Design and construction of “Lo Valledor” Station, Line 6 of Santiago Subway (Chile).

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ABSTRACT: Line 6 of Santiago Subway (Chile) is 15.2 km long and has 10 stations. The Project for Executive Engineering of Shafts & Galleries for the Line 6 was awarded to the Consortium Zañartu-Geocontrol in March 2012. The construction of Section I, where Lo Valledor Station is located, was awarded to the Consortium METRO 6 Ltda., constituted by SALINI and IMPREGILO and works began in March 2013. The project was carried out following the methodology of called “Diseño Estructural Activo” (DEA) and the construction of the tunnel station will be built with the method known as Self Supporting Vault. In late October 2013 the access shaft was built, and a large part of the access gallery as well.

1 INTRODUCTION

Line 6 of Santiago Subway (Chile) is 15.2 km long and has 10 stations. It starts in the southwest area of the city, crosses Line 2 (Franklin Station), Line 5 (Nuble Station), Line 3 (Nuñoa Station) and ends after Los Leones Station, which is a common station to Line 1. (Figure 1).

The Project for Detail Engineering of Shafts & Galleries for the Line 6 was awarded to the Consortium Zañartu-Geocontrol in March 2012. Stations and interstation tunnel have been projected to be built by the NATM, method traditionally used in Santiago.

The construction of Line 6 has been divided into four sections, from west to east and in the first of them it is located Lo Valledor Station.

The construction of Section I was awarded to the Consortium METRO 6 Ltda., which is constituted by SALINI and IMPREGILO and the works began in March 2013.

2 LO VALLEDOR STATION CHARACTERISTICS

Lo Valledor Station is a that station whose platforms are 4 m wide, which means a useful width of the tunnel station of 15.5 m, as shown in Figure 2.
The station consists of an access shaft, which has a diameter of 25.6 m, an access gallery which is going to be used to change platforms and an auxiliary gallery to change platforms. Within the tunnel station a mezzanine has been foreseen for the distribution of travelers. Figure 3 shows a perspective of the station.

3 CHARACTERISTICS OF THE GROUNDS

The grounds to be excavated are constituted by a shallow layer of fillings, with a thickness of 1-3 m and sandy-silty gravels typical of the city of Santiago, which come from the 1st and 2nd Deposition of Maipo River.

Figure 4 shows a profile of Lo Valledor Station, with the ground to be excavated. The tunnel station crown is 11 m below the surface which means 71% of the useful width of the station.

Table 1 presents the geotechnical properties of the grounds.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Anthropic Filling</th>
<th>Gravels</th>
</tr>
</thead>
<tbody>
<tr>
<td>γ (kN/m³)</td>
<td>17,0</td>
<td>22,5</td>
</tr>
<tr>
<td>σₘₐₓ (kPa)</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td>φₘₐₓ (°)</td>
<td>33</td>
<td>45</td>
</tr>
<tr>
<td>c (kPa)</td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td>φ (°)</td>
<td>35</td>
<td>50</td>
</tr>
<tr>
<td>Eₑ (kPa)</td>
<td>20.000</td>
<td>42.000</td>
</tr>
<tr>
<td>ν</td>
<td>0,3</td>
<td>0,25</td>
</tr>
<tr>
<td>ψ(°)</td>
<td>0</td>
<td>12</td>
</tr>
<tr>
<td>Kₒ</td>
<td>0,65</td>
<td>0,9 - 0,0533 (Z&lt;6)</td>
</tr>
</tbody>
</table>

Z = depth related with the Surface of the ground (m)

4 CONSTRUCTIVE METHOD

Traditionally, the construction of caverns in the Santiago Subway is done by the method of the "side drift", which is characterized by dividing the section to be excavated into five subsections, and has eight discontinuities in the support structure, as shown in Figure 5.
With this method the construction of large section tunnels can be approached, but the average speed of advance is very low and also the stability of the tunnel is achieved only when the entire subsections are excavated.

To improve the performance of the method so far employed in Santiago, the Consortium Zañartu-Geocontrol proposed the Self Supporting Vault method, which was designed in 2010 by Geocontrol to build a very difficult section in Archidona Tunnel, Malaga (Spain).

The Self Supporting Vault is based on the classic layout of top heading and benching, with the particularity of placing, practically together, the primary and secondary linings, to get both of them to work as a very rigid structure against ground pressures.

