading excavation, only few infiltrations were registered, probably due to the watering system of the golf course and seasonal rains. At the excavation of the bench a continuous water flow has been registered, but without creating stability problems due to the presence of water.

Santiago de Chile is located at a high seismicity area, According to the Chilean standards the seismic acceleration to be considered are 0.3g and 0.15g respectively as horizontal and vertical acceleration.

On September 16th, 2015, an earthquake of magnitude 8.4 Mw was recorded in the region of Coquimbo. Consequently, an intensity VII in the Mercalli scale was registered in Santiago. Once tunnel inspection and monitoring analysis were performed, it was determined that this event did not affect the structure.

3 SPECIAL DESIGN REQUIREMENTS

Regarding the design of the tunnel, the following technical aspects were crucial during the development of the project:

- To minimize the subsidence induced at surface,
- To reduce traffic impact during construction, and
- To minimize the maintenance costs associated to water pumping during exploitation.

The minimization of the induced settlements in surface was a key aspect of the design. This is a consequence of the alignment of the tunnel, that goes nearly in its entire length, below a private property as the golf course “Los Leones” and tangent to Kennedy Avenue. Any damage over both elements must have been strictly avoided. Therefore, the design of the support and the construction phases of the tunnel was carefully accomplished for the mentioned purposes. Four numerical models were carried out using FLAC 3D code focusing in particular to the stresses acting on the support elements and the induced settlements.

A second major issue has been to minimize the impact on the traffic during the construction. In order to reduce this issue, a temporary underground roadway was excavated. The length of this access to the main tunnel was 190 m, with a cross section of 5.0 m x 6.5 m. This access goes with an extremely low overburden under Vitacura Avenue and Perez Zujovic roundabout but it has allowed to start the tunnel excavation on his 4-lane section without any disturbance to the existing traffic.

This underground access finally connects with the central drift of the 5-lane section, but the excavation of this largest section of the project was postponed until the traffic over the surface in the roundabout was dismantled. Figure 4 illustrates the complexity of the temporary access previously excavated to initiate the construction of the tunnel.

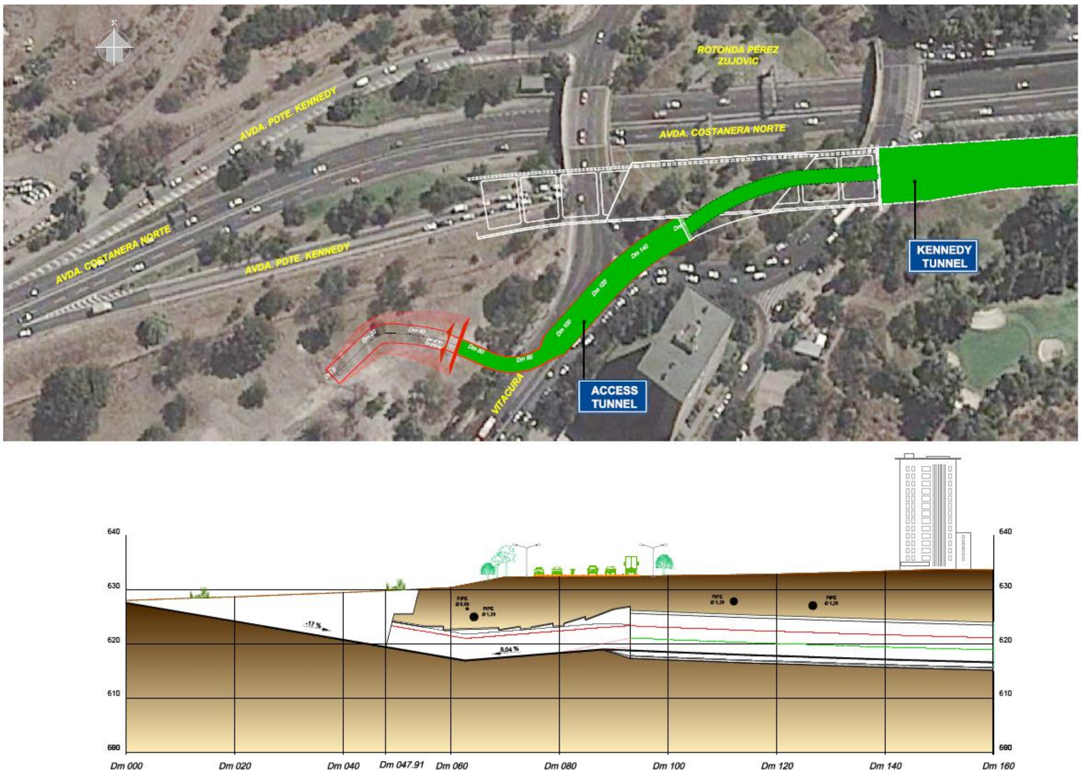

Figure 4. Temporary access tunnel alignment and section. Kennedy Tunnel.

