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Comparison between Numerical Modelling and Subsidence of Tunnels Excavated in Fine Soil in the North-West of Santiago de Chile.

Subsidencia de Túneles Excavados en Suelos Finos del Noroeste de Santiago de Chile versus Modelación Numérica.

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ABSTRACT: This paper focuses on the analysis of subsidence induced by tunneling in the extension of Line 3 of the Santiago Metro in Quilicura, a district located in the northwest of Santiago, Chile. The project takes place in a particular geological context, characterized by the presence of fine soils known as "northwest fines", where previous experience of tunneling has been limited. In this study, the data obtained during the monitoring of the ground displacements induced by the excavation of the tunnels are analyzed and the fundamental parameters defining the settlement troughs derived from these displacements, such as the settlement volume and the position of the inflection point, are determined. In addition, numerical models are created using the FLAC 3D software, which reproduce the geotechnical conditions encountered during construction (as-built stratigraphic profiles) and the excavation and support sequence used, with the aim of determining the constitutive model that best fits the monitoring data and the corresponding geotechnical parameters.

KEYWORDS: tunnels, numerical modeling, geotechnical monitoring, topographic monitoring, fine soils, subsidence.

1 INTRODUCTION.

The purpose of this work is the analysis of the subsidence obtained during the excavation of interstation tunnels of the project "extension of Line 3 of Metro de Santiago" (hereinafter the acronym EL3 will be used), located in a particular geological context of the city where fine soils called "northwest fines" predominate (see Valenzuela, 1978) and where there was little previous experience of tunneling.

To increase the level of knowledge of the area, a soil survey campaign was carried out between July and December 2016, which initially included 13 deep test pits up to 25 meters deep, 3 test pits for horizontal load testing, 2 geotechnical borings of 35 meters deep each and MASW geophysical testing to measure shear wave velocities. This background information was used as the basis for the designs.

In this work, the data obtained during the monitoring of the ground displacements induced by the excavation of the tunnels (between 2019 and 2021) will be analyzed and the basic parameters defining the settlement troughs derived from them (settlement volume and position of the inflection point) will be determined.

Additionally, numerical models are made, using FLAC 3D finite difference software, which reproduce the geotechnical conditions detected during construction (as-built stratigraphic profiles) and the sequence of excavation and support used, to determine the constitutive model that best fits the monitoring data and its corresponding geotechnical parameters.

2 PROJECT DESCRIPTION

The extension of Line 3 developed in the municipality of Quilicura (Figure 1), is a subway line located in the northern area of Santiago, with a total length of 3.4 kilometers and three new stations (Ferrocarriles, Lo Cruzat, and Plaza de Quilicura), benefiting the quality of life of 210,000 inhabitants.

Figure 1. L3 Extension project (EL3) Referential Layout Metro de Santiago

The construction of the tunnels was carried out using the NATM method (New Austrian Tunneling Method), whose fundamental criterion is to consider the ground surrounding the excavation as part of the support system; in other words, the ground must be treated as construction material. This construction system has been successfully applied to tunnels excavated in the soils of Santiago.

The tunnels layout is developed in soils known as "Northwestern fines", which are different from the rest of the city since most of the Santiago Metro tunnels were excavated in soils predominantly composed of gravels and boulders (Figure 2). During the engineering development, it was observed that these fine soils presented significantly higher settlement levels compared to previous Metro de Santiago tunnel projects located in areas predominantly composed of gravels. For this reason, higher monitoring threshold values were used (see chapter 3.4).

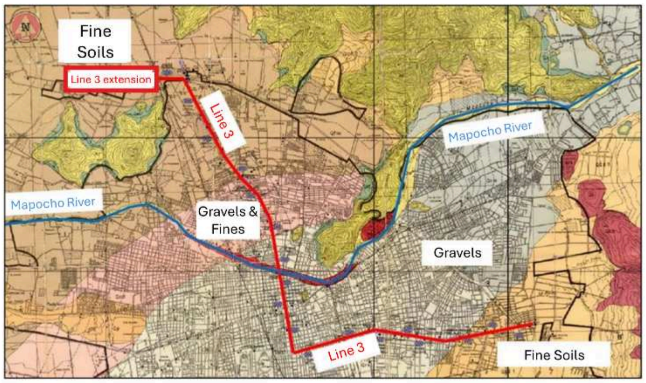

Figure 2. Geological map of Santiago according to Valenzuela G. 1978 (Layera S. 2018).

