Design and Engineering during the Construction of Los Leones Station (Line 6, Santiago Subway, Chile)

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1. INTRODUCTION

Santiago de Chile is a 7 million inhabitant city which has a 103 Km long subway network operated since 1975 by Metro S.A. This network is used on a daily basis by 2.3 million people.

In 2012 Metro S.A. started the biggest enlargement of the network in its history, through the design and construction of the new Line 3 (21.7 Km) and Line 6 (16.5 Km).

The detailed engineering contract for civil underground works of Line 6 (L6) was awarded to the Consortium integrated by ZAÑARTU Ingenieros Consultores and GEOCONTROL S.A., in which Geocontrol was in charge of the design of 11 stations and 14.5 Km of tunnel.

L6 crosses L3 in Ñuble and Ñuñoa Station, L2 at Franklin Station and ends, intersecting L1, at Los Leones Station as shown in **Figure 1**.

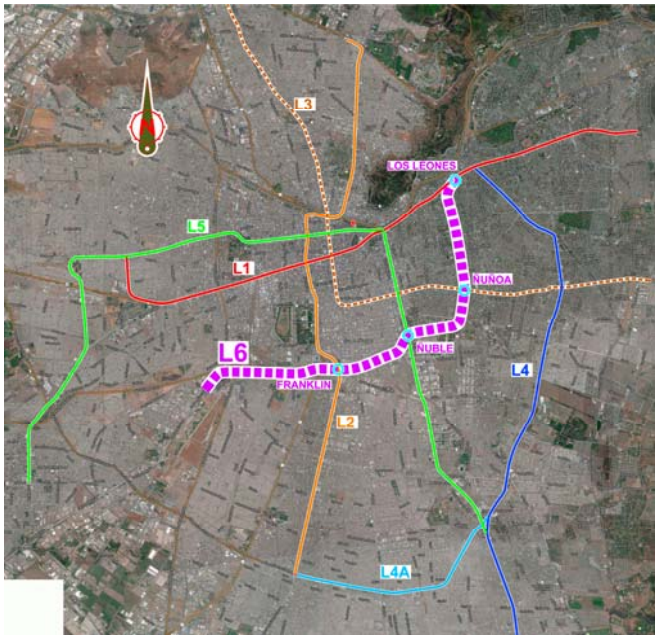

Figure 1. Santiago Subway network.

2. LOS LEONES STATION DESIGN

2.1. Location and Characteristics

Los Leones Station is placed at the North end of the L6, next to the same named station of the L1 and it has four construction units, as is shown in **Figure 2**:

I.- Access Shaft (49 m x 47 m).
II.- Access Gallery (34 m long).
III.- Station Tunnel (120 m long).
IV.- Connection Gallery with L1 (104 m long).

A singular feature of Los Leones is that the western section of the station tunnel, built from the access gallery, is located below an underground parking lot which is located in Providencia Avenue, as shown in **Figure 3**. It is important to highlight that the distance between the vault of Los Leones Station Tunnel and the foundations of the underground parking lot is only 6 m.

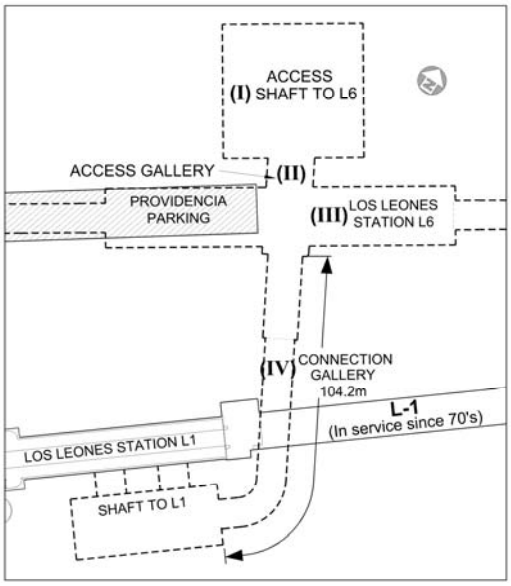

Figure 2. L-6 Los Leones Station and its connection with L1.

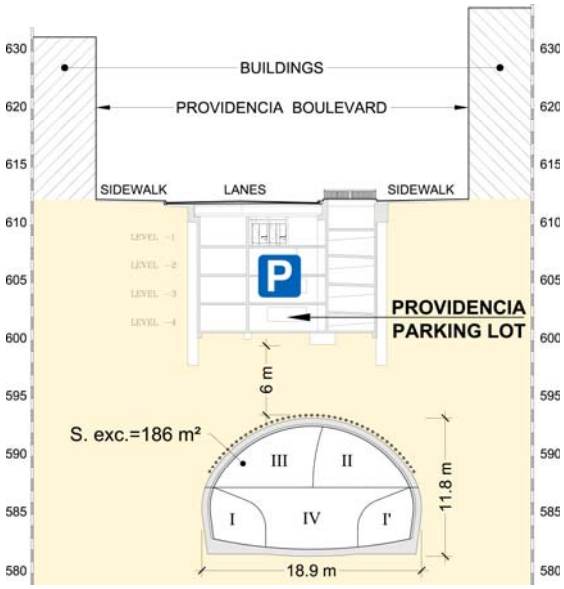

Figure 3. Cross-section of Los Leones Station.

2.2. Ground Characteristics

The ground to excavate is a very well graded granular soil originated by the 1st Deposition of Mapocho River. The largest particles of this soil are boulders with a diameter up to 55 cm and the proportion of fine particles ranges between 2 and 8%. This soil presents an almost perfect elasto-plastic behavior since it maintains the peak shear strength, measured by "in situ" tests, up to a strain of 8%.

Its behavior is well reproduced by the Mohr Coulomb constitutive model, with a cohesion c = 35 kPa a friction angle of 47.5°, large strain Young's Modulus (E) of 300 MPa and a Poisson ration (ν) of 0.25. The permeability of this soil is k=3 10^{-4} m/s and its well graded particle size allows the water to percolate without the fines being dragged out.

2.3. Construction Methods

For more than 20 years, the Santiago Subway stations have been constructed using NATM or Sequential Method, performing the excavation with mechanical means and the support with lattice girders and shotcrete. It should be noted that the final lining is also made of shotcrete [Mercado *et alt*. 2004].

Los Leones Station construction has been designed with two variants of NATM; one is the regular method used at the other Line 6 stations (self-supported vault) and the other one is specifically employed to build the East part of the Station Tunnel, below the Providencia parking lot.

2.3.1. Self-Supported Vault Method. The construction of eleven stations of the L6 is based on a new construction method called Self Supported Vault (SSV) which its most important feature is to build a shotcrete vault which must satisfy these conditions:

I.- To be able to resist the weight of the whole overburden soil if the arch effect is not possible.

II.- To transfer the axial forces in the vault inside the soil mass far from the tunnel walls taking advantage of the bearing capacity of the soil.

III.- To make possible the benching excavation in only one construction phase.

These conditions are achieved by building the primary support and the final lining as close as possible to the tunnel face, supporting the vault on two large elephant feet and two longitudinal brace beans.

Applying the SSV method the subsidence, after the construction of a station with a cross-section between 160 and 190 m^2 in Santiago gravels and with a track depth of 22 m under the surface, is usually between 30 and 60 mm.

In Los Leones Station, the SSV method has been used in the Access Gallery and in the East part of the Station Tunnel.

Figure 4 shows the cross-section designed for the East Tunnel of Los Leones Station which has a total excavated area of 182.5m^2.

In order to prevent the negative effects of some hypothetical changes in the ground strength, the vault construction is made in two phases; each one with an excavation section of about 35 m^2 which allows the use of heavy machinery, as it is illustrated in **Photo 1.**

