Numerical Analysis of a Tunnel Intersection

Analyse numérique de l'intersection de tunnels

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ABSTRACT: This paper presents a numerical study of the static behavior of the intersection of two major metro lines located in a soft lacustrine clay deposit overlaid by a very dense clayed sand deposit, in Mexico City. The intersection consists of a new tunnel excavated under an existing metro station-tunnel system, using the earth pressure balance, EPB, construction technique. This required the construction of a support structure for the station foundation. This structure was built inserting metallic beams under the foundation, and supporting these beams with metallic frames. In order to build the support structure, a couple of excavations were previously carried out at each side of the station foundation, using Milan walls. A 3D finite differences model was developed to simulate the construction procedure. An elasto-plastic model with a Morh-Coulumb failure criterion was used to represent the stress-strain soil behavior of the geomaterials found at the site. The vertical and horizontal displacements in the soil mass due to the construction of the support structure and the excavations of the tunnel were computed. From the numerical study, insight was gained regarding the behavior of this type of structures built in very soft clay.

RÉSUMÉ : Cet article présente une étude numérique du comportement statique de l'intersection des deux principales lignes du métro à Mexico situées sur des dépôts d'argile lacustre doux superposé d'un sable argileux. L'intersection consiste en un nouveau tunnel excavé sous le système d'un tunnel de station de métro existant, en utilisant la technique de construction à pression de terre, EPB. Il a été pour ceci nécessaire de construire une structure de support pour les fondations de la station de métro. Cette structure a été réalisée en insérant des poutres métalliques sous les fondations, et en supportant ces poutres par l'intermédiaire d'un cadre métallique. Afin de construire la structure du support, il a été réalisé auparavant deux excavations de chaque côté des fondations de la station en utilisant des murs Milan. Un model tridimensionnel des différences finies a été développé pour simuler la procédure de construction. Il a été utilisé un modèle élasto-plastique Morh-Coulomb pour la représentation du comportement contrainte-déformation des géomatériaux rencontrés sur le site. Les déplacements verticaux et horizontaux se produisant au sein du sol suite à la construction du support structurel et à l'excavation du tunnel ont été calculés.

KEYWORDS: tunnel intersection, numerical model, finite differences.

1 INTRODUCTION.

Construction of tunnels induce changes in the original stress state of a soil mass. These modifications lead to displacements [1, 2], which, in some cases, may affect nearby buildings due to differential settlements on the surface. For that reason, these stress changes and displacements have to be studied to guarantee the safety of such structures. This problem becomes more challenging in tunnel intersections, where tunnel-tunnel interaction must be assessed. This can be achieved by numerical analysis. In this paper, a numerical analysis of the static behavior of an intersection between a new tunnel of a major metro line and an existing metro station located in Mexico City is presented. The site is found in the so-called "Transition zone" (zone II), where clays and silty clays of medium to high compressibility are overlaid by a very dense clayed sand deposit. The project site location, and the Mexico City geotechnical zoning [3] are shown en Figure 1. The intersection consists of a new tunnel excavated under an existing metro station, using the EPB technique. The existing metro station is a box type structure 8.7 m wide and 6.3 m tall, which was built first excavating and casting the walls with the Milan method, second, removing the soil in-between the walls in order to form the box structure, and third, casting a cover slab on top of the walls to form the box. The street level was achieved by means of a filling placed over the slab. The new tunnel has a diameter of 10.18 m. The primary lining is comprised of seven precast reinforced concrete dowels 1.5 m long and 0.40 m thick that integrates a ring. Grouting operations to fill up the void left between the ring and tunnel wall were performed simultaneously with the lining installation. Two working areas were excavated for construction operations at both sides of the intersection (see Figure 2), also by the Milan method.