Waterproofing of the tunnel was another main aspect considered in the design phase. For this reason, and in order to minimize the maintenance costs, a pumping rate lower than 500 l/min was stablished in the construction contract. Thus, along all the tunnel and between the concrete of the support and the lining was foreseen to install a waterproofing system composed of a geomembrane and a waterproof sheet.

4 CONSTRUCTION CHALLENGES

There are several aspects of this project that entails construction challenges, among them it can be emphasized the following:

- The dimensions of the tunnel excavation cross section are extraordinarily large as the five lanes section has 22.9 m wide and 13.65 m height which entails an area over 250 m^2.
- The tunnel was entirely excavated in soils. This fact obliges to take into account several factors such as face stability, limitation of the unsupported span, induced deformations, the stress acting on the support, or safety factors at the support, and systematization of the excavation cycle.
- The tunnel was located in an urban environmental with a quite low overburden (10 to 16 m) and below a private property with no allowed access. Therefore, the limitation of the induced deformations and the monitoring at surface involved several difficulties for the design and also for the control during the construction.

5 DEVELOPED SOLUTIONS

The following solutions were developed for the excavation, support and lining of the tunnel:

5.1 *Excavation*

The construction method has been a Sequence Excavation Method, following NATM philosophy, using an elephant foot after finalising the top heading excavation. Depending on the geometry this top heading has been excavated using two or three side drifts, while the benching was always excavated using three phases. The excavation has been done using hydraulic excavator, backhoe and wheel loader.

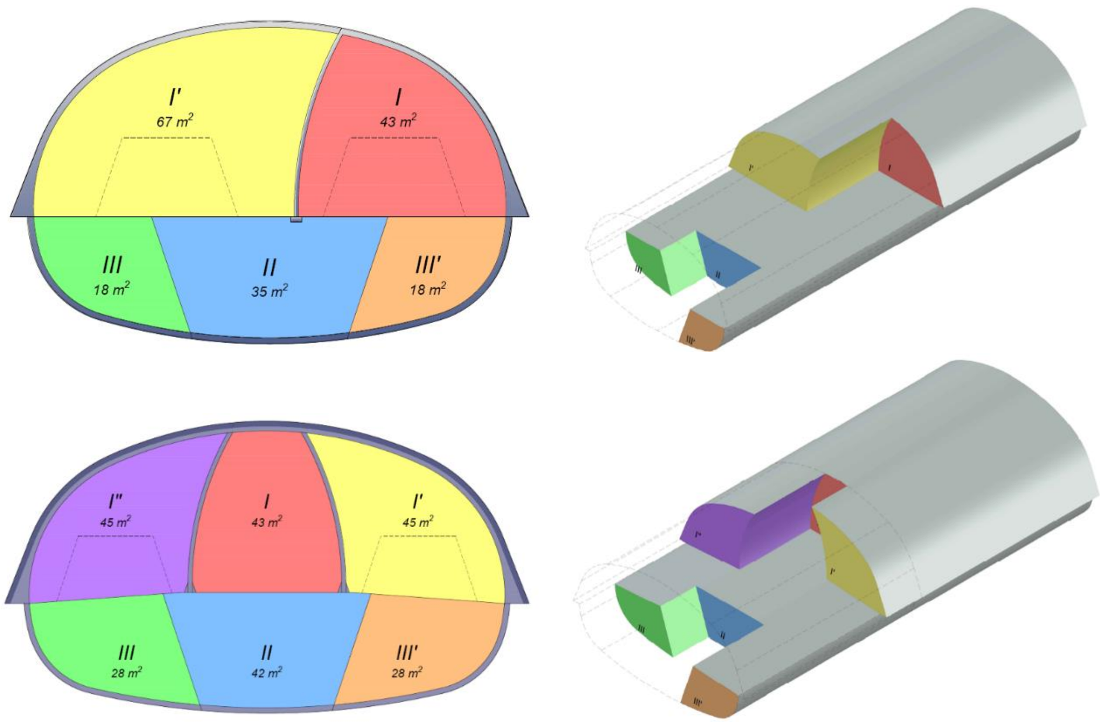

Figure 5. Excavation phases used for the 4 and 5 lanes sections. Kennedy Tunnel.

5.2 *Support*

The support of the typical section consists in a 3 cm shotcrete sealing, HEB-120 steel arches with elephant foot spaced 1.0 m and 27 cm shotcrete Sh35. Systematically buttress at the face and occasional canopy tubes have been used in specific section in which a minimum induced deformation at surface, was allowed.

Figure 6 show the construction sequence for the four-lane section.

Figure 6. Construction sequence for the four-lane section.