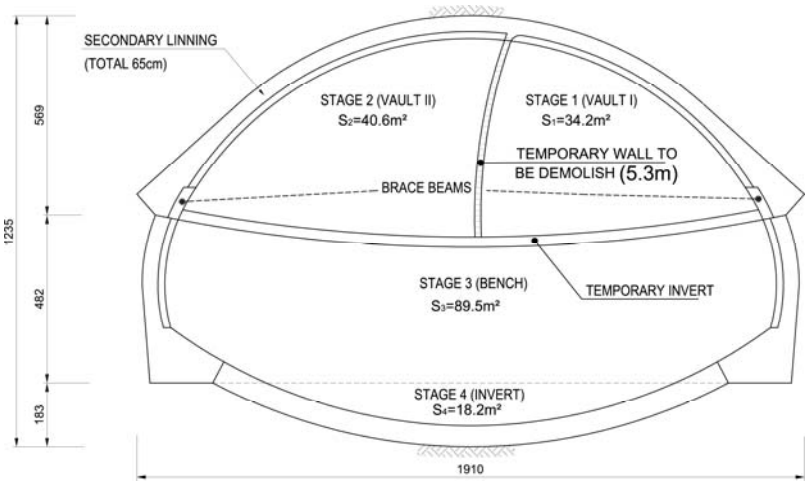

Figure 4. East Tunnel of Los Leones Station constructed by SSV method.

Photo 1. Vault excavation at Los Leones East Station Tunnel.

Some constructive details of the brace beans and the elephant foot are shown in **Figure 5**.

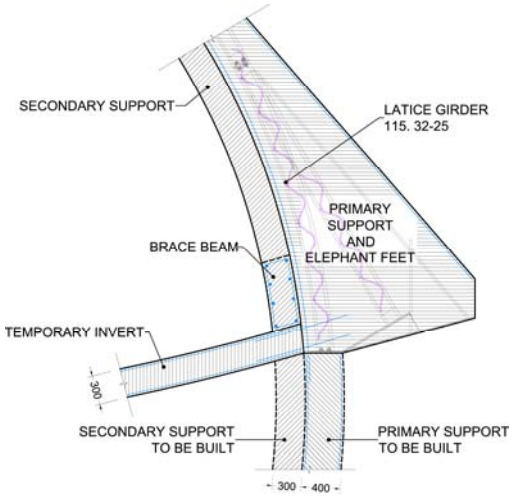

Figure 5. Elephant foot and brace beans details.

2.3.2. Side-Wall Foundation Galleries Method.

The West part of the Station Tunnel had to be built under Providencia parking lot and, due to this, the subsidence must be minimized. For this reason, the Side-wall Foundation Galleries (SFG) Method was selected.

The SFG Method is well known around the world and its main target is to provide a rigid as possible foundation for the vault of tunnel.

The SFG Method was used by Geocontrol, ten years ago, at the Teixonera and Vall d'Hebron Stations in the Line 5 of Barcelona Subway (Spain).

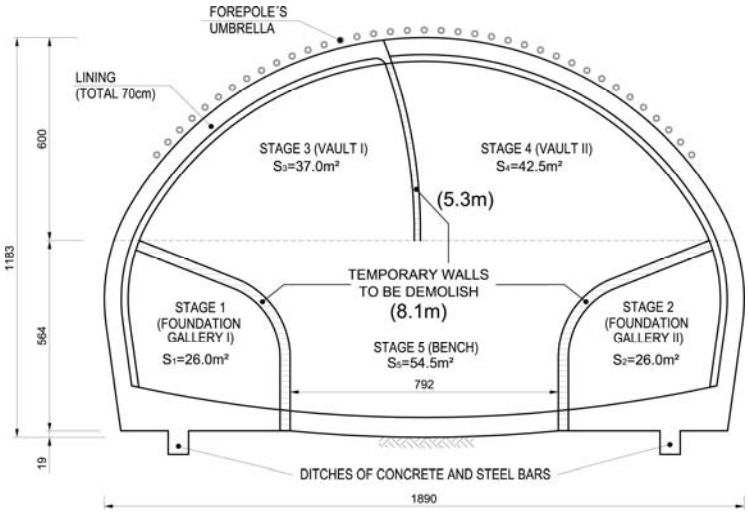

Figure 6. SFG method at the West part of Los Leones Tunnel Station.

Figure 6 shows the geometrical disposition adopted at Los Leones Station, that means a total excavation surface of 186 m^2. The construction of two ditches, with concrete and steel bars at the bottom of both side-wall galleries minimizes its horizontal movements and allows to excavate the central bench without a temporary invert.

In **Figure 7** the details of theses ditches are shown.

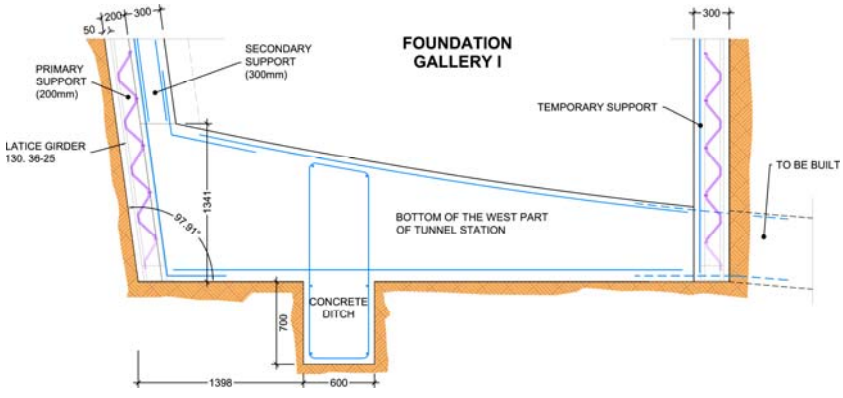

Figure 7. Bottom ditches' details.

There are five important differences between SSV and SFG methods:

I.- The cross section is excavated in four stages in the SSV and five in the SFG.

II.- The length of temporary support that has to be demolished is 5,3 m in the SSV method and 21,5 m in the SFG.

III.- The vault excavation is made under the protection of heavy umbrellas.

IV.- During the excavation of the tunnel face, stages 3 and 4, the ground at the face was improved by self-bored cemented bolts.

V.- In order to fill the possible voids after the vault excavation, the ground behind the vault was grouted.

For these reasons the SFG method is a 46% more expensive that the SSV method; but the SFG method reduces the subsidence by 23%.

2.4. Design Methodology

The design of Los Leones Station has been made using the Active Structural Design (DEA), methodology optimized by Geocontrol in the 90's [Celada. 2011]. DEA methodology has three design phases, which are shown in **Figure 8**.

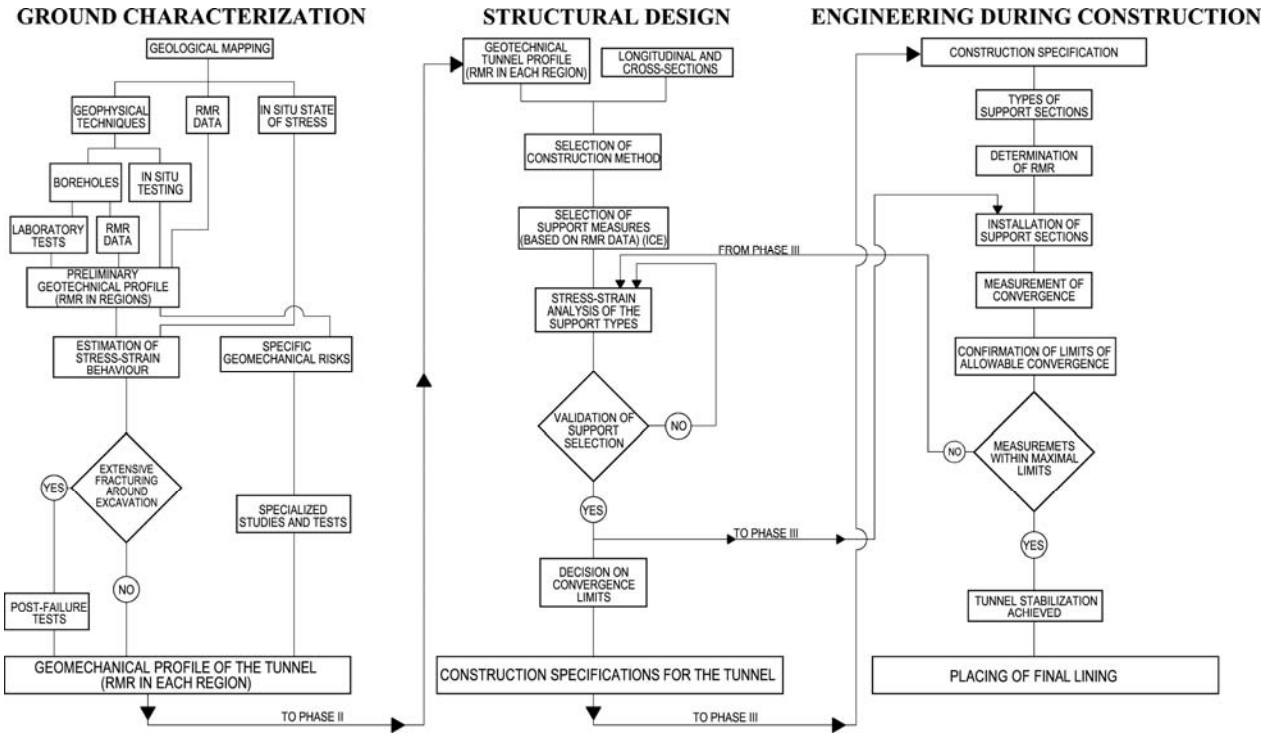

Figure 8. DEA activities flow chart.

The target of each DEA's phases are:

I. **Ground Characterization**, to know its strain-stress behavior as accurately as possible.
II. **Structural design**, made by 3D models and solved in a sequential manner to calculate the support loads and ground movements during all construction stages.
III. **Engineering during Construction**, to check that the calculated prognosis is in agreement with the reality, to detect possible anomalous behavior and to solve it.

In the following sections, the activities carried out to define the structural design of Los Leones Station are presented.

2.4.1. Ground Behavior Model. Regarding the strain behavior of Mapocho gravels, two stages have been identified: before reaching the peak stress and once the peak stress has been reached.

Before reaching the peak stress it has been assumed that this soil follows the small strain modulus model [Jardine. 1984]; which is characterized by its dynamic modulus during the first small movements and the static modulus is used after a strain of 1%.

Once the peak stress is reached, a 4% shear strain was considered as acceptability criteria. This is a conservative assumption because in the *in situ* shear tests did not show a strength drop before 8% shear strain.

2.4.2. Construction Procedure Model. The adopted constructive methods are sequential in each of its different phases, which implies that to perform a realistic simulation it is necessary to split the tridimensional model in many faces perpendicular to the excavation axes. The width of elements perpendicular to the tunnel axis should be equal to the excavated length in each advance cycle.

To minimize the calculation time, two tridimensional models have been used in Los Leones Station. The first one was used to calculate the East Station Tunnel, built by means of SSV method; the second one was used for the Western Station Tunnel, built by means of SFG method. In **Figure 9** both models are shown.

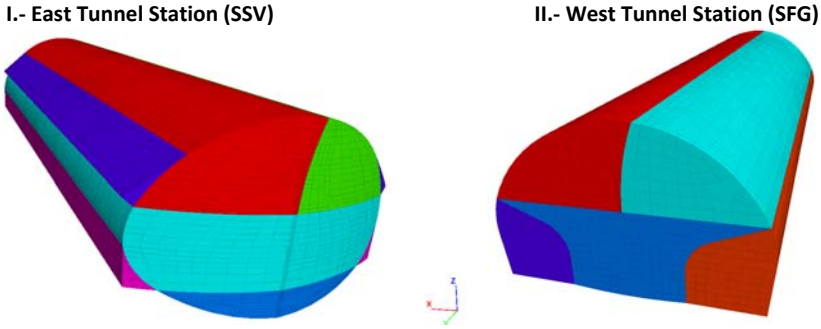

Figure 9. Los Leones Station3D Model.

2.4.3. Structural Check. The two tridimensional models used to simulate the construction procedure of Los Leones Station have been solved by means of the code FLAC 3D [Itasca. 2012]. The shotcrete, both of the primary and the secondary support, has been checked in static and dynamic conditions following the criteria given by the ACI 318 standard.

To assess the behavior under an earthquake a methodology already employed in other Santiago Subway lines is used. It consists of inducing a transversal shear deformation in the structure [Wang 1993]; its magnitude, in the case of Los Leones Station gravels, has been of 0.35 mm/m.

The effectiveness of this design methodology was verified during the earthquake, that took place in February 2010, which had a Richter magnitude of 8.8 and that did not cause any damage in Santiago Subway structures.

In **Figure 10** the model of the distortion induced by the earthquake in Los Leones Station is shown.