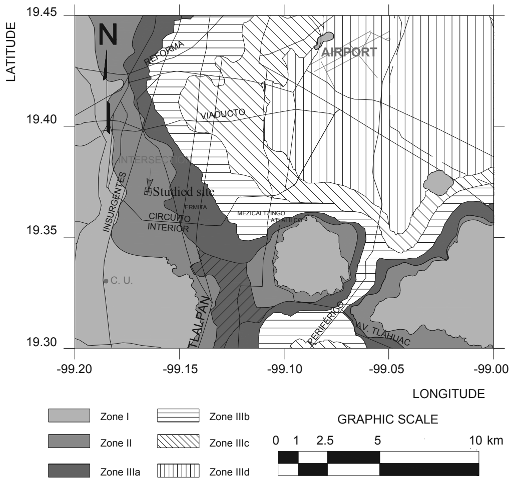

Figure 1. Project site location and geotechnical zoning

These excavations were supported with metallic frames to avoid excessive lateral displacements. The boring machine went from one area to the other one underneath the existing station. A soil-cement improvement was used in the entrance and exit of the intersection. After the new tunnel was completed, two runways were built at both sides of the tunnel for operating purposes. A plan view and a cross section of the intersection are shown in Figures 2 and 3 respectively.

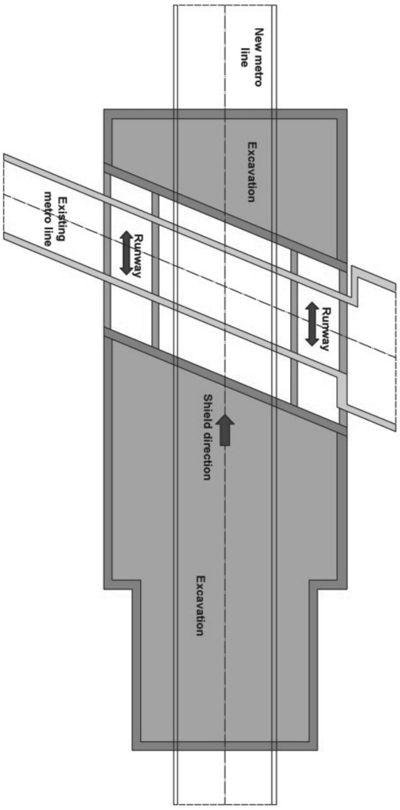

Figure 2. Plan view of the intersection

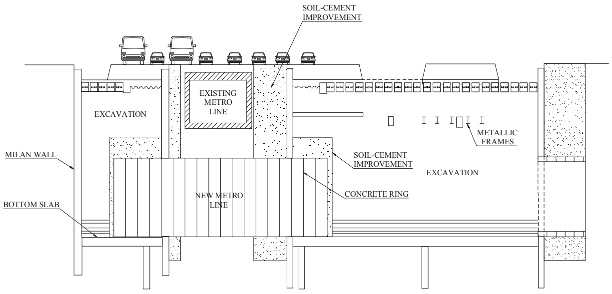

Figure 3. Cross section of the intersection

2 SOIL CONDITIONS

Typical subsoil conditions found at the site are presented in Figure 4. The top layer is a 1 m thick manmade fill of sandy clay and gravel. Underlying this fill a 3 m thick layer of very soft to soft olive-brown sandy clay is found, with water contents ranging around 50%, and standard penetration test, SPT, blow counts around 1. This layer rests on top of a 6.75 m thick very soft to soft olive and olive-brown clay layer with volcanic glass and roots, with water contents going from 75% and 400%, and SPT blow counts ranging from 1 to 5. This stratum is underlain by a 5 m thick, medium to firm olive-gray and brown clay layer, with fine sand lenses, and water contents between 10% and 250%, and SPT blow counts between 14 and over 50. Finally, below this layer and until the maximum explored depth, a very dense clayed sand with gravels, exhibiting water contents between 20% and 60%, and blow counts over 50, is found. The water table is located 4.5 m below ground surface.

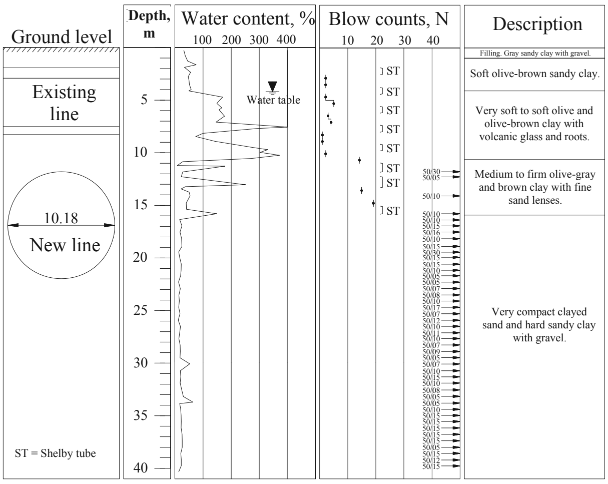

Figure 4. Ground conditions found at the site

3 NUMERICAL MODELING

3.1 *Description of the model*

The analysis of the intersection behavior was carried out using the computer software FLAC^{3D} [4], which is based on the finite differences technique. This software allows analyzing stress and strain states in three dimensions generated by loading and unloading process in elasto-plastic materials. The implemented model for the analysis is shown in Figure 5, it is comprised by 271,530 zones. In this figure, it can be seen also the location of the existing tunnel, one of the excavations at the side of the intersection, and the location of the new tunnel. The base of the model was considered fixed in the three degrees of freedom and the vertical faces, which limit the model, were fixed for horizontal displacements but free to move vertically. The geomaterials were modeled assuming an elasto-plastic behavior with a Mohr-Coulomb failure criterion. The material properties of the soil and reinforce concrete elements are summarized in table 3.1 and table 3.2 respectively. The primary lining and other structural elements were modeled as linear elastic.

Table 1. Soil properties used in the analysis

Material	Mohr-Coulomb parameters		ν	E
	c [kPa]	ϕ [°]	-	[kPa]
Manmade Fill	5	28	0.35	4500
Soft clay	12	25	0.28	3100
Very Soft clay	10	25	0.28	1800
Medium clay	25	30	0.30	7400
Very dense sandy clay	60	40	0.30	17000

ν = Poisson Ratio, E = Elastic Modulus

Table 2. Concrete parameters used in the analysis

Compression strength at 28 days, f'$_c$ (kPa)	Elastic Modulus , E (MPa)	Poisson ratio, ν
29420	17000	0.20

3.2 *Analysis stages*

The analysis procedure includes the next stages:

a) Calculation of the initial stress state generated by self-weigh and the piezometric conditions.

b) Calculation of the stress state generated by the construction of the existing metro line. This stage considers the excavations, and casting of the walls and slabs (bottom and cover) at the same time.

c) Calculation of the stress state and vertical displacements generated by the excavations at both sides of the intersection. In this stage, it is considered that the excavations are made simultaneously with the walls and the slabs (bottom and cover), so that, the horizontal support is present only at the level of the slabs.

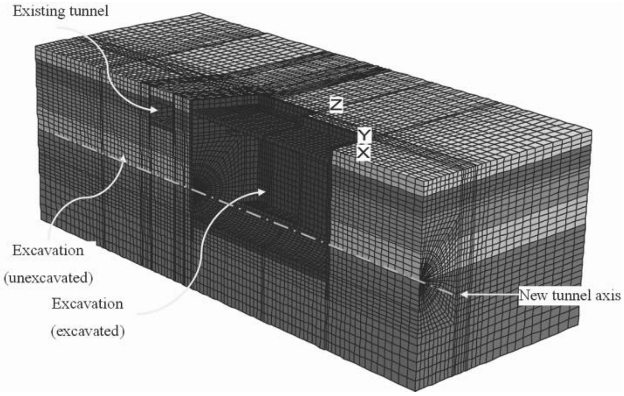

Figure 5. 3D Finite differences model

d) Calculations of the stress state and displacements generated by the excavation of the new tunnel. In this stage the tunnel support (primary lining) is also installed.

e) Calculation of the stress state and displacements generated by the excavation and construction of the runways of the new tunnel.

4 ANALYSIS RESULTS

4.1 *Excavations at sides of the intersection (stage c)*

Figure 6 shows the vertical displacements computed in the stage c. The maximum expansion occurs at the bottom of the excavation, in the east side of the intersection with a magnitude of 2.2 cm. This expansion is in agreement with the low compressibility soils that are found at the bottom of the excavation.