The support of the five lanes section consists in a 5 cm of shotcrete sealing, for the vault Norwegian arches spaced 0.75 m were envisaged, additionally it was disposed a ring of HEB-160 arches spaced 0.75 m and 20 cm of shotcrete Sh35. Both arches share an elephant foot foundation. Figure 7 show the construction sequence for the five-lane section, in which the top was constructed in three excavation phases and the bench in three phases similar to the four-lane section.

Figure 7. Construction sequence for the five-lane section.

Finally, a transition was necessary between the four lane section and the five-lane section, as shown in Figure 8.

Figure 8. Transition between the four-lane and the five-lane sections.

5.3 *Lining*

Finally, and separated from the support by the waterproofing system a reinforced concrete lining was envisaged. Its thickness varies from 20 cm to 40 cm depending on the water column to be resisted. Three different lining sections have been designed and constructed:

- Lining A, 40 cm thick and heavily steel reinforced, for the design water table located above the tunnel vault,
- Lining B, 35 cm thick and with a medium reinforcement, for the design water located from the tunnel vault to its invert, and
- Lining C, 20 cm thick with light reinforcement, for the stretch in which the water table is located below the tunnel invert.

A third lining layer with an homogenous thickness of 10 cm with polypropylene fibres for fire protection was also considered.

In the five lanes section the thickness of the lining will be 50 cm.

Figure 9 show the construction sequence used to implement the lining.

Figure 9. Construction sequence for the lining.

5.4 *Monitoring*

Due to the extremely low overburden of the tunnel and the number of excavation phases, the control of the induced deformations and subsidence during construction have required a very strict control. This control has been done with the following monitoring elements:

- Inclinometers and extensometers installed from surface prior to the excavation of the tunnels along the tunnel alignment.
- One section of pressure cells (Dm 1374) installed around the emergency exits structures.
- Convergence sections, every 25 m.
- Settlement profiles at surface

Along the typical section of the tunnel, the maximum settlement measured at surface have been 12.4 mm at the Dm 1145, showing its higher slopes after the demolition of the temporary support wall of the left side drift.

In the 5-lanes section of the tunnel the maximum settlement measured at surface was 12.8 mm at the Dm 1037, with the higher slopes related to the excavation of right side drift and the second to the demolition of the temporary support walls of the central drift.

The maximum convergence along the typical section was 14.4 mm at the Dm 1465, with a maximum velocity of 3.66 mm/day. This behaviour was related to the demolition of the temporary support walls. It is significant that after it, a “divergence” deformation was registered at AC and AB arrays.

In relation to the 5-lanes section of the tunnel the maximum convergence registered was 57.52 mm at the Dm 1070 with a convergence velocity of 2.03 mm/day. Also, it was related to the demolition of the temporary support walls.

Figures 10 show the disposition of the convergence arrays for the two existing sections of the tunnel.

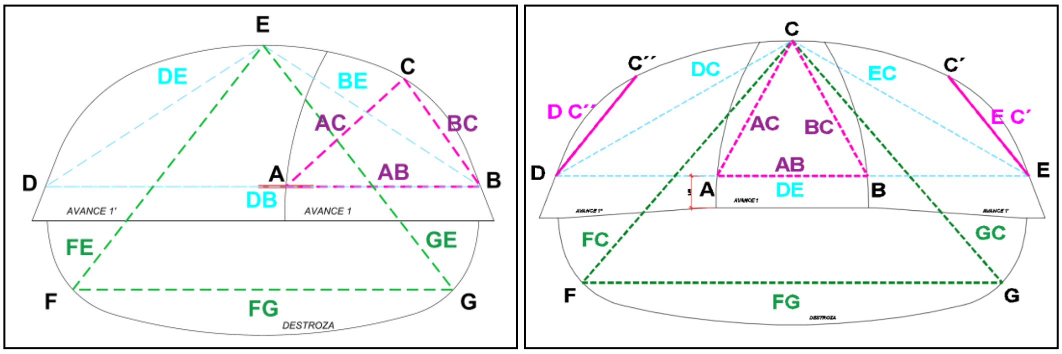

Figure 10. Convergence arrays disposition for 4-lanes and 5 lanes sections.

6 CONCLUSIONS

The excavation of the tunnel started on October 24th, 2014 and it finished on February 16th, 2017. If we consider the total constructed length of 1,166 m. The average advance rate is 1,4 m/day.

- The main challenges during the construction of the Kennedy Tunnel have been:
- The dimensions of the excavation section, over 250 m^2; 23.2 m width.
- The tunnel is entirely excavated in alluvial gravels and partially under the water table, implying several factors such as face stability, canopy tubes, elephant foot, several excavation phases, to ensure a safety construction.
- The tunnel is located in an urban environmental with an extremely low overburden (10 to 16 m), so the limitation of the induced deformations and the monitoring at surface has been a paramount aspect.
- Because its location, in one of the densest urban areas of Santiago, any affection to the existing surface traffic was not allowed by the Authorities.