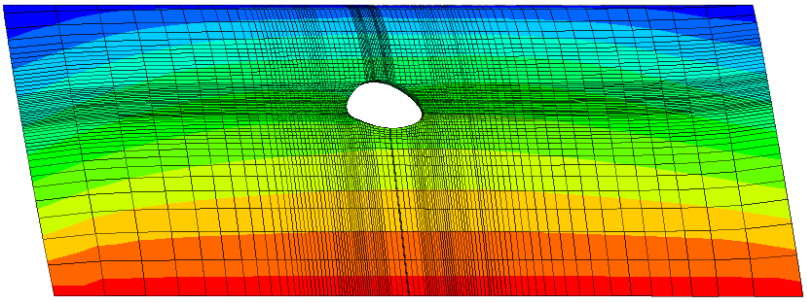

Figure 10. Seismic distortion modeling at Los Leones Station.

According to ACI 318 Appendix C, in order to check the structure dimensioning the following load combination: 1.3 x E + 1.0 x S has been adopted; being E the value for static loads and S the value for seismic loads.

2.5. Forecast of Movements Induced by the Construction

The target of Phase III of DEA Methodology is to verify the movement induced during the construction of the works, for which it is essential that in Phase II, dedicated to structural calculation, these movements have been also calculated.

In the particular case of Los Leones Station, the most significant calculated movements have been these ones:

- Maximum subsidence, located in the intersection between the Access Gallery and the Station Tunnel……32 mm
- Descent of the 4th floor structure of the Providencia underground parking lot……..21 mm

3. ENGINEERING DURING CONSTRUCTION OF LOS LEONES STATION

As well as in the rest of L6 stations, two different teams have supervised Los Leones Station construction; the first one, named *Inspección Técnica de Obra* (ITO), was in charge of the physical inspection of the works carried out and the second one, named *Supervisión de Obra* (SdO), was in charge of solving engineering problems occurring during the works.

L6 Section IV Works were awarded to EIOSSA Consortium, which is formed by the Chilean company Echevarría Izquierdo and the Spanish company Obras Subterráneas. The underground works of Los Leones Station started in August 19, 2014 with the construction of the Access Gallery vault phase and finished in September 16, 2015. The main aspects of Los Leones Station construction monitoring are presented in the following sections.

3.1. The Ground Features

The ground excavated during Los Leones Station construction has been the Mapocho River 1st deposition gravels, as predicted in the Project.

The most relevant difference between the construction conditions and the design has been a moderate presence of water in the ground due to an infiltration from the water network facilities of Santiago. To recalculate the subsidence, due to the water infiltration, it was decided to reduce the gravel deformation modulus by 20%.

3.2. Access Gallery Construction

The Access Gallery, which is 34 m long, and has a 157 m^2 cross section has been built with the SSV method. As primary support lattice girders and a shotcrete layer of 40 cm with a steel mesh where used. The liner, secondary support, was also a shotcrete layer 30 cm thick and steel mesh. In **Table 1**, both the construction time and the output of the Access Gallery are summarized.

Table 1. Construction time and outputs at the Access Gallery.

Stage	Length (m)	Construction Time (days)	Output (m/day)
Top Heading	34	52	0.65
Bench and Invert	34	12	2.83
Total	**34**	**64**	**0.53**

3.3. East portion of the Station Tunnel Construction

The length of the East portion of the Station Tunnel is 50 m, as shown in Figure 2. The primary support was lattice girders, a 45 cm layer of shotcrete and steel mesh. The secondary support was a layer of 20 cm of shotcrete. In **Table 2**, the construction time and the outputs, for each stage, are summarized.

Table 2. Time construction and outputs at the East Tunnel Station.

Stage	Length (m)	Construction Time (days)	Output (m/day)
Top Heading	50	70	0.71
Bench and Invert	50	30	1.67
Total	**50**	**100**	**0.50**

3.4. West part of the Station Tunnel Construction

As it was shown in Figure 2, the West Station Tunnel length is 55 m and it has been constructed using SFG method, as was pointed in section 2.3.2. The West Station Tunnel construction started on May 8th, 2015 and finished by September 16th, 2015, after 151 working days. **Photo 2**, shows the beginning of the construction of the Side-Wall Foundation Galleries at the West Station Tunnel.

Photo 2. Side–Wall Foundation Galleries construction at the West part of the Station Tunnel.

In **Photo 3**, the demolition of temporary support of side-wall galleries and the bench excavation is shown.

Photo 3. Bench excavation and demolition of the temporary support of the side-wall galleries.

