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Geotechnical Evaluation of Displacements of a Tunnel-Shaft Connection due to Regional Subsidence Considering Rigid and Flexible Coupling in Structures Projected in Mexico City Difficult Soft Soil Conditions Using 3D Numerical Modeling

Jorge Bricio GUILLÉN[a,1], Oscar LUNA[a], Omar VARGAS[a] and Raúl BERNAL[a]
[a] *Gerencia de Estudios de Ingeniería Civil, CFE, México*

Abstract. In this document, the comparison, with the aid of the three-dimensional finite element method, of the long-term behavior of a tunnel-shaft connection is made from two hypotheses; the first considering the rigid connection as a monolithic concrete structure between the shaft wall and the tