Geotechnical Engineering in the XXI Century: Lessons learned and future challenges
N.P. López-Acosta et al. (Eds.)

doi:10.3233/STAL190094

Criteria to Perform Ground-Segmented Tunnels Lining Interaction Analysis, Using an Hybrid Method

Marco PÉREZ ÁNGELES [a,1], Diego Forero BUITRAGO[a], Gabriel AUVINET GUICHARD[a] and Rui GRILO BIBI[b]
[a] *Instituto de Ingeniería, UNAM*
[b] *Mota ENGIL*

Abstract. A criterion proposed by Instituto de Ingeniería, UNAM (II-UNAM) to perform ground-lining interaction analyses for tunnels, when these are formed by segmented rings and double lining, is described. The criterion can be introduced in the "hybrid" analysis method, which is an iterative procedure between geotechnical and structural numerical modeling, where the convergence in terms of diametrical displacements between both types of modeling allows determining the effective stiffness of the tunnel [1]. The criterion allows calculating loads and mechanical elements for the tunnel lining and checking serviceability limits corresponding to constructive or operative aspects. It is useful in the design stages, for revisions of tunnels that are under construction or for existing tunnels affected by new engineering works. In this paper, it is applied to check the interference of a new deep foundation with an existing tunnel.

Keywords. Analysis criteria, terrain-segmented lining tunnel interaction, double linings, hybrid analysis method, iterative procedure, geotechnical and structural numerical modelling, effective tunnel stiffness, interference.

1. Background

In the former lake area of Mexico City, a large number of tunnels have been built, mainly for transport and drainage, using tunneling machines. These machines build tunnels with a support system formed by a primary lining (segmented rings) and a cast in place continuous secondary lining. Constructive joints between segments and contiguous rings require special attention in ground-linings interaction analyses. Some analytical solutions [2] allow performing this type of analysis. The results obtained with these solutions are similar to those obtained by 2D numerical modeling that allow representing the segments and their joints, with plate-type elements and elastic-plastic ball joints, respectively [3]. However, it has been concluded that this type of numerical and 2D analytical modeling overestimate the flexibility of the segmented tunnels and can underestimate mechanical elements.

[1] Corresponding Autor, Coordinación de Geotecnia, Ciudad Universitaria, Apdo. Postal 70-472, Coyoacán, 04510, CDMX, México (+52 55) 5623 3500 ext. 8557. E-mail: MPerezAn@iingen.unam.mx (M. Pérez-Ángeles), DForeroB@iingen.unam.mx (D. Forero-Buitrago),GAuvinetG@iingen.unam.mx (G. Auvinet-Guichard), rui.bibi@mota-engil.com.mx (R. Bibi-Grilo)

Some authors [3], [4] and [5], using finite difference and finite 3D elements codes, were able to represent the global behavior corresponding to the coupling effect between two or more contiguous segmented rings. In those investigations, it was concluded that the coupled system leads to a rigid global behavior of the tunnel. The 3D numerical modellings are considered the most complete since they allow to represent the most relevant boundary conditions, both in the field and in the structure. Their main disadvantage is that they require a long computing time.

2. Criteria for carrying out ground-double tunnel lining interaction analysis, using hybrid analysis method

The II-UNAM has proposed a geotechnical criterion to calculate stresses and displacements induced by the construction of circular tunnels in soils. This criterion combines numerical modelling techniques and analytical solutions to assess the main effects on the ground and the double lining system during the constructive procedure and the tunnel life [6].

The tunnel is initially considered as a continuous element. To take into account the effect of constructive joints between segments and rings, the flexural stiffness of the element representing the lining and those representing the complete support system is reduced by applying reduction factors α and α', respectively [7]. These factors are obtained through iterative processes between the geotechnical modelling and structural analysis [1]. Structural models must adequately represent the coupling between contiguous rings and the non-linear two-dimensional behavior of the segments and their joints. The effective stiffness of the lining can be determined when the convergence in terms of diametric displacements between geotechnical and structural models is achieved ("hybrid" analysis method). This criterion also allows considering the serviceability limits corresponding to constructive or operative aspects.

