Performance of the tunnel lining subjected to decompression effects on very soft clay deposits

Performance du revêtement du tunnel soumis à des effets de décompression sur les dépôts d'argile très mous

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ABSTRACT: Superficial channels on very soft clay deposits undergoing consolidation processes can generate tension zones that potentially can induce semi-vertical cracking. During construction of any underground works, such as tunnels, these cracks can be reactivated, especially if the construction process causes significant changes in the initial stress state of the ground, and then generates important deformation of the tunnel lining from confining loss around the tunnel, especially if dowels rings are used as lining. On the other hand, it is also possible to generate significant lining deformations if there are changes in the state of stress in the ground's surface due to the dredging of channels. This paper presents a case history about the behavior and numerical modeling of the primary tunnel lining during and after tunneling with an EPB machine in Mexico City soft clay deposits subjected to decompression stresses caused by the dredging of channels. Total displacements induced during tunneling under superficial channels were high but less than 1% of the tunnel diameter. After dredging, such channels' additional deformations were induced in the lining because of a reactivation of pre-existent cracks in the clay deposit. Numerical modeling was carried out to study the optimal solution. Based on numerical results, two solutions were applied: lining reinforcement and soil improvement.

RÉSUMÉ : Canaux superficiels sur les dépôts d'argile très douces en cours de processus de consolidation peut générer des zones de tension qui peut potentiellement induire des semi-verticale fissuration. Lors de la construction des ouvrages souterrains, tels que les tunnels, ces fissures peuvent être réactivés, surtout si le processus de construction entraîne des changements importants dans l'état initial des contraintes du sol, puis génère une déformation importante du revêtement du tunnel de la perte de confinement autour du tunnel, surtout si les chevilles des anneaux sont utilisés comme doublure. Cet article présente une étude de cas sur le comportement et la modélisation numérique du revêtement du tunnel principal pendant et après un tunnel avec une machine EPB dans les dépôts de Mexico argile molle soumis à une décompression contraintes provoquées par le dragage des chenaux. Déplacements totaux induits lors des tunnels sous canaux superficiels étaient élevés, mais moins de 1% du diamètre du tunnel. Après dragage ont été produites déplacement supplémentaire relance revêtement se craquelle. Les modèles numériques ont été utilisés pour étudier ces facteurs et déterminer la solution optimale. Avec ces résultats, nous proposons deux solutions: augmenter le revêtement et l'amélioration des sols.

KEYWORDS: tunneling in soft soils, soil fracture, decompression stresses, Mexico city tunnels.

1 INTRODUCTION

The Túnel Emisor Oriente (TEO, Spanish acronym for Eastern Emitter Tunnel) will be the new drainage system for Mexico City. It is located to the north of the city and it is a circular tunnel 62 km long, of 7 m inner diameter, set at variable depths between 30 and 155 m. It crosses all types of soils along 97% of its length, from very soft to hard, with the rest of the length crossing volcanic rock. For its construction, Earth Pressure Balance (EPB) tunnel boring machines are used, with a primary lining formed by dowels rings with sections 0.35 and 0.40m thick (COMISSA 2010). Almost the entire tunnel is under the groundwater level, with pore pressures of up to 0.8MPa.

The project's first trajectory, approximately 8 km long, is located at a zone of very compressible clays with low shear resistance, with water content in the order of 300%, running parallel to a surface channel. A particular aspect of this section is that on land near the channel surface cracks have been observed, and in the zone where the tunnel crosses under the channel (1+032 to 1+300) it has been observed that before the crossing (0+920 to 1+032) important primary lining deformations have occurred, with a tendency to their stabilization. This anomalous behavior of the tunnel has been caused by a diversity of factors, among which stand out the channel's dredging and the presence of intense fracturing at the zone of that channel.

The objective of this work is to evaluate the effects on the tunnels of the unloading induced by dredging surface channels located on cracked clayey deposits, and as a particular case the TEO project is presented.

2 GEOTECHNICAL CONDITIONS

Stratigraphy. Subsoil conditions at the zone where the atypical deformations occurred on the tunnel's primary lining are (Fig 1):

i. *Superficial Crust* (0 to 3m). It is a stratum formed by interspersions of sandy silts and hard silty sands, and on occasions fills up to 2m thick.
ii. *Superior Clayey Series* (3 to 26m). These are clays and silts of high plasticity with thin lenses of volcanic ash and sandy silts.
iii. *Hard Layer* (26 to 28 m). These are interspersions of sandy silts and silty sands (tunnel is located at the inferior part of the Superior Clayey Series resting on the Hard Layer).
iv. *Inferior Clayey Series* (28 and 42 m). It is a very compressible clayey deposit.