As described in the Soil Mechanics Report, five Geotechnical Units (U-1 to U-5) were identified along the Metro L3 Extension route, which are broadly summarized in Table 1. Unit U-2, "*Northwestern fine soils*", is the main unit where the tunnels are projected, consisting of silts and sandy clays (ML, CL and CL-ML) with high consistency generally below 3m depth and very high consistency below 8 m depth. Additionally, due to the presence of strata of clean sands that can be "shelled" to the touch, it was considered that Unit N°2 might contain lenses of sands and even gravels up to 1.5 m thick, which are considered an integral part of the geotechnical unit.

The description of the different soil units that have been defined for the L3 extension project and their resistance parameters are presented in Table 1 and Table 2, respectively, while Figure 3 shows the stratigraphic profile of the route.

2.1 *Water table*

The Soil Mechanics study identified water table depths varying between 18.75m and 23.40m along the layout of the EL3 project. Therefore, the bottom portion of the tunnel (hereinafter referred to as "*bottom*") was designed with its lower level above these depths, a condition which meant that the ground cover of the tunnels was of the order of an equivalent diameter in certain sections of the route. It is important to mention that around the Frei Montalva Construction Shaft (CCU), no water table was identified during the campaign.

Table 1. Summary of Geotechnical Units

During the construction phase of the project, it was observed that the measured water table was deeper than the level identified during the geotechnical explorations. Water table monitoring was carried out using three vibrating wire piezometers installed at the Frei Montalva (CCU), Las Parcelas and O'Higgins construction shafts (see Figure 1).

The above confirms the historical trend of the continuous lowering of the water table, as indicated in the hydrogeological study requested by Metro. It follows from the above that the planned height of the bottoms in the project would not meet the water table, which has been confirmed by the excavations carried out during the construction phase.

3 TUNNEL-INDUCED MOVEMENTS AND DEFORMATIONS

It should also be noted that the construction of urban tunnels involves the coexistence with surface activities and, therefore, should alter the normal development of these activities in the city as little as possible. In any construction of an urban tunnel, priority must be given to safety aspects, both for the workers carrying out the work and for people, real estate, and activities in general existing on the surface or within the influence zone of the subway excavation, without neglecting environmental aspects.

Table 2. Summary of Geotechnical Units Soil Mecha

One of the key aspects to guarantee safety during construction is based on the implementation of a permanent monitoring system, both tunnel excavation itself and of the movements induced by it on the surface and, logically, also of their correct and timely interpretation and analysis.

The monitoring results allow, during construction, verification of the initial hypotheses considered in the design of the subway works, to provide the necessary information to confirm the integrity and stability of the tunnel, and to determine the subsidence induced in the structures located on the surface within the area of influence of the excavations.

3.1 *Tunnel Induced Movements and Deformations*

Tunnel construction is inevitably accompanied by surface movements induced by the redistribution of perimeter forces around the excavation section and their corresponding radial convergences (movements towards the interior of the excavation reducing its theoretical section) as well as by the consolidation effect (in saturated soils). Vertical movements usually manifest on the surface in the form of a settlement trough like the one shown in the diagram in Figure 4.

It has been shown that the settlements induced by tunnel construction start before the arrival of the excavation face, as can be seen in Figure 4. The settlements are projected forward of the excavation face by about 2.4-i, with "i" being the inflection point of the settlement trough, which corresponds to the point where the function changes concavity.

Most analysis methods used to interpret subsidence are of empirical origin and are based on field observations. On the other hand, the theoretical estimation of the expected maximum surface settlement is challenging to obtain because it depends on multiple variables, including temporal factors.

Figure 3. EL3 Project Stratigraphic Profile

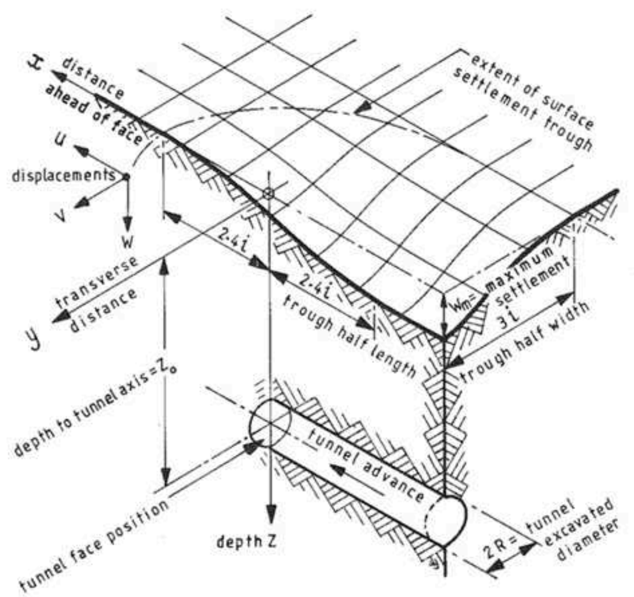

Figure 4. Attewell Subsidence Basin (after Yeates 1985)

Another interesting parameter to consider is the constant "k". The following expression is usually assumed to calculate the inflection point of the trough as a function of the depth, H, of the tunnel center (considering its equivalent diameter):

$$x_i = k \cdot H \tag{1}$$

Where:
x_i = Trough inflection point.
k= Constant "k".
H=Depth of the center of the tunnel considering its equivalent diameter.

3.1.1 *Definition of Tunnel Reference Value*

The reference values of the control parameters that govern the behavior of the tunnel during its construction, obtained either from the predictions of the numerical models or through monitoring, which are usually considered are the following:

- Expected Value: It is the value of the control parameter obtained from the numerical models, for the service states, without majoring. To consider these values, it must first be confirmed that the model accurately represents the real behavior of the terrain (i.e. there must be a initial stage of model-monitoring adjustment).
- Measured Value: This is the measurement of the topographic (or other) monitoring of the works. It is assumed that its maximum value is very close to the expected value for normal working and ground conditions. It is important to note that monitoring is performed to detect deviations from the Expected Value.
- Alarm Value: This is a value of the control parameter associated with the loss of serviceability of the work, primarily due to large deformations. Exceeding this value implies the need to adopt certain preventive and/or corrective measures. It must be established in such a way that there is a safeguard, or sufficient safety coefficient, against failure due to ground rupture or the generation of significant damage to the structures that may be affected. It is higher than the expected value.

3.2 *Performance Parameters Tunnels*

This approach is based on the use of dimensionless parameters, gathered from experience and statistical analysis, associated with limit values or values close to failure.

A comprehensive summary of the most common ones can be found in the study published by Negro, A. et. al (2009). The main parameters considered for this work are summarized below.

3.2.1 *Slope of surface and sub-surface settlement curves (yt)*

Laboratory test results show that the maximum slopes in the settlement basin, near to ground collapse, are around 1/10 for softer or looser soils and 1/30 for stiffer or denser soils. The 1/10 threshold was used in the project because the predominant materials are primarily fine soils with occasional presence of sand lenses.

3.2.2 *Volume of the settling basin in relation to the tunnel area (%Vs)*

The volume of transverse settlements per meter of length, with respect to the area of the excavated tunnel is a good index of performance. It is accepted that the settlement curve can be represented by the normal probability distribution curve (Gaussian curve).

This parameter was initially related to the volume of soil loss; however, Negro (1979) extended the suggestions made by Peck, Hendron and Mohraz (1972), recognizing that both parameters are related to the quality of the construction.

For normal quality, settlement volume values of less than 0.5 - 1% are expected. Under near-failure conditions, this index reaches values between 3% and 40%. These ranges of values were considered in the EL3 project as serviceability limits and ultimate failure thresholds, respectively.

3.2.3 *Dimensionless settlement (U_t)*

Based on tunnel model tests carried out at Cambridge Univ. for tunnels in sands and clays, Negro and Eisenstein (1991) related the safety factor to the vertical displacement at the tunnel keystone and identified a dimensionless parameter (Ut) associated with near-collapse conditions. This parameter is defined as:

$$U_t = \frac{S_t \bullet E_0}{D_{eq} \bullet \sigma_0} \tag{2}$$

Where:
U_t = dimensionless settlement in the tunnel ceiling.
St=Settlement measured at the tunnel ceiling (measured with a subsurface control point).
D_{eq} = Equivalent tunnel diameter.
E_0 = Strain modulus initial tangent in situ at an equivalent radius above the roof.
σ_0 = Effective in-situ stress at keystone level.

For safety factors of 1.5 the value of Ut varies between 0.5 and 1.5. Ut= 1.0 is considered as the limit of serviceability. On the other hand, the models indicated that for Ut values higher than 1.8, collapse conditions occurred.

3.3 *Instrumentation and Monitoring*

It has been previously mentioned that one of the fundamental principles of NATM is to consider the ground as part of the support system; for this reason, instrumentation and a monitoring program should be implemented to follow and control the deformations produced in the ground during the construction of the tunnels.

Monitoring surface settlements allows for the evaluation of the transverse and longitudinal settlement curves of the ground surface associated with tunnel excavation. By conducting monitoring in advance of tunnel construction, it is possible to understand the evolution of these curves from the beginning of the settlements until their stabilization after the excavation face has passed through the respective monitoring profile.

To control the stability of the excavations resulting from the construction of the project's interstation tunnels, the following was implemented.

3.3.1 *Surface Points (As)*

These are made of 25 mm diameter steel bolts, approximately 20 cm long, with rounded heads, embedded in concrete cubes that are semi-buried in the ground or on the existing pavement.