The analysis stages for the application of the criteria proposed by the II-UNAM to obtain the reduction factors of the stiffness of the linings that make up the tunnel support system are described below:

- **Stage E_0.** Representation of the geotechnical units and the hydraulic and boundary conditions of the problem, as well as the existing structures that are considered most relevant in the determination of the initial stress state.
- **Stage E_1**. Dissipation of excess pore pressure (EPP) generated in stage E_0 to obtain the state of stress in the ground before construction of the tunnel.
- **Stage E_2.** Decompression of the ground by excavation procedure of the tunnel.
  In soft soils such as those of Mexico City lacustrine zone, it is considered irrelevant in terms of the alteration of the initial state of stress [8].
- **Stage E_3.** Numerical representation of the primary lining (RP) with plate-type elements and dissipation of the generated EPP
- **Stage E_4**. Correction of the flexural stiffness (*EI*) of the plate-type element to represent the effect of the joints between segments of the rings that make up the RP, applying a reduction factor (α). Different values must be assigned to this factor and the corresponding distributions of loads and displacements be obtained.
- **Stage E_5**. Enter in the structural model each of the load distributions on the PR, corresponding to the stress distributions associated with diferent values of the α factor, obtained in stage E_4.

- **Stage E_6.** Compare the diametric displacements of the linings obtained with the geotechnical and structural models. When they are sufficiently close, the corresponding value of the α factor can be considered as adequate for representing the behavior of the RP in the geotechnical modelling (Figure 1).
- **Stage E_7**. Replace the plate-type element by a volume element with equivalent properties and thickness, corresponding to the corrected stiffness of the plate-type element
- **Stage E_8**. Recalculate stage E_3 to verify that the stress and displacement fields in the ground are sufficiently close to those initially obtained with the plate-type element with corrected stiffness.
- **Stage E_9**. Numerical representation of the secondary lining (RS) with a plate-type element perfectly attached to the interior of the segmented ring and dissipation of the EPP generated by its construction.
- **Stage E_{10}**. Total abatement of pore pressures in the field, in such way that the initial pore pressures in the field become EPP.
- **Stage E_{11}**. Dissipation of EPP generated in the previous stage. The efforts and displacements obtained on the SS will be those that represent the effect of the regional subsidence on the tunnel.
- **Stage E_{12}**. Correction of the flexural stiffness (*EI*) of the plate-type element to represent the effect of the tunnel support system (SST), applying a reduction factor (α'). Different values must be assigned to this factor and the corresponding distributions of loads and displacements must be obtained.
- **Stage E_{13}**. Enter in the structural model each of the load distributions on the SST, corresponding to the stress distributions associated with different values of the α' factor, obtained in step E_{12}.
- **Stage E_{14}**. Compare the diametric displacements of the linings obtained with the geotechnical and structural models. When they are sufficiently close, the corresponding α' factor can be considered as adequate to represent the behavior of the SST in the geotechnical modelling (Figure 1).

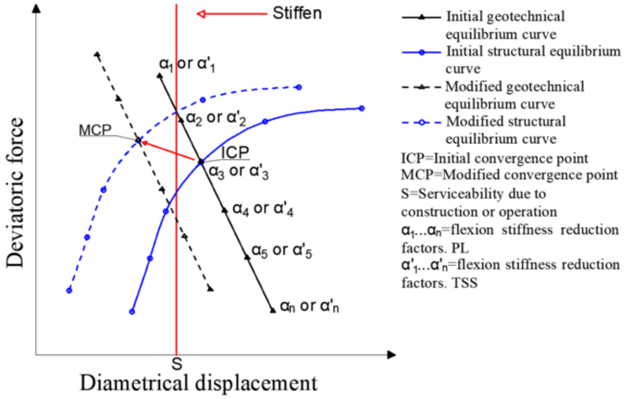

Figure 1. Geotechnical-structural convergence for segmented and double lining tunnels.

Figure 1 schematically shows the graph of geotechnical-structural convergence for primary lining and final support system. This graph is a representation of "equilibrium point" curves obtained from the soil-lining interaction analyses performed with the geotechnical and structural models, for different tentative values of the lining stiffness.

The intersection point between both curves is the point of convergence (ICP) of the geotechnical and structural numerical modellings and the associated loads and mechanical elements can be used for design of the lining.

If a maximum diametric displacement (red line, Figure 1) is established as a service limit by constructive or operational specifications of the project, then the point of convergence within the graph should be on the left side (MCP) of this limit and the corresponding loads should be considered for design.

Depending on the position of the convergence point with respect to the serviceability limit (SL), the designer could consider the possibility of making the lining more flexible when it is on the left side of the red line or, on the contrary, stiffening it when it is on the right side of the same line.

3. Application example

A tunnel section of the Mexico City deep drainage system that could be affected by a causeway deep foundation is reviewed. Figure 2 shows the stratigraphic profile, the hydraulic conditions and the topography of the area, the tunnel position, the future foundation location and its elements. The tunnel's depth is 38m and its final diameter is 7m. The tunnel supporting system consists of two linings, the primary formed by 35cm thick segmented rings and the interior cast-in-place lining is also 35cm thick. The foundation is built below a drainage channel and supports a load of 3950kN. It consists of a 2.5m thick slab, with dimensions in plant 8.9x8.9m and is supported on 49 piles of 19m in length. The foundation slab and piles are represented by plate-type elements. Table 1 shows the properties of the structural elements and Table 2 shows the geotechnical model.

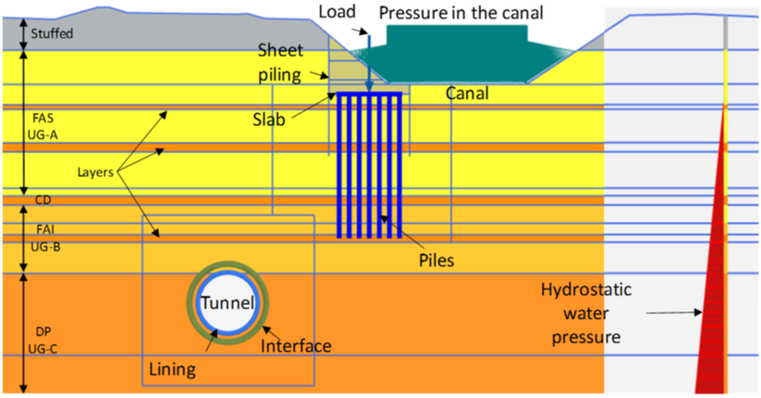

Figure 2. Analysed section.

Table 1. Properties of structural elements.

	e (m)	f´c (MPa)	ν_s	γ_c	α	E (kPa)	EI (kN/m)	EA (kN/m)
RP	0.35	35	0.15	24	0.3	2.6E7	1.7E4	5.2E6
RS	0.35	35	0.15	24	1	2.6E7	9.4E4	7.0E6
PEC	0.45	35	0.15	24	1	2.6E7	6.9E4	4.1E6
PI	0.45	35	0.15	24	1	2.6E7	2.3E4	1.4E6
LC	2.5	35	0.15	24	1	2.6E7	3.3E7	6.5E7

Table 2. Properties of soil strata.

Material	γ (kN/m³)	e	C´ (kN/m²)	ϕ´(°)	Cr	Cc	E´ (kN/m²)	ν´	E (kN/m²)	ν
CS	14	-	10	30	-	-	20000	0.4	22222	0.5
FAS	12	6	0	40	0.3	4	550	0.3	5500	0.5
L	14	-	30	40	-	-	30000	0.3	33834	0.5
CD	14	-	30	40	-	-	30000	0.4	33834	0.5
FAI	12	5.5	0	40	0.2	3.5	670	0.3	6700	0.5
DP	14	-	100	30	-	-	20000	0.4	22222	0.5

Figure 3 shows the results of the primary lining-ground interaction analysis (radial and shear stresses over the lining). Analyses were performed with a numerical geotechnical model, considering a reduction factor, $\alpha = 1$. Vertical and horizontal forces obtained directly from the previous results are also shown. Finally, a "deviatory" force is presented, that is the difference between the sum of vertical and horizontal forces. A graphical representation of the value of the deviating force vs the horizontal convergence (GhC) obtained with the same models of the geotechnical equilibrium is presented (Figure 4). The same analyses were performed with α values equal to 0.75, 0.5, 0.25 and 0.1. The distributions of resultant forces were entered into the structural model of the primary lining and structural horizontal convergences (ShC) were obtained.

A second lining is placed to absorb the loads due to the effects of regional subsidence. The analysis steps described in the methodology were carried out. The picture on the right of Figure 4 shows the results obtained. The dotted line is a projection of the geotechnical interaction curve.

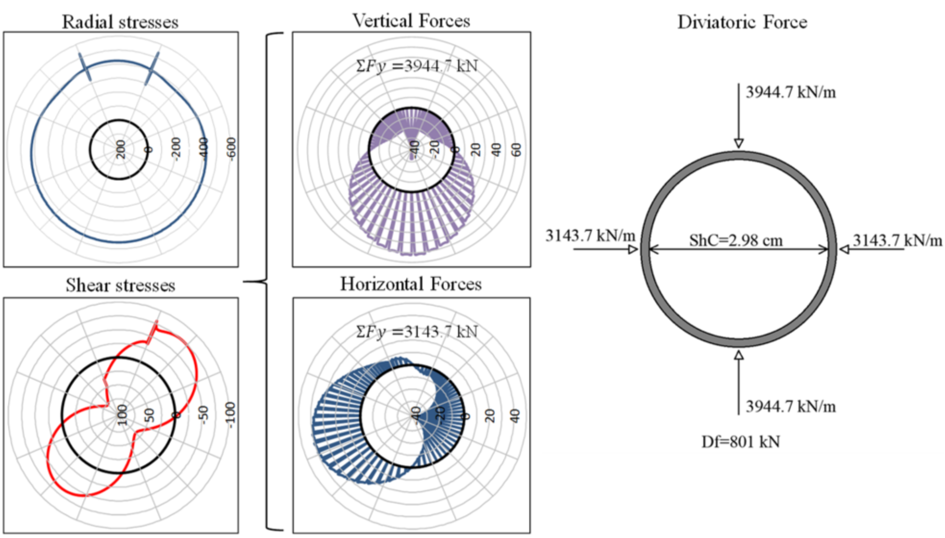

Figure 3. Stress and forces diagrams.

The forces corresponding to the point of convergence are the design loads. With the structural modelling, strains, plastic points and mechanical elements of the primary lining and the support system were calculated.

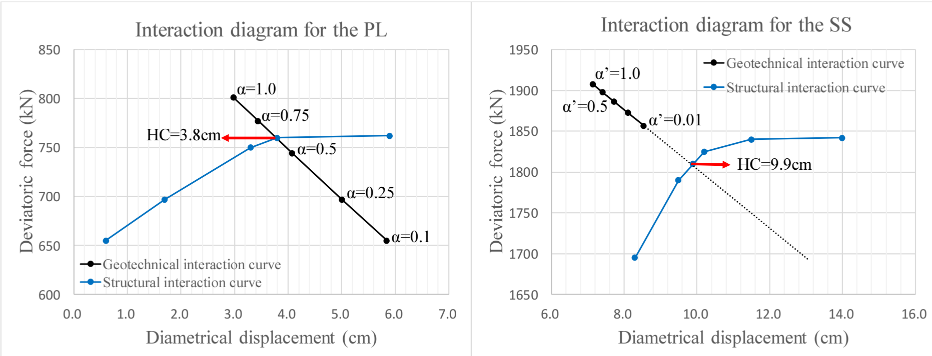

Figure 4. Interaction diagrams for the analysis without causeway.

Figure 5 shows the effect of the short-term interaction of the ground with the primary lining. Plasticization of two joints of the first segmented ring and four joints of the second is observed. The horizontal convergence is less than the 1% of the primary lining diameter (8.4m) considered to be the serviceability limit.