Conditions of subterranean water. At this zone the groundwater level is located at 3m depth, and the pore pressure measured at the tunnel's axis is in the order of u_{axis}=145kN/m^2, which is 65kN/m^2 less than the hydrostatic pressure.

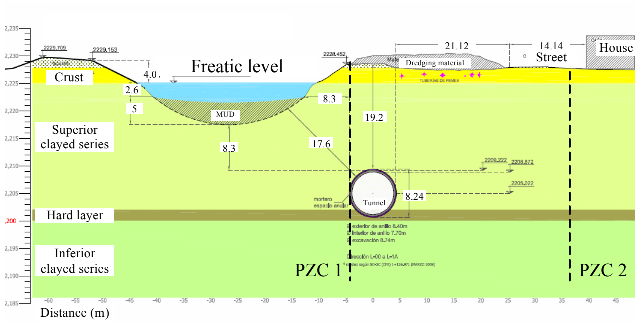


Figure 1. Stratigraphic section of the zone where atypical deformations were observed (1+000).

Cracking. Because the channel was built excavating the land, it is considered a zone of unloading. During construction of the tunnel's shafts near the channel, the presence of subsoil cracking has been observed. In order to verify the existence of that unloading zone, and the presence of developed cracking given the low value of the shear resistance factor for Valley of Mexico clay (K_{IC}≈1.9t/m$^{3/2}$), the k_o stress ratio at rest was determined at the site, and an exploration campaign was carried out with piezocones in zones near to and far from the channel. The stress ratio at rest for the superior clayey series was k_0=0.19 for the zone near the channel, whereas at the zone away from the channel the value was k_0=0.6. It is to be pointed out that the low k_0 value measured for the superior clayey series at the channel zone is evidence of the state of decompression due to the channel's influence, and vertical cracking presented by the superior clayey formation. One way of observing cracking on clayey soils is to measure point resistance and friction of the electric cone, because when a discontinuity crosses, the values of such resistance decrease. When comparing electric cone point resistances in soundings carried out near to and far from the channel, resistances are observed to descend at certain depths in the case of the cone near the channel, a condition not present in the far-away cone (Fig 2).

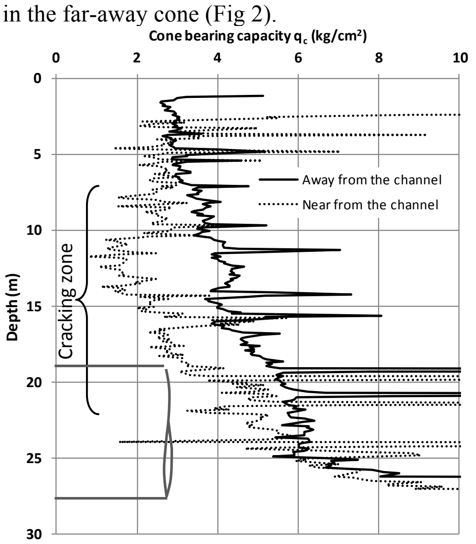


Figure 2. Soundings of piezocones carried out at the channel's zone of influence and away from it.

3 INSTRUMENTATION AND BEHAVIOR

The tunnel's instrumentation consisted of placing piezometers, bar extensometers, doing convergence measurements at the ring sections, and pressure cells at the point of contact between soil and primary lining (COMISSA 2011).

In general, the tunnel's behavior during construction coincides with those determined at the design stage, meaning that the displacements of the primary lining were in the order of 40mm, with top measurements of 60mm (80mm is the value of 1% of the tunnel's diameter). Nonetheless, prior construction of the secondary lining, and once the primary lining's stabilization was reached, with deformation speeds below 1 mm/day, and after the reinjection at the point of contact of lining and soil along the section built, a sudden increase in convergences was observed at the tunnel section 0+920 to 1+032 (rings 610 to 730), which is attributable to various extraordinary events that occurred at the tunnel's environment, which induced a change in the original geotechnical conditions. This event coincided with channel dredging activities, as observed on the convergence graphs of the rings located at that zone (Fig 3).

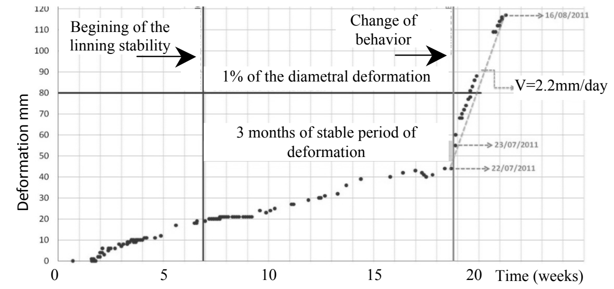


Figure 3. Example of deformational behavior at zone with important displacements (ring 671).

4 NUMERICAL MODELING

In order to assess the unloading effect at surface and the fracturing present at the superior clayey series, a bi-dimensional analysis was carried out with the Finite Element Method. In this analysis, the soil's fracturing is represented by a decrease of the clay's mechanical properties.

Analysis procedure. Taking the soil parameters registered on site as reference, the topographical section of the tunnel showed in Fig 1 was considered for the analysis and study of the tunnel's behavior, reproducing the initial geotechnical conditions, modified by the soil's fracturing, and the effect of the channel dredging activities. 2D numerical analysis was done in stages, the following being the main ones:

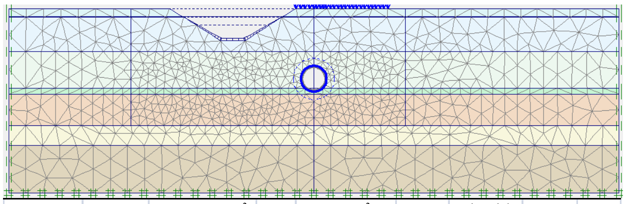
i. Evaluation of geostatic stress conditions
ii. Construction of the channel and placement of the borders
iii. Excavation and placement of the tunnel's primary lining
iv. Change of subsoil properties, induced by fracturing
v. Land consolidation by the decrease of pore pressure at a 6 month interval
vi. Channel dredging inducing variable unloading between 85 and 97kN/m^2
vii. Decrease of groundwater level of 1 m.

Numerical model. The finite elements mesh shown in Fig 4 was used, with the mechanical properties indicated in it. An important hypothesis considered in the analysis is to admit that both the tunnel's construction and the channel dredging process are produced under undrained conditions of the soil. In effect, taking into account the time during which the deformation develops, it is adequate to consider that this subsoil behavior is under undrained conditions. The only stage in which the undrained behavior is not considered is the one produced by the consolidations over 6 months.

5 RESULTS

A numerical analyses were carried out in order to determine the state of stresses and deformations at each stage of analysis both in the subsoil and in the lining, with or without considering subsoil cracking.

Table 1 shows the results obtained at each stage of analysis. The displacement obtained when the soil presents no fracturing is indicated in parenthesis, and it is observed that the displacement induced with cracking is always larger.



Layer	Thickness (m)	Cohesión (kN/m^2)		φ(°)	E_u (kN/m^2)		m_v (m^2/kN)	Unit weight (kN/m^3)	Poisson ratio	K_o
		Original	Altered		Original	Altered				
Crust	2.8	24	24	28	12000	8400		16	0.35	0.36
Soft Clay 1a	11.2	26	19	0	6600	2885	0.0034	11.9		0.54
Soft Clay 1b	11.8	37	30	0	5985	4615	0.0029	11.5		
Hard Layer 1	1.7	59	47.2	0	13000	10400	0.0012	15.4		0.5
Soft Clay 2a	10.5	95	76	0	12069	9655.2	0.0006	12.5		0.54
Hard layer 2	6.5	59	47.2	0	39000	31200		15.4		0.5
Soft Clay 2b	15.5	91	72.8	0	12426	9940	0.0004	12.5		0.54

Figure 4. Mesh of finite elements and mechanical properties of the subsoil.

