# Control of regional subsidence around a tunnel with the method of longitudinal confining walls

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ABSTRACT
Tunnels built in clay deposits in Mexico City are subjected to long term loads and displacements which are generated by subsidence from pore pressure collapse due to deep water pumping. In order to diminish such effects, this paper proposes a control method based on building longitudinal walls to confine the tunnel. The solution has several advantages: it is controllable, adaptable and reversible at all times. It was proposed to Line 12 of the Mexico City subway system, between Ermita and Mexicaltzingo stations, where thick clay volumes exist in a consolidating process, although these stations are supported on strata with little deformation capacity. The method's efficiency is confirmed by two- and three-dimensional numerical analysis, and the confining walls' length is defined to avoid serious tunnel deformations or instability. The solution also controls boundary differential settlements.

RESUMEN
Los túneles construidos en los depósitos de arcilla de la ciudad de México están sometidos a cargas y desplazamientos de largo plazo generados por la consolidación del suelo al abatirse las presiones de poro por el bombeo profundo. A fin de disminuir dichos efectos, en este trabajo se propone un método de control que consiste en construir muros longitudinales confinantes al túnel. Con esta solución tiene varias ventajas: constructivamente es controlable, adaptable y reversible en todo momento. Se estudia la implementación de esta técnica al tramo de túnel de la línea 12 del metro de la ciudad de México, entre las estaciones Ermita y Mexicaltzingo, donde se presentan espesores importantes de arcilla en proceso de consolidación, pero adicionalmente estas estaciones se encuentran apoyadas en estratos poco deformables donde la subsidencia es despreciable. Mediante análisis numéricos bi y tri-dimensionales se estudia la eficiencia del método de control y se define la longitud de los muros confinantes tal que se eviten las deformaciones importantes en el túnel así como su inestabilidad. Además, se muestra la efectividad de la solución en el control de los asentamientos diferenciales inducidos en las colindancias.

## 1 INTRODUCTION

The tunnel linking the Mexicalzingo and Ermita stations of Line 12 in the Mexico City subway system is 2.5 km long, with 10.2 m diameter, running along Ermita Avenue, embedded in clay deposits of the city's transition zone, which are subjected to accelerated subsidence processes originating from pore collapse.

These subway stations are supported on deposits with very little local subsidence, but the tunnel itself is affected by a variable annual subsidence of 3 to 6cm (Rodriguez y Soria, 2010), inducing long term stress concentrations at its support, and differential settlements around the tunnel affecting adjacent premises and Ermita Avenue, which has heavy traffic. Subsidence effects are critical at the areas with larger clay thickness and near the stations, in particular Mexicalzingo station.

To diminish those effects, the following solutions are proposed:

a. Improvement with injections of mortar into the soil under the tunnel.
b. Isolation of the tunnel zone with longitudinal and confining walls, and soil improvement with mortar injections under the tunnel.
c. Isolation of the tunnel zone with longitudinal and confining walls, and plastic screening on the top part of the longitudinal walls.

This article presents the numerical analysis of these solutions, verifying the substantial reduction of differential subsidence both in longitudinal and transversal directions, and reduced stress concentration on the tunnel's coating

## 2 GENERAL DESCRIPTION OF THE PROJECT

Line 12 of the Mexico City subway system crosses the city through the middle, east (Tlahuac) to west (Mixcoac). See Fig 1. Its total length is 25.6km, of which 2km are on the surface, 11.6km on a raised viaduct (east zone) and the rest in a tunnel (west zone).

Since soil will be excavated along the entire tunnel, an earth pressure balance (EPB) machine will be used as the main excavating procedure, except at the tunnel's west end, where a conventional tunneling procedure is used.


Figure 1. Line 12 layout with its construction zones (Benamar y Zaldívar, 2010).

Stratigraphic conditions along the tunnel's layout are variable, from volcanic, fluvial and alluvial deposits from the Las Cruces and Monte Alto mountain ranges, to highly compressible lacustrine clay deposits of the Mexico Valley and some basalt deposits sneaking in from the Santa Catarina hillsides.