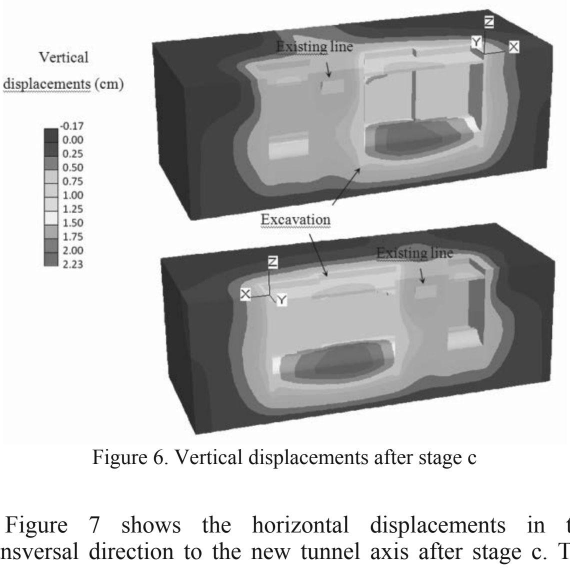

Figure 6. Vertical displacements after stage c

Figure 7 shows the horizontal displacements in the transversal direction to the new tunnel axis after stage c. The maximum horizontal displacements occur in the walls of the excavation and have a magnitude of about 0.7 cm. Similarly, figure 8 shows the horizontal displacements along the longitudinal direction of the new tunnel axis after stage c. The maximum displacements are between 1.4 and 1.7 cm and occur in the walls of the excavation, in the west side of the intersection.

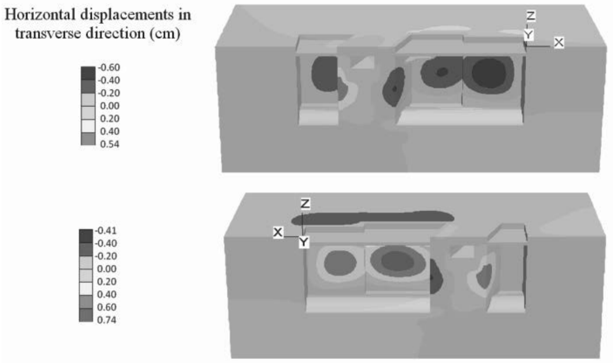

Figure 7. Horizontal displacements in transverse direction (stage c)

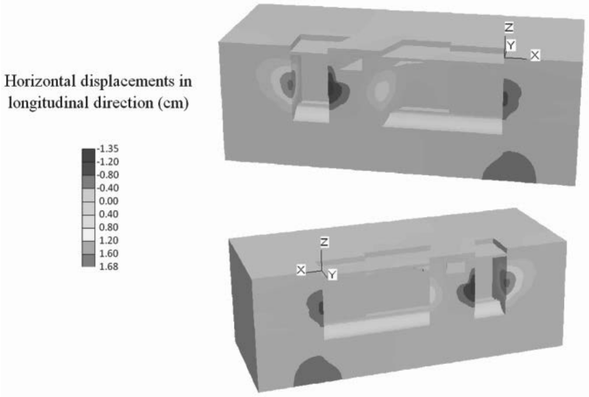

Figure 8. Horizontal displacements in longitudinal direction (stage c)

4.2 *Excavation and construction of the new tunnel line (stage d)*

Figure 9 shows the vertical and horizontal displacements computed after analysis stage d, in which it can be observed the following:

- Close to the existing metro line, vertical expansions of about 0.3 cm are generated. In the intersection zone, the tunnel crown settles 0.3 cm while the bottom expands 0.6 cm.
- Nearby the existing metro line, the maximum horizontal displacement in the transverse direction to the new tunnel axis is about 0.4 cm, and points towards the new tunnel axis.

On the other hand, due to the construction of the new line outside the excavations, and in the intersection zone, the following effects occur:

- The new tunnel crown settles 0.4 cm and the bottom expands 1.5 cm.
- The maximum horizontal displacement in the transverse direction to the new tunnel is 0.8 cm, and tends to open the sides of the tunnel.
- The maximum horizontal displacement in the longitudinal direction is 0.1 cm, and tends to push towards the center of the excavations. The computed horizontal displacements are small, which shows that the excavations walls and soil-cement improvement work efficiently to reduce such movements. Likewise, the expansions are small due to the low compressibility of the soil at the bottom of the excavations.