The structure is complemented by two elephant foots in order to minimize its descent during the benching and with a conventional invert.

Being this the first time that this method is applied in Santiago and taking into account the small overburden existing over the tunnels, the excavation of the vault has been proposed in two phases with a partition wall, which is demolished before starting the benching.

Figure 6 shows the tunnel station construction phases, according with the concept of Self Supporting Vault.

5 UNION BETWEEN THE ACCESS GALLERY AND THE TUNNEL STATION

The tunnel station has a cross section of 15.5 m and an access gallery of 13.5 m, so the union between both of them involves the excavation of an important surface, especially considering the limited thickness of overburden over the crown.

To maintain the idea that both primary and secondary linings placed during the construction of the top heading has a rigid behaviour against the ground pressures at the junction between the gallery and the Tunnel Station Access, the following measures have been adopted:

I.- The excavation is always performed under the protection of a micropiles umbrella, reinforced with steel pipes.

II.- Primary lining is reinforced 6 m before the union, placing steel arches each 0.5 m instead of 1 m.

III.- Cast beams, built on the sides of the top heading, become warped beams to adapt them to the union to be excavated.

Figure 8 shows a view of the linings elements which are planned to build the unions between the galleries, access galleries and the tunnel station of Line 6.
6 DESIGN METHODOLOGY

In the Project of L-6 a methodology called “Diseño Estructural Activo” (DEA) proposed by Celada (2011) has been employed, based on the following principles:

I.- Ground characterization in the most realistic possible way.

II.- Dimensioning the Type Sections by calculations considered realistic, specifying the expected convergences measures during construction.

III.- Measuring the convergences during the construction of the tunnel comparing it with the predictions in the calculations and if it exceeds the expectations, reinforce the support after making new calculations.

To implement DEA the flow activities shown in Figures 9, 10 and 11 must be followed.

Phase I is dedicated to know the stress-strain behavior of the ground, in the most reliable way possible, obtaining as a result of its application the geomechanical profile of the works to design.

Phase II takes as an input the geomechanical profile data obtained in Phase I and the geometric definition of the works to design. The purpose of Phase II to dimension the supports and calculate the convergence that will occur during the construction.
Phase III is dedicated to verify, during the execution of the works, that the calculations forecast are confirmed in reality. Usually it is done by checking the convergence measures and/or the subsidences.

7 VALIDATION METHOD AND Lining calculation

In each one of the 10 stations of Line 6 the constructive method has been validated and the lining to be placed has been dimensioned, taking into account the geometry of each station, the characteristics of the grounds and the existence of nearby buildings.

7.1 Validation method and dimensioning

With these constraints the validation and dimensioning process is performed using numerical modeling techniques in three dimensions, since the two-dimensional
modeling does not provide sufficient representative and accurate results.

In the case of Lo Valledor Station the model which has been performed is presented in Figure 12, which is 240 m long, 168 m wide and 80 m high.

![Model of Lo Valledor Station](image)

Figure 12. Model of Lo Valledor Station.

This model consists of 660,000 elements which allow to represent with great precision the constructive processes that is expected to be employed.

This great accuracy results in the identification of the most sought areas of the works, aspect of great interest in the case of junctions, and to calculate accurately the influence of the works in the surrounding grounds, essential aspect when there are buildings nearby.

These advantages have their counterpart in the high calculation time needed, specially when these are sequential, so that in each round of excavation (usually 1 m) it calculates the stress-strain model to reach an equilibrium. This implies that, in Lo Valledor Station, the validation process of the model must be solved 240 times with the program FLAC 3D.

Consequently, the calculation time takes about 9.8 full days, working with a microprocessor i73960x, with six cores up to 4.26 MHz and 15MB of cache memory.

7.2 Constitutive model and lining elements

As a constitutive model to reproduce the behavior the classic Mohr-Coulomb was employed associated with a "small strain" behavior to make sure that the model of deformation decreases while it increases the ground deformation.

Figure 13 shows the curve which relates the ground module with the shear strain, such that, initially, the ground module is determined "in situ" by dynamic tests.

![Figure 13. Variation of shear modulus with unitary strain.](image)

When the shear strain reaches 1% the deformation model is determined by laboratory tests, which is about 10 times smaller than the dynamic.

With this methodology, which extends the calculation process while reassigning the modules to all the model elements depending on their deformation, the model displacements obtained are very consistent with the reality; as have shown some calculations in the nearness of the Big Ben in London (UK) or the Temple of La Sagrada Familia in Barcelona (Spain).