The channel's presence induces lateral displacements of the tunnel toward the channel, and the tunnel's deformation is asymetrical, with an increase of 3.9cm in the lining's horizontal diameter during the tunnel's construction. The consolidation process makes the soil descend in an almost uniform manner, inducing a horizontal divergence of 0.22cm in the tunnel, which is less tnan that obtained in a previous stage. The effects of dredging the channel and reloading the surface produce displacements from the tunnel toward the channel, with horizontal diameter increases of approximately 4.5cm, which is in the order of what is obtained during the tunnel's construction. When adding up all the stages, the total divergence obtained of the tunnel's horizontal diameter is 8.6cm. These results are important because they confirm what is observed in tunnel convergence measurements. In effect, displacements induced at the construction and dredging stages are of the same order. Dredging and reloading stages generate from 2 to 8cm of displacement, with a total variable horizontal divergence of the primary lining of between 4 and 9cm, which is comparable to what was observed (6 to 15cm).

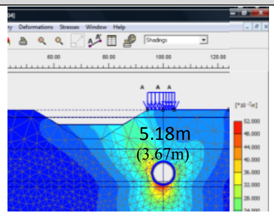
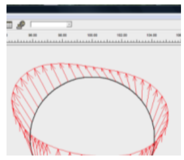
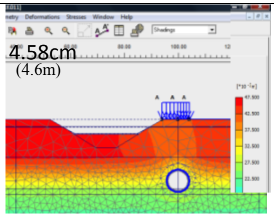
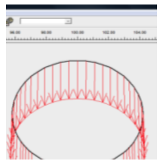
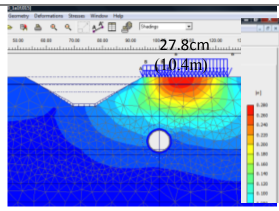
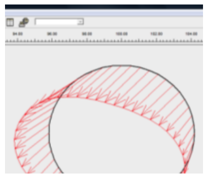
Actions carried out to mitigate the atypical deformation. To guarantee the tunnel's adequate behavior, the following mitigation measures were implemented to reduce the sudden increase of deformations on the tunnel's rings:

- ✓ Suspension of the channel dredging and reload activities
- ✓ Removal of material product of the channel dredging placed on the borders and above the tunnel's zone
- ✓ Reinjection of the contact between soil and the primary lining at the zone detected with sudden deformational increase (rings 600 to 730).
- ✓ Reinjection of the contact between soil and the primary lining at zones of rings 530 to 600 and 820 to 850, which correspond to the zones where overload of channel dredging material is registered, and where decompression occurred due to the dredging itself.
- ✓ Reinjection of the contact between soil and the primary lining at zone of rings 200 to 400, where overload of Grand Canal dredging material is registered, decompression due to its dredging and a tendency to sudden deformation similar to the one at the zone of rings 600 to 730.
- ✓ Placement of metallic lining at the zone with sudden deformations, in those rings that present excessive deformation and with deformational speeds above 2mm/day.

6 CONCLUSION

One of the main effects of superficial unloading on soft soils is the generation of cracking, which in turn causes a reduction of the soil's shear resistance and the geostatic horizontal stress (confining stress reduction of the tunnel lining), and an increase in the soil's deformability. These factors make tunneling difficult in soft soils, mainly regarding aspects of the application of pressures at the excavating front and injection at the point of contact between soil and ring lining.

Table 1. Numerical model results considering each construction stage and post-construction factors.

STAGE	Displacements (m)	Horizontal divergence of the tunnel lining (cm)
Tunnelling		3.9 (2) 
Decreasing pore pressure during 6 monts		0.2(0.2) 
Dredging and overload		4.5(2.1) 
TOTAL		**8.6 (4.3)**

A tunneling case history in soft soils is described, where cracking occurs in the subsoil, induced by the superficial unloading caused by the construction of a channel. This discharge generates relative and absolute displacements of the tunnel toward the channel zone, which were increased by channel dredging activities up to values that cause structural instability conditions of the lining.

This observed behavior is confirmed by means of a numerical model that considers the tunnel's construction process and the channel's dredging activities. The model's results indicate that the unloading and reloading effects on the subsoil are short term processes and their nature is mainly elastic.

As corrective measures, the following activities were proposed: suspension of the channel dredging, reinjecting of the contact between soil and the primary lining rings, and placing metallic frames. As preventive measures, subsoil improvement is considered, by means of injection of self-setting slurries, reinjection of mortar at the ring section-soil point of contact, and placement of a continuous secondary lining.

7 REFERENCES

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