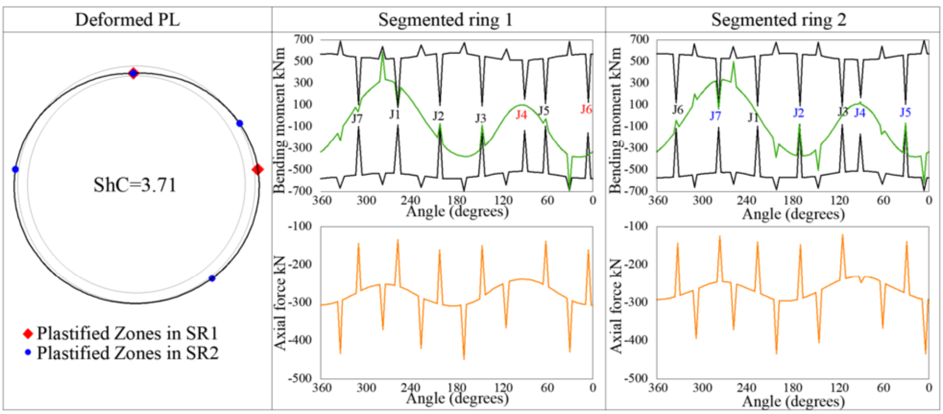

Figure 5. Results on the primary lining.

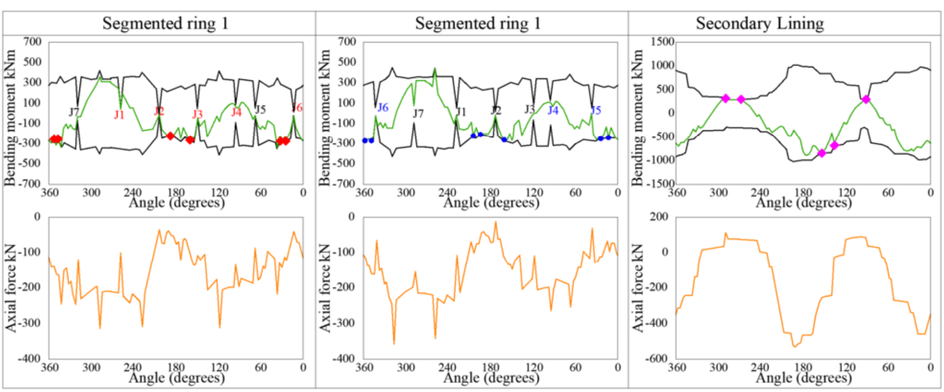

Figure 6. Mechanical elements on the support system without causeway.

Figure 6 shows the effect of the long-term interaction of the ground with the tunnel support system. A greater plasticization is observed in the segmented rings. The plasticization of some points of the secondary lining is also observed. The primary lining could not withstand the magnitude of the moments and axial forces due to regional subsidence. The maximum horizontal 9.9cm convergence exceeds the established service limit (left image, Figure 7). The results of these analyses confirm the need of a secondary lining.

To evaluate the influence of the causeway on the tunnel, ground-lining interaction analyses were carried out again following the stages described in section 2. The results allowed concluding that the construction of the highway reduces the deviatory effect corresponding to the regional subsidence over the tunnel (right image, Fig 7). The foundation "restores" the efforts in the area laterally deconfined by the discharge induced by the channel.

In both cases of analysis (without foundations and with foundations), the results of long-term ground-tunnel interaction analyses indicate that the system of maintenance exceeds the service limit. However, the interpretation of the results should not ignore the objective of these analyses, which was to verify the interference of the causeway and the tunnel, not the design of it. Therefore, it can be concluded that the tunnel is not significantly affected by the construction of the causeway in the area corresponding to this analysis section.

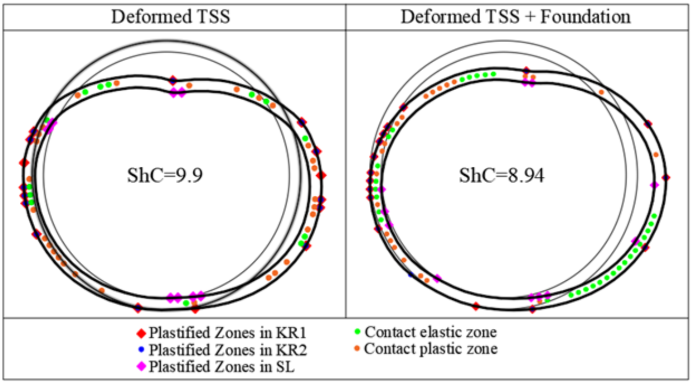

Figure 7. Distorted and plastic points for the SS without causeway and with causeway.