In **Table 3**, both construction time and achieved performances of the West part of the Station Tunnel are shown.

Table 3. Construction time and outputs at the West part of the Tunnel Station.

Stage	Length (m)	Construction Time (days)	Output (m/day)
1st Side-wall Gallery	55	38	1.45
2nd Side-wall Gallery	55	36	1.53
Top Heading	55	61	0.90
Bench and Invert	55	16	3.44
TOTAL	**55**	**151**	**0.36**

The 0.36 m/day obtained in the West Station Tunnel with respect to the 0.50 m/day achieved in the East Station Tunnel, represents a reduction of 28 %, which is in accordance with the greater complexity of SFG method over SSV method. The **Photo 4** shows the West part of the Los Leones Station Tunnel after its construction.

Photo 4. Los Leones Tunnel Station, part West, after its construction.

4. MEASURED MOVEMENTS

4.1. Surface Subsidence

Two months before the Access Gallery excavation began, subsidence in the surface above Los Leones Station was being monitored by means of topographical milestones. As occurred in the rest of L6 Stations, the maximum subsidence has always taken place in the intersection between the gallery access axis and the Station Tunnel, whose time evolution is shown in **Figure 11**.

The maximum subsidence generated by the construction of the underground works of Los Leones Station was 43 mm; because 5 mm of subsidence are due to the Access Shaft construction, the distribution of the maxima subsidence are the following:

- Access Gallery ……16.5 mm (37.5%)
- East Station Tunnel ……15.8 mm (35.9%)
- West Station Tunnel ……10.7 mm (26.6%)

  Total……43.0 mm (100%)

The maximum settlement on the 4th floor of the Providencia parking lot was 28 mm and no damage was noticeable after de construction of Los Leones Station.

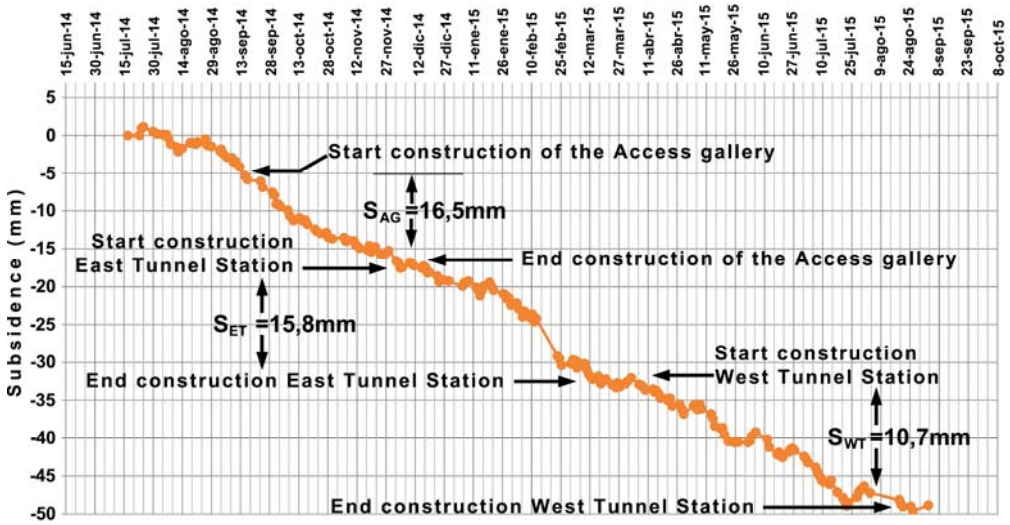

Figure 11. Maximum subsidence evolution at Los Leones Station.

5. CONCLUSIONS

Los Leones Station, which belongs to the new Line 6 of Santiago Subway, is 19 m wide and is divided into two sections. The East Station Tunnel has 50 m of length and the overburden height is only 17 m while the West Station Tunnel has 55 m length and has been built 6 m below the Providencia parking lot.

Like the rest of L6 Stations, the East Station Tunnel has been built with SSV method but the West Station Tunnel has been built with SFG method in order to decrease the induced subsidence on the Providencia parking lot; which shows no damages after the construction.

The construction of Los Leones underground works has been carried out in 12.5 months, which can be considered an excellent result regarding the difficulties involved in the construction of this Station.

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