In order to understand the intersection behavior, Figure 10 shows the vertical and horizontal displacements in the new tunnel at the intersection zone, which shows the following:

- The maximum expansion in the new tunnel bottom is 0.5 cm, while the tunnel crown settles 0.1 cm. Thus, the tunnel lining tends to move towards the tunnel axis 0.6 cm.
- The maximum displacements in transverse direction to the new tunnel are about 0.2 cm and occur at both sides of the tunnel.
- The maximum displacements in longitudinal direction are of 0.05 cm and occur in the tunnel bottom, in opposite direction respect to the tunnel crown, and also interact with the excavation wall at the west side of the intersection.

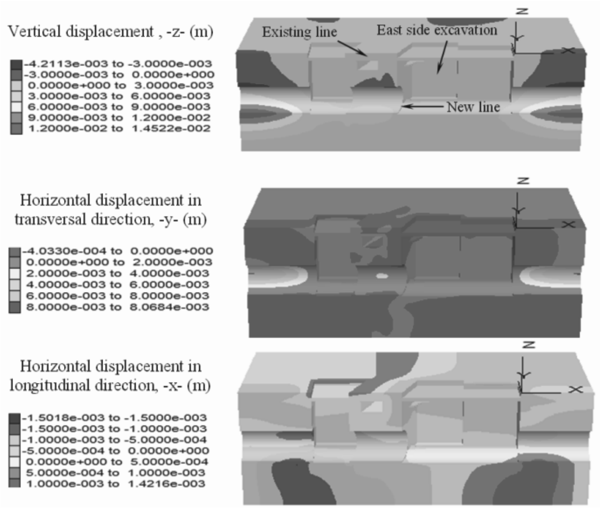

Figure 9. Vertical and horizontal displacement after stage d

4.3 *Excavation and construction of the runways of the new tunnel line (stage e)*

From the vertical and horizontal displacements computed after analysis stage e, the following is observed:

- The maximum expansion in the proximity of the new tunnel is about 0.05 cm, and at the bottom of the runways is of 0.1 cm.
- The maximum horizontal displacement in transverse direction to the new tunnel is 0.1 cm.
- The maximum horizontal displacement in longitudinal direction around the tunnel and the runways is 0.4 cm and close to the existing line is about 0.2 cm.

These results show that the construction of the runways will not affect the behavior of the intersection.

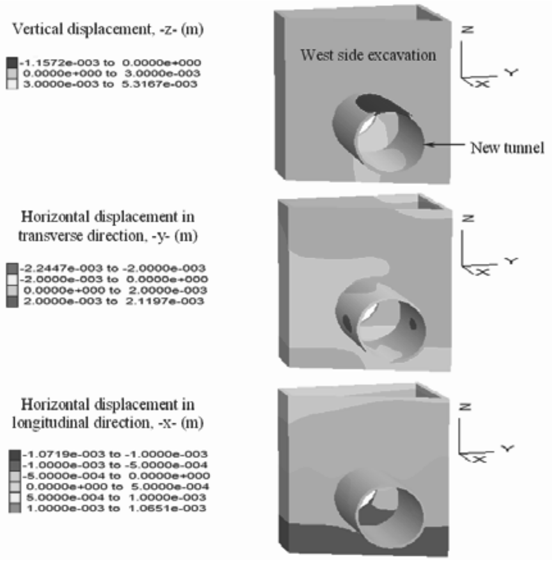

Figure 10. Vertical and horizontal displacement after stage d in the intersection zone.

5 CONCLUSIONS

Regarding the excavations at the sides of the intersection (stage c), it can be concluded that both horizontal displacements are small, and thus, the excavation will be adequately supported by the excavation walls, and it will not pose any risk to the future stability of the structure. With respect to the excavation and construction of the new tunnel, it was found that overall, the excavation and construction of the new tunnel will not affect the existing one. In addition, the numerical study also shows that the excavations walls and the soil-cement improvement efficiently reduce the movements of the tunnel lines.

6 REFERENCES

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