Regarding to the support elements, tubular gantry through elements, such as piles, the frames using elements, such as beams and the shotcrete through plate elements type like shells, it has been taken into account, the setting time.

Figure 14 shows the structural elements which model the primary support.

![Figure 14. Modelling the primary support.](image)
7.3 Seismic Simulation

Line 6 of Santiago Subway is a very near the surface underground work, since the overburden is less than the width of the excavations, and it must be constructed excavating in grounds consolidated in a high seismic area.

Therefore the behavior of the support designed for the effects of an earthquake has been checked which, in a simplified form, with longitudinal and transverse strains.

Generally in tunnels longitudinal seismic strains are much smaller than the cross ones and in the case of Line 6 of Santiago Subway it was found that longitudinal stresses are negligible.

To simulate the behavior of the primary and secondary support against the cross strains of a seism, once simulated the overall construction of Lo Valledor Station the model has been subjected to a cross strain of 0.35 mm per meter. Figure 15 shows a model view of Lo Valledor Station deformed with the aforementioned deformation.

To try to achieve a greater realism, it has been assumed that the aforementioned cross strain acts in two orthogonal directions, as shown in Figure 16.

Figure 15. Model of Lo Valledor Station subjected to a cross strain of 0.35 mm/m.

Figure 16. Orthogonal directions to implement the cross seismic strain.

This means that, after making the calculations that simulate the various phases of the construction to reach the final geometry, two calculations have been performed with pre-set cross strain, in order to simulate the effect of the seism.

7.4 Results of the calculations

The calculations performed allow to know the ground movements and the strains on the elements of the constructive support in each phase.

Figure 17 shows the distribution of shear strain in the construction of the first phase of the top heading.

This figure shows that the shear strain is in the order of 10-3 which, according to Figure 10, assumes that the calculations are being carried out considering that the grounds module are twice the static module.

Figure 18 shows the distribution analogous to the previous one, when the excavation of the tunnel station is completed.
Figure 18. Shear strain distribution after de construction of the whole tunnel station.

Regarding strains on the support elements, Figure 19 shows the axial forces in the steel arches after the construction of Phase I of the top heading and Figure 20 the homologous distribution in the final stage.

Figure 19. Axial forces on steel arches after the excavation of Phase I of top heading.

Figure 20. Axial forces on steel arches after the construction of the whole tunnel station.

Finally Figure 21 shows the bending moments distribution after the completion of the tunnel station.

Figure 21. Bending moments distribution after the construction of the whole Tunnel Station.

With these data the reinforcement of support have been dimensioned, following the instructions of Chilean Standards NCh-430-OF2008.

Metro SA has set at 35 mm the maximum subsidence that can occur when building a station, when there are no nearby buildings that could be affected by these movements.

To calculate the subsidence produced after the construction of Lo Valledor Station the displacement distribution model has been employed, calculated after the ending of the construction of the station, as shown in Figure 22.

Figure 22. Distribution of vertical displacements when the station was finished.

With the data of Figure 22 the subsidences of Lo Valledor Station have been drawn, as shown in Figure 23.
8 MONITORING

According to the principles of the DEA, presented in section 6, a monitoring system has been defined to monitor the process of the underground stabilization of L-6 and to assess the degree of agreement between the calculations and the reality.

Figure 24 shows the monitoring system, used in Lo Valledor Station, which is based on the measures of convergences and subsidences.

During the benching phase, it is expected that the convergence measurements will be done with optical methods, which are less accurate than mechanical measurements, but they are more operative in excavations with significant height.

9 EVOLUTION OF THE WORKS

The construction of the shaft of the Lo Valledor Station began on March 13th, 2013 and in August the bottom shaft reached the level to build the umbrella of the Access Gallery, that was built at the beginning of September as is shown in Picture 1.

The Access Gallery was completed in October, as is shown in Picture 2.
When the Access Gallery was finished the construction of two umbrellas, right and left, which protect the beginning of the Tunnel Station began.

Picture 3 shows the construction of the left umbrella and the right umbrella, that is already built.

Also, this picture shows the warped beam that gives the continuity to the right tie beam of the Access Gallery.

The monitoring data shows convergences closed to the values foreseen in the Project and the behavior of the terrain, that is really good, matches very well with the Project.

REFERENCES