The subway line has 20 stations and, since it crosses densely populated areas and considering stratigraphic conditions, the solution is underground for the west section and superficial for the east section. Transition is at the Mexicalzingo station zone.

### 1.1. Mexicalzingo and Ermita stations

Both stations are supported on hard strata, with the foundation for Mexicalzingo station made of pile walls resting on the hard layer, whereas Ermita station rests on the deeper deposits.

### 1.2. Inter-station tunnel

It is of circular section, with 10.2m exterior diameter, with a single support system, formed by 0.4m thick rings of 8 elements (7 main pieces and 1 keystone). The support's discontinuity makes it flexible, but it also reduces its resistance, and filtrations are allowed, depending on the level of induced deformation. Therefore, in the long term it is to be expected that subsidence will induce cracks and filtration.

### 1.3. Stratigraphic profile

Fig. 2 shows the representative stratigraphic profile along the inter-station tunnel's zone, which is formed by a surface crust 8 m thick, followed by layers of very compressible clay down to a depth of 27m. Then there is a stratum 2m thick named hard layer, and then another very compressible clay layer 3m thick named lower clay series. Finally, there are high resistance and low deformation fluvial deposits. The same figure shows pore pressure conditions and the current level of phreatic water (2m), where important pressure collapse occurs, mainly from 16m deep downward, caused by deep water extraction. Table 1 shows the soil's mechanical properties used in the numerical analyses.

The tunnel has an approximate east-west orientation, and toward the western Ermita station, clay soil thickness tends to disappear, as well as pore pressure.

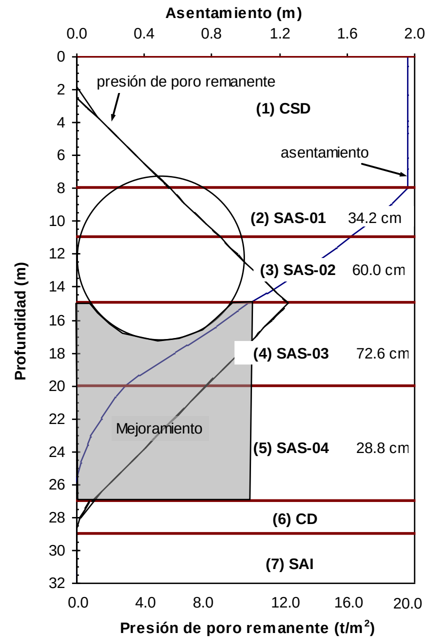



Figure 2. Stratigraphic and piezometric profiles of the Mexicaltzingo-Lumbrera site

Table 1. Soil mechanical properties

| Unidad | Profundidad (m) | | Resistencia cortante | | | | Deformabilidad | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | Corto plazo | | Largo plazo | | Corto plazo | Largo plazo | | |
| | De | Hasta | $c_u$ (t/m$^2$) | phi | $c_d$ (t/m$^2$) | phi | $E_u$ (t/m$^2$) | $m_v$ (m$^2$/t) | $m_{v,corr}$ (m$^2$/t) | Ed (t/m$^2$) |
| CS | 0 | 8 | 10 | 25 | 10 | 25 | 1500.0 | 0.000 | 0.000 | 1500.0 |
| SAS1 | 8 | 11 | 4.6 | 0 | 1 | 20 | 920.0 | 0.019 | 0.030 | 32.8 |
| SAS2 | 11 | 15 | 6.2 | 0 | 1 | 20 | 1230.0 | 0.017 | 0.026 | 37.8 |
| SAS3 | 15 | 20 | 8 | 0 | 1 | 20 | 1615.0 | 0.012 | 0.019 | 51.9 |
| SAS4 | 20 | 27 | 11.5 | 0 | 1 | 21 | 2300.0 | 0.008 | 0.013 | 77.9 |
| CD | 27 | 29 | 20 | 28 | 20 | 28 | 4000.0 | 0.000 | 0.000 | 4000.0 |
| SAI | 29 | 32 | 19.2 | 0 | 1 | 23 | 3890.0 | 0.008 | 0.013 | 77.9 |
| MOD | ZONA | | 100 | 0 | 100 | 0 | 1790.0 | 0.000 | 0.000 | 1790.0 |

| Unidad | Profundidad (m) | | Peso volumétrico | | Rel. Poisson | | Coef. emp. |
|---|---|---|---|---|---|---|---|
| | | | Seco | húmedo | Corto plazo | Largo plazo | reposo |
| | De | Hasta | $\gamma_s$ (t/m3) | $\gamma_h$ (t/m3) | $\nu$ | $\nu$ | ko |
| CS | 0 | 8 | 1.30 | 1.38 | 0.35 | 0.35 | 0.538 |
| SAS1 | 8 | 11 | 1.15 | 1.18 | 0.30 | 0.35 | 0.493 |
| SAS2 | 11 | 15 | 1.15 | 1.18 | 0.30 | 0.35 | 0.493 |
| SAS3 | 15 | 20 | 1.15 | 1.20 | 0.30 | 0.35 | 0.493 |
| SAS4 | 20 | 27 | 1.30 | 1.35 | 0.30 | 0.35 | 0.493 |
| CD | 27 | 29 | 1.60 | 1.60 | 0.35 | 0.35 | 0.538 |
| SAI | 29 | 32 | 1.30 | 1.35 | 0.30 | 0.35 | 0.493 |
| MOD | ZONA | | 2.00 | 2.10 | 0.25 | 0.25 | 0.538 |

## 3 PROPOSED SOLUTIONS

In order to reduce regional subsidence, both in the tunnel area and the adjacent soil, and long term mechanical elements generated on the coating, various solutions were proposed, among which the following stand out:

a. *Mortar injections under tunnel*. As a subsidence control measure in the tunnel area, improving the existing soil under the tunnel was proposed (see Fig. 2) using a plastic mortar with volumetric weight of $15kN/m^3$, elastic module $E=179kN/m^2$ and cohesion $c=100kN/m^2$. This solution, as shown later, was inadequate from the point of view of stresses generated on the lining and of the surrounding differential subsidence.

b. *Longitudinal confining walls and bottom improvement*. This solution consists of placing walls along either side of the tunnel, with frictionless wall on the side of the soil next to the tunnel. The purpose of the confining longitudinal walls is to reduce the differential subsidence that affects the boundaries and the tunnel zone, with improvement by mortar injections under the tunnel. Given that the longitudinal walls are supported on the deeper deposits, they tend to emerge when regional subsidence advances, so it will be necessary to do corrective surface maintenance.

c. *Longitudinal walls and superficial screen*. This solution is similar to the previous one but soil improvement under the tunnel is replaced by a superficial screen that accompanies the longitudinal walls, which is placed on the side facing the tunnel and down to the depth of the tunnel's keystone, in order to control differential subsidence by reducing the friction generated on the confining walls, when soil descends due to subsidence.

## 4 NUMERICAL ANALYSIS

The numerical analysis of the proposed solutions was through the two- and three-dimensional finite element method (2D and 3D FEM), considering the soil's elastic plasticity behavior by means of the Mohr-Coulomb yield criterion in both short and long term conditions. For the longitudinal walls plate elements are used, whereas for the bottom improvement and that of the superficial screen solid elements are used with elastic plasticity behavior, also following the Mohr-Coulomb yield criterion.

Fig. 3 shows the 2D FEM models for the solutions with improvement of the bottom part of the tunnel (a), longitudinal walls and improvement (b), and longitudinal walls with superficial screen (c).

## 5 RESULTS

### 5.1 Project's initial condition

As a starting point, long term subsidence was determined without the tunnel, on open field, for a lifetime of 50 years. The maximum subsidence obtained was 1.96m. When considering the presence of Mexicalzingo station in the stratigraphic profile, which is supported on the hard layer, a subsidence of 5cm was obtained, so in the long term there will be a difference of 1.91m between the station and the surrounding area.

Fig. 4a shows the numerical analysis taking the tunnel into account. Note that the subsidence determined for open field is at the tunnel's far section, but on the tunnel's axis the surface subsidence is 1.31m. In this case, there is a 65cm difference with respect to the open field. Fig 4b shows deformations and mechanical elements obtained on the tunnel's lining, generated during the constructive process, but mainly due to the thinning produced in the clayey strata SAS-1 to SAS-3 by pore pressure decrease over 50 years. Maximum deformations of the tunnel's section of 2% of its diameter are observed (a horizontal lengthening of 20.6cm), indicating a critical condition on the lining ring's structural work, and mechanical elements larger than the resistant ones, so that the long term working conditions of the tunnel's support are inadequate, and nearby streets and buildings could be affected by surrounding differential subsidence.

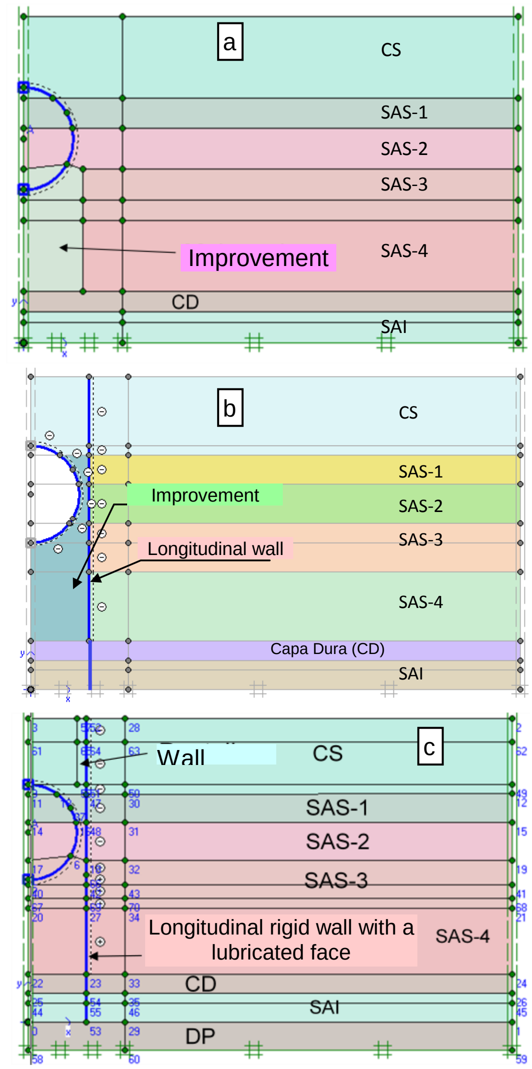
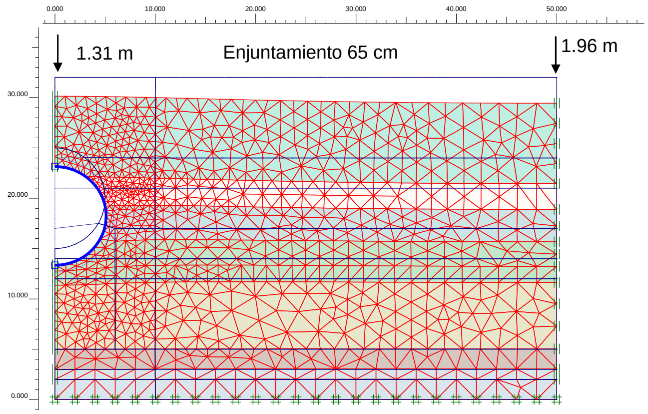



Figure 3. Conceptual models with 2D FEM, to study solution with bottom improvement (a), longitudinal walls and improvement (b), and longitudinal walls and superficial screen (c).

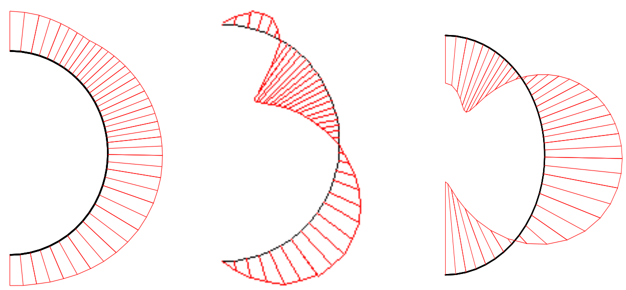
### 5.2 Analysis of the solutions

Fig. 5 shows the deformations obtained for the various proposed solutions: a) improvement of the tunnel's bottom part, b) confining longitudinal walls supported in deeper deposits with soil improvement in the tunnel's bottom part, and c) confining longitudinal walls supported in deeper deposits with accompanying superficial screen.

The same figure also indicates observations for each solution.




a) Deformed mesh



Max axial =-935 kN/m    Max shear =-372 kN/m    Max moment =656 kN-m/m

b) Mechanical elements on lining

Figure 4. Deformed mesh of finite elements (a) and mechanical elements on coating (b), for the tunnel's long term working conditions.

According to Fig. 5, improvement of the soil under the tunnel reduces the zone's subsidence, but also increases the differential subsidence produced in the surrounding areas, so the solution was to use the superficial plastic screen. The confining walls work to isolate the tunnel zone from the boundaries and reduce the differential subsidence to a minimum; also, the longitudinal wall defines a frontier that presents an abrupt change of levels. The third method, apart from isolating the tunnel from the boundaries, considers control of the negative friction force on the inner sides of the confining walls, which is capable of nullifying the subsidence under the tunnel; the accompanying superficial plastic screen's function is to reduce these negative friction forces on the wall's top side and cause the superficial soil's weight to produce subsidence under the tunnel where required along the tunnels' layout.

Therefore, the solution that meets the proposed objectives is that of longitudinal walls and accompanying plastic screen; nonetheless, it is possible to ask the following questions: Is it necessary to use the confining walls along the entire length of the tunnel walls? What is the optimal length for the walls?

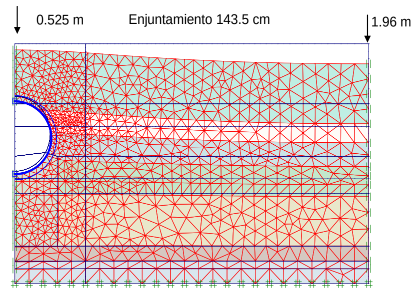
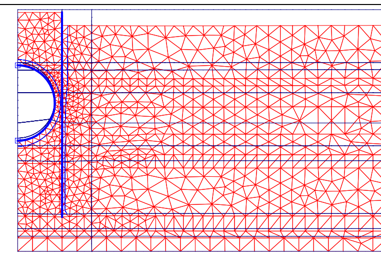
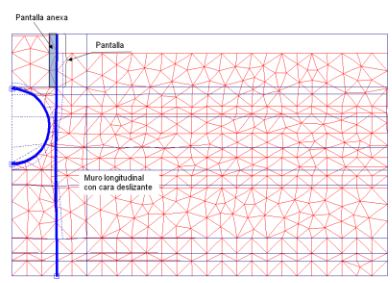
| Proposed solution | Deformed finite elements mesh<br>Comments |
|---|---|
| Improved soil bellow tunnel |  |
| | Significant reduction of settlements, from 1.31m to 0.52m, but the differential settlement are higher, 1.44m, which will affect the surrounding structures. The mechanical elements in the lining are inadmissibles. This solution requires time to improve the soil beneath the tunnel. |
| Confined walls and improved soil bellow tunnel |  |
| | Differential settlements are small and the mechanical elements are admsissibles. It is not possible to control subsidence and it is required to improve the soil bellow tunnel, before construction. Installation of the confined walls could be after tunnel construction. |
| Confined walls with Accompanying superficial screens |  |
| | Differential settlements are small and the mechanical elements are admsissibles. It is possible to control subsidence and it is required to improve the soil bellow tunnel, before construction. Installation of the confined walls and screens could be after tunnel construction. |

Figure 5. Deformed finite elements mesh for the various proposed solutions, and their respective comments.

These questions refer to the fact that long term subsidence is almost null at the station zones and where improvement for the EPB machine's entry/exit is applied, whereas there are no restrictions in the remaining section.

To answer these questions, one must refer to the 3D numerical model, where it is possible to take into account the problem's three dimensional effect, meaning the station's presence, the improvement zone and the solution with confining walls.