4. Conclusions

The stages of analysis to be followed for the application of a criterion proposed by II-UNAM for ground-tunnel interaction analyses were presented. The reduction factors of the stiffness of the linings of the tunnel support system are determined using iterative procedures between geotechnical and structural numerical modelling (“hybrid" analysis). This criterion also allows considering the serviceability limits established by constructive or operative aspects.

The section of a deep drainage tunnel system in Mexico City that is under the influence of deep causeway foundations was reviewed performing ground-linings interaction analysis. The analysis criterion implemented in the II-UNAM methodology allowed to adequately represent the main effects on the ground and the lining during the constructive process and the tunnel useful life-time.

The criterion also allowed pointing out that long-term loads cannot be supported by the primary lining only. Therefore, the need for a secondary lining continues to be justified when tunnels are built in soft soils subject to subsidence due to consolidation processes.

In both cases of analysis (without and with foundations), the long-term results indicate that the support system exceeds the serviceability limit. However, these should not be considered as the final results since many properties and characteristics of the problem were estimated. The correct interpretation of the results should be adjusted to the objective of this analysis, which was to verify, under the same established conditions, the difference between long-term behaviors of the tunnel with and without foundations. Considering the above, the results allowed concluding that the construction of the causeway actually reduces the deviating effect corresponding to the regional subsidence over the tunnel. In fact, the foundation "restores" the efforts in the zone laterally deconfined by the discharge induced by the channel. Therefore, it can also be concluded that the tunnel is not significantly affected by the construction of the causeway in the area corresponding to this analysis section.

References

[1] Farjeat E., Delgado S., “Diseño de dovelas para túneles del metro alojadas en arcillas compresibles de la Ciudad de México”, Tunnels and water, Serrano (ed), Rotterdam, (1988) ISBN 9061918219

[2] El Naggar, H., Hinchberger, S.D, “An analytical solution for jointed tunnel linings in elastic soil or rock”. Canadian Geotechnical Journal, (2008). 45: 1572-1593. doi: 10.1139/T08-075.

[3] Juárez J.A, Pérez A.M y Auvinet G, “Análisis de interacción suelo-estructura para túneles dovelados” XXIX Reunión Nacional de Ingeniería Geotécnica, (2018), Vol 1, León Gto, SMIG, pp 343-352.

[4] Klappers C, Grülb F and Ostermeier B, “Structural analyses of segmental lining-coupled beam and spring analyses versus 3D-FEM calculations with shell elements”. Proceedings of the ITA-AITES 2006 world tunnel congress, safety in the underground space, (2006) 6 pp.

[5] Arnau O y Molins C., “Three-dimensional structural response of segmental tunnel linings”. *Engineering Structures*, (2012), 44, 2010-221

[6] CFE (Comisión Federal de Electricidad) Capítulo B.5.1. “*Túneles y Lumbreras*”, Manual de Diseño de Obras Civiles, México.

[7] Pérez, A., M., Forero, D. and Auvinet, G. (2018) "*Análisis geotécnicos para la interferencia de estructuras superficiales con túneles existentes*", Proceedings, XXVII National Meeting of Geotechnical Engineering, León, Gto., Mexico

[8] Auvinet G. y Rodríguez J. (2010). "*Análisis, diseño, construcción y comportamiento de obras subterráneas en suelos*", Proceedings, XXV National Meeting of Geotechnical Engineering, Acapulco, Gro., Vol. 1: 33-42, Mexico

[9] Deere D.U. *et al.* (1969). "*Design of tunnel liners and support systems*", Final Report, Department of Civil Engineering, University of Illinois, Urbana, I11.

[10] Peña, F., Galván, A. y Meli, R., (2012) “*Comportamiento estructural de juntas entre dovelas de concreto prefabricado para túneles*”, Concreto Cemento Investigación y Desarrollo, Vol. 3, Núm 2, pag 2-18. Enero-Junio.

[11] Pérez A., M. and Auvinet G. (2013a). "*Stress and displacement fields in a tunnel lining and surrounding ground*", 5th International Young Geotechnical Engineers' Conference, Ecole des Ponts Paris Tech, France.

[12] Rodríguez J.F. y Auvinet G. (2012). "*Criterios para el diseño del revestimiento definitivo de túneles en suelos blandos*", Magazine of the Mexican Society of Geotechnical Engineering, No. 225: 20-28. Mexico City.