3.3.2 *Sub-Surface Points (Ps)*

These are created using steel profiles anchored at a depth located more than 1 m above the tunnel keystone (see Figure 5).

This anchorage is made at the base of a borehole using cement mortar or lean concrete. A bolt or measuring point is welded to the upper end of the steel profile. Finally, the instrument must be protected by a rigid box installed at surface level.

3.3.3 *Convergences (CP)*

These correspond to the internal deformation control points in the tunnel, equipped with high precision, positive-centered optical reflecting prisms. The reflector will have a defined center and will allow measurements from both sides without the need to be rotated.

3.3.4 *Monitoring Points in Structures and Buildings (AE)*

To measure the settlement of structures and buildings in the vicinity of the tunnels, the same instruments used to determine the settlements were employed.

The only difference is in the reference points, which are embedded in external walls or surfaces, or in internal load-bearing walls of the building, by means of reference bolts.

3.3.5 *Monitoring Program*

The monitoring program for interstation tunnels includes various configurations: basic, medium and high-level. This work will analyze the monitoring sections that include control points for the measurement of convergences (PC), surface settlements (AS), settlements of structures (AE) and subsurface settlements (PS).

Figure 5 details the T-5 type monitoring section, which is configured by a subsurface point along the tunnel axis, surface points, and convergences inside the tunnel. The dimensions of the figure are for reference only.

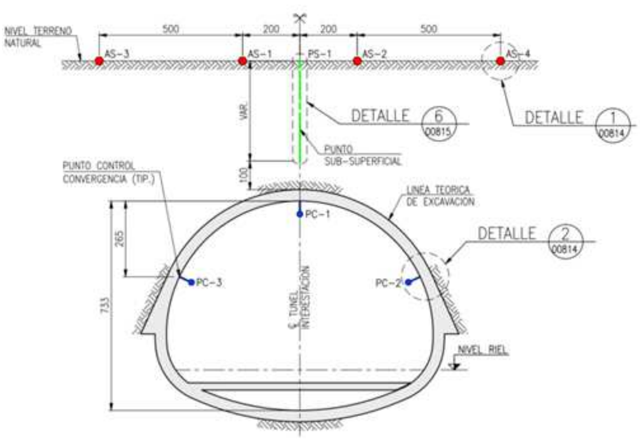

Figure 5. Monitoring Section Type T5 - High Control Level Control (ARCADIS-WORLEY CONSORTIUM, 2016).

Special monitoring of structures that could be affected by tunnel construction was conducted at the following locations:

- Intersection of the concessioned vehicular highways Ruta 5 Norte with Vespucio Norte, located between Pique Frei Montalva and the Maneuvering Queue of Los Libertadores Station L3.
- Vehicular viaduct (reinforced earth ramp) located at the crossing of the State Railways Company (EFE) railway line, between the Ferrocarriles and Pique Frei Montalva stations.
- Housing building adjacent to the Lo Cruzat Poniente interstation tunnel, between Lo Cruzat and Plaza de Quilicura Stations.

3.4 *Original Project Excavation Sequence and Definition of Threshold Values*

For the modeling, an initial advance of 1 m was considered for the top part of the tunnel section (hereinafter referred to as "*top heading*") with a maximum offset of 6 m between the top excavation front and the ring closure with the invert; the invert closure was performed in 2 m sections. Additionally, the case was analyzed for an offset between the top and the invert of 12 m.

The settlement basins of the models performed show different settlement values depending on the stratigraphy and top excavation advance, with the most unfavorable case being the fine soils and sands with a 6 m lag, which reaches a maximum value of about -38 mm (see Figure 6).

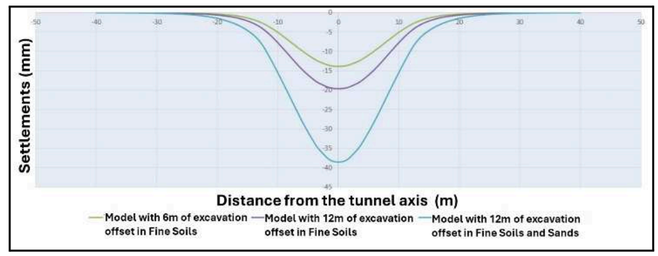

Figure 6. Estimated Surface Settlement Curves for Rail Elevation=13 m (ARCADIS-WORLEY Consortium 2017).

A single expected threshold of -18 mm was used to control the project's inter-station tunneling, since, as shown in Figure 6, for fine soils with top lags of 6 m and 12 m, settlement values of approximately 14 mm and 20 mm are estimated.

Instead, the alarm value used was -33 mm, defined according to the dimensionless settlement performance parameter (Ut=1,20), outlined in chapter 3.2.3.

3.4.1 *Flexible Excavation Sequence*

During the development of the construction phase, the contractor gradually requested flexibility in the excavation sequence of the inter-station tunnels by issuing Requests for Information (RFI), which were approved by the SDO (Site Supervision) team of the AWPA Consortium (Arcadis-Worley), these representatives ensured the Engineering Design Intent in the field, mainly through monitoring and stratigraphy of the excavation fronts.

In most work fronts, authorization was given to maintain a maximum offset length of 20 m between the top heading excavation front and the bottom, together with the execution of bottom in passes of 6 m (or 6 frames depending on whether they were excavated in lengths of less than 1 m).

Since a greater presence of sand was detected around the layout near to the Lo Cruzat Construction Shaft, settlements were recorded that exceeded the expected threshold (-18 mm) with values between -20. mm and -27.5 mm. Specifically in the PK -1+665 section, a maximum value of -32.4 mm was reached, close to the alarm value (-33 mm). On the other hand, some settlement basins caused angular distortions that exceeded the serviceability threshold (1/500), with a maximum value of 1/306 in section PK -1+665.

It is important to emphasize that the maximum values of settlements and angular distortions were located within the vehicular lane of Matta Avenue (areas close to the tunnel axis), with zero settlements and considerably lower angular distortions in the areas with building lines, thus reducing the possibility of generating eventual damage to the structures.

3.4.2 *Construction Sequence Restriction per Residential Building*

Due to the high settlements previously recorded together with the considerable thickness of 5 m of anthropic fill detected in the exploration campaign and the proximity of the interstation tunnel to a residential building (maximum distance 5.3 m between the tunnel edge and the building corner), the contractor was instructed to implement the following actions in order to reduce surface settlements between sections PK -1+790 and PK-1+815 (see Figure 7).

- Execute top heading excavation passes spaced 50 cm apart.
- The frame type is changed, raising the frame support from the rail level to the tunnel equator level (decreasing the top heading excavation sections).
- Increased monitoring in the area.

The settlements observed in the area with a maximum gap of 20 m between the top heading and bottom prior to the building, and those in the area where the construction sequence was reduced due to the location of the building, are presented in detail in the following chapter, where numerical modeling was performed for both scenarios.

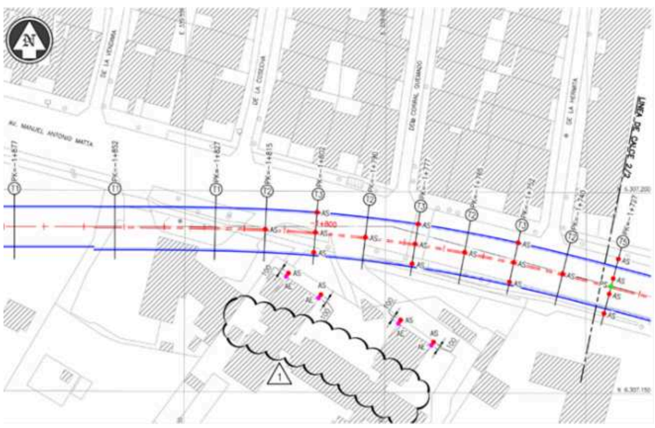

Figure 7. Original Monitoring Sections of the Lo Cruzat Oriente Substation Tunnel Building (CONSORCIO ARCADIS-WORLEY, 2016)

4 NUMERICAL MODELING

The constitutive model implemented for the development of the project is characterized by the Mohr-Coulomb failure criterion and a nonlinear envelope for volumetric change called CY Soil (Cap-Yield). It can be adjusted according to different soil behavior characteristics through the selection of hardening laws and employs a stress-strain law like the hyperbolic model considering the incidence of the stress path on the deformation modulus.

One of the important characteristics of this constitutive model is that it allows the incorporation of a frictional hardening law, which better reproduces the stress-strain behavior of soils in drained conditions. It also has the advantage of simulating the hardening effect in unloading-reloading stages, especially in the case of unloading (excavations).

4.1 *Comparison of Monitoring vs. Numerical Modeling Results*

Surface and subsurface settlement curves were obtained from the Cysoil models made in FLAC3D, using the excavation sequences previously described. Figure 8 shows the settlement distribution obtained from FLAC 3D of the Lo Cruzat Poniente Inter-Station Tunnel model, which includes the excavation sequence restricted near to the residential building.

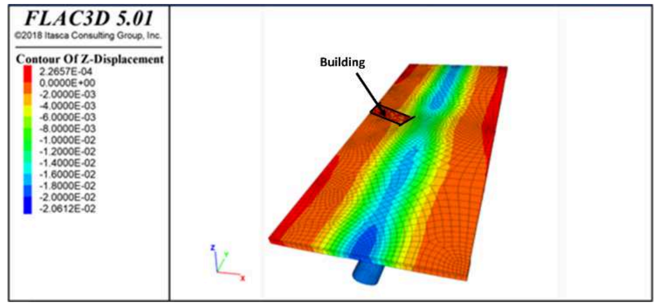

Figure 8. Distribution of surface settlements in the Lo Cruzat Poniente Inter-Station Tunnel model (Residential Building).

Once the settlement curves of the models have been obtained, they can be exported to an Excel file, for plotting alongside the monitoring curves, adjusted using the least squares procedure.

4.1.1 *Settlement Troughs Flexible Excavation Sequence (20 m maximum offset)*

Figure 9 represents the settlement basin of the Las Parcelas East Inter-Station Tunnel, while Figure 10 corresponds to the Lo Cruzat Poniente Tunnel, both excavated with a maximum lag of 20 m. In both figures, it is observed that the curves obtained from the numerical models are more extended or present a greater amplitude than the adjusted monitoring curves, consistent with the findings reported by Layera, S (2018).

In addition, Figure 11 shows two different models created in the same area, considering the presence or absence of 1 m thick sand lenses observed at the excavation face, with the purpose of analyze their influence on the settlement results of the models.

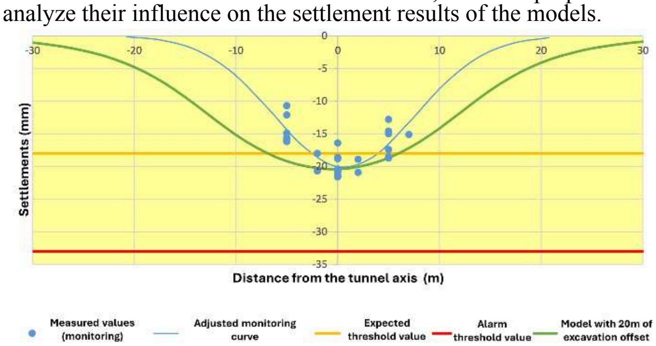

Figure 9. Settlement Troughs Las Parcelas East Substation Tunnel - Maximum Vault-Counter Vault Offset 20 m.

Figure 11. Lo Cruzat Poniente Intersection Tunnel Model (on the left without sands,

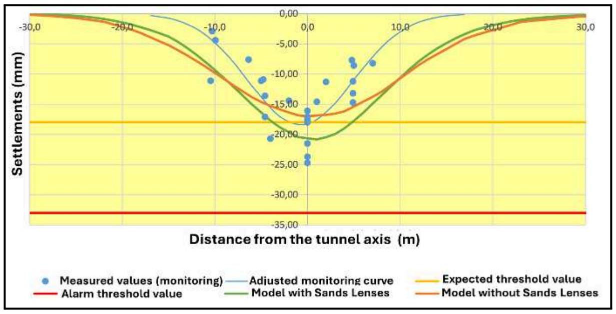

Figure 10. Settlement Troughs Lo Cruzat Poniente Inter-Station Tunnel - Maximum Vault-Contra-Vault Offset 20 m (Prior to the Residential Building).

4.1.2 *Construction Sequence Restriction for Residential Building*

Figure 12 shows the settlement basins in the numerical model where the excavation sequence is reduced due to the presence of the building. Unlike what was observed in the other 2 settlement basins, with a maximum excavation lag of 20 m (Figure 9 and Figure 10), in this case, the adjusted monitoring curve presents a shape like those of the numerical models. It is considered that this difference in the results could be explained by the existence of a greater number of monitoring data points farther from the tunnel axis (points located beyond the inflection point of the trough).

It can be observed that the model including sand lenses generates greater settlements and maximum slopes than those obtained in the model without sand, both for the sequence with a maximum lag of 20 m and for the area near the residential building. In other words, the use of the design hypothesis that contemplates the presence of sand lenses with thicknesses less than 1.5 m, included within the U-2 geotechnical unit, could result in an underestimation of settlements during construction.

To evaluate the influence of monitoring data located beyond the inflection point of the basin, the following section will analyze the basins obtained in another sector of the project, corresponding to the intersection with concessioned highways, where the monitoring points were increased as discussed in chapter 3.3.5.

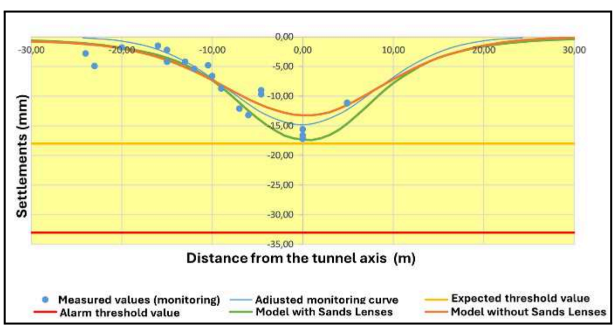

Figure 12. Settlement Troughs Lo Cruzat Poniente Inter-Station Tunnel - Housing Building Sequence.

4.1.3 *Settlement Basins Intersection of the concessioned vehicular highways Ruta 5 Norte with Vespucio Norte located between Pique Frei Montalva and the Maneuvering Queue of Los Libertadores Station L3.*

To confirm the previously observed influence of monitoring points far from the tunnel axis (after the inflection point of the curve), data from the Frei Montalva East Inter-Station Tunnel are analyzed. In this study area, the tunnel was excavated adjacent to a vehicular highway as shown in Figure 13. For this reason, it was decided to increase the monitoring, as discussed in chapter 3.3.5, by incorporating additional points on the columns of the highway viaduct.

In this area of the project route, adjacent to the sector studied by Layera S. (2018), a greater concentration of gravels is detected at the excavation face, maintaining fine northwest soils (Unit U-2) between the keystone of the tunnel to the artificial fills on the surface (average thickness 1.5 m).

Due to the proximity to the highway, from KP 0+700 towards the east, the excavation sequence could not be made more flexible, maintaining the sequence indicated in chapter 3.4. On the other hand, in the area before the highway, excavation was allowed with a maximum offset of 20 m (section 3.4.1), recording settlements considerably greater than the expected value with a maximum of -24.2 mm at PK 0+605 and 0+616, it is important to mention that these monitoring sections are in a garden adjacent to the highway, without nearby structures (see Figure 13).

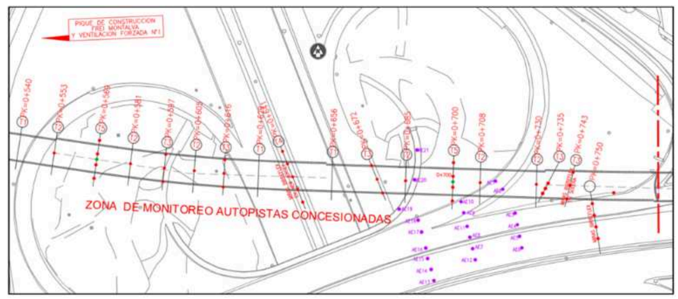

Figure 13. Monitoring Point Plan Frei Montalva Inter-Station Tunnel Crossing with Freeways

To perform the analysis, first, only the monitoring points located at a maximum distance of 5 m from the tunnel axis are selected. Figure 14 corresponds to the least squares fitted curve; additionally, the settlement trough of the numerical model is presented, which is like what was previously seen in Figure 9 and Figure 10, i.e. the monitoring trough is narrower than that of the CYsoil model.

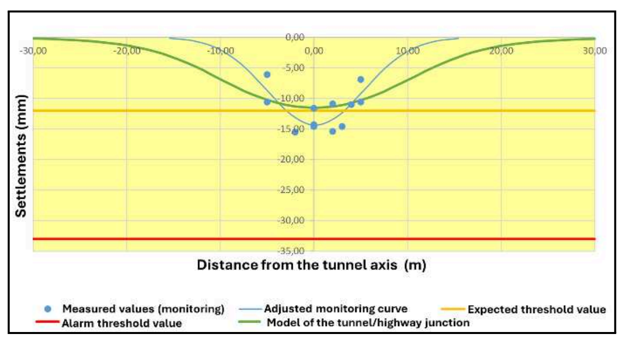

Figure 14. Settlement Curves of Numerical Model and Adjusted Curve with Monitoring points at 5 m from the Frei Montalva Inter-station Tunnel axis.

Simultaneously, a new adjustment is made considering all the monitoring points located at more than 5 m, obtaining a much larger basin, similar to that of the CYSoil model, as shown in Figure 15, confirming the hypothesis previously observed in the settlement basin of the Lo Cruzat residential building (Figure 12).

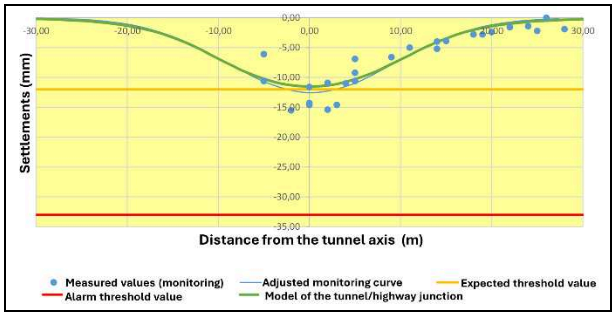

Figure 15. Numerical Model Settlement Curves and Adjusted Curve with Monitoring Points at 5 m from the Frei Montalva Inter-station Tunnel axis.

As described in the previous paragraph and as can be seen in Figure 15, it is concluded that by having monitoring points as far as possible from the tunnel axis (and from the inflection point of the trough), it is possible to fit a monitoring curve with similar characteristics to those obtained with the CYSoil constitutive model. Otherwise, the troughs fitted with points located within a maximum distance of 5 m from the tunnel axis are more closed than those obtained from numerical models due to the lack of monitoring data beyond the inflection point of the trough.

5 FINAL COMMENTS AND FUNDAMENTAL PARAMETERS SETTLEMENT BASINS

According to the analyses performed, it was observed that the characteristics of the monitoring basins adjusted with points close to the tunnel axis (located within the inflection point distance) differ from those obtained by numerical modeling. This situation was observed in the sections of Las Parcelas Oriente and Lo Cruzat Poniente tunnels excavated with a maximum offset of 20 m.

On the other hand, around the residential building of the Lo Cruzat Poniente Inter-Station Tunnel, the number of monitoring points was densified, resulting in a greater amount of measurement data farther from the tunnel axis. In this way, by means of a least squares adjustment, we obtained a settling basin with similar characteristics to those obtained by means of the CYSoil constitutive model in Flac 3D.

Table 3 summarizes the key parameters of the basins analyzed in this study area. The K value is similar in the monitoring basins and in the CYsoil model with sand lenses.

Table 3. Fundamental parameters of settlement basins Lo Cruzat Poniente Inter-Station Tunnel - Residential Building Sector.

To ratify what was observed in the Lo Cruzat housing sector, in Section 4.1.3 we analyzed the monitoring data from the Frei Montalva Oriente interstation tunnel, a sector in which additional points were installed due to the proximity of the tunnel to vehicular highways.

In this zone, two monitoring settlement curves were fitted: the first one considering only the points close to the axis, while the second one included all the additional points installed, obtaining fundamental parameters of the same order as those observed in the settlement curve of the CYSoil numerical model. Table 4 shows the fundamental parameters of the settlement basins in this area of the project.

6 CONCLUSIONS

Observing the results of the present work, it is considered that with the CYSoil constitutive model, using the geotechnical parameters provided by the Soil Mechanics project, it is possible to adequately predict the behavior of the "Fine Soils of Northwest Santiago", providing a reasonable estimate of the settlements to be expected during construction.

The work of Layera, S. (2018) concluded that the settlement curves for Cysoil presented similar maximum settlements obtained in monitoring, but with a larger amplitude (inflection point further away from the tunnel axis), such observation could have been influenced by the analysis of monitoring points located at a distance lower than the inflection point.

Table 4. Fundamental parameters of settlement basins in the Frei Montalva

To obtain an optimal interpretation of the settlement basins, it is essential to have an abundant collection of monitoring data, especially in the distant sectors, i.e. those located beyond the inflection points of the basin. For this reason, it is highly recommended to increase the number of monitoring points in the standard monitoring sections of future tunnel projects, at least for those located at a certain distance (100-200 m).

It is estimated that the ideal is to have at least seven monitoring points in the cross sections, of which at least for two to four are located beyond the turning point. To achieve materialize this type of sections, the intersection of streets transversal to the tunnel axis can be utilized.

The numerical models carried out with the presence of sand lenses in the excavation face of the Lo Cruzat Inter-station Tunnel generate higher settlements, both for the sequence with a maximum lag of 20 m and for the area of the residential building. In other words, the use of the design hypothesis that contemplates the presence of sand lenses with thicknesses less than 1.5 m, within the U-2 geotechnical unit, could result in an underestimation of settlements during construction.

Based on the data analyzed in the present work, it is considered that for preliminary evaluations in future tunnel pre-projects to be developed in the Soils of similar characteristics to the Fine Soils of Northwest Santiago (for the range of soil coverages studied) the fundamental parameters of the basins can be estimated using the following values ranges:

- Settlement volume, Vs (%): 0,40%-0,43%.
- k=i/H : 0,52 – 0,63; for depths H of 17,6 m and 12,9 m respectively.

Finally, it is proposed that a future a sensitivity analysis be conducted on the different parameters of the constitutive model or other relevant factors, such as the coefficient of earth pressure at rest (K_0), to improve the fit between the results of the numerical models and the monitoring.

7 RECOMMENDED WORKING LINES TO BE FOLLOWED

It is suggested that, in the future, a sensitivity analysis of the different parameters of the constitutive model or other relevant factors, such as the coefficient of thrust at rest (K0), be studied to try to improve the fit between the results of the numerical models and the monitoring.

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