Fig. 6 shows the finite elements mesh that was used, indicating the station's zones, the improvement zone in the EPB machine's entry/exit, the condition with confining walls, and the tunnel without adaptations or restrictions.

Given the computing requirements, a parametric analysis was carried out varying the tunnel's free length

(TL, Fig. 6), meaning the tunnel's length with no longitudinal walls, in order to calculate the deformation along the tunnel at its bucket's level. The tunnel's free lengths considered were 50, 60 and 70m.

Fig. 7 shows the deformations at the tunnel bucket's level for the tunnel free lengths analyzed; as example of interpretation, the deformation 50-70 corresponds to 50m of longitudinal wall and 70m of free tunnel. The same figure indicates the deformation produced by a 5% aperture restriction of the voussoir rings, failure restriction, and a 3% service restriction. The difference between deformations 50-50, 50-60 and 50-70 is due to the numerical model's limitations. Nonetheless, the 50-70 deformation, the least smooth slope, is very near the deformation calculated with service restriction (3%), so that in the long term (50 years) the tunnel would present no structural problems on its lining.

Fig. 7 shows that the more removed a free tunnel section is from the zone with longitudinal walls, the tunnel's weight (service load) increases, as does the subsidence, but no high values are obtained in the mechanical elements on the tunnel's coating. This condition can generate doubts about the performance of the longitudinal walls along the tunnel, but stratigraphy has an important role in making decisions in that respect, because upon leaving the Mexicalzingo station behind, the thickness of the compressible clay is reduced.

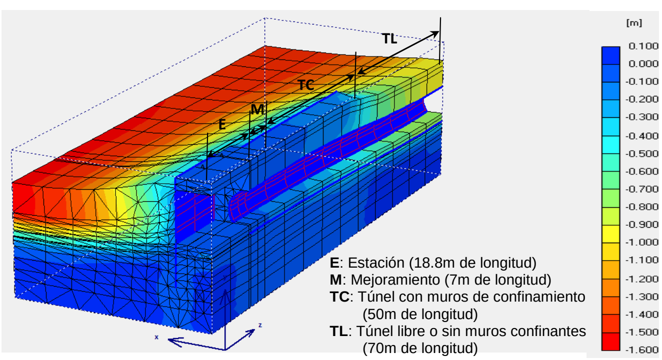



Figure 6. Deformed 3D finite elements mesh for the study of the definition of the confining wall length.

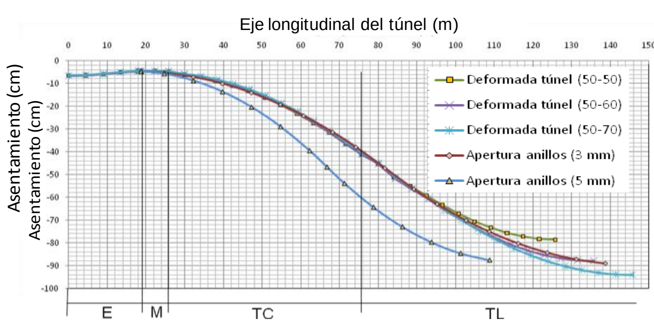



Figure 7. Influence of the free tunnel's length (TL)

## 6 CONCLUSIONS

A solution is presented to reduce differential superficial subsidence produced at the zone of the tunnel and its surroundings, as well as the values of the mechanical elements on the tunnel's lining by the effect of regional subsidence existing between the Mexicalzingo and Ermita stations of Line 12 of the Mexico City subway system.

The proposed solution consists of the construction of confining longitudinal walls located at the sides of the tunnel and supported at the deeper deposits, additionally accompanied by superficial plastic screens of variable depth, which will help to control subsidence at the tunnel's zone by reducing the negative friction generated in the confining walls.

The solution was studied using 2D and 3D finite element numerical methods, which prove that the solution is capable of reducing the subsidence generated at the tunnel's zone without producing important differences in the surrounding zones, and diminish the working conditions of the tunnel's only lining. Based on the results of the 3D model, we recommend applying the solution at a length of no more than 50m.

## 1 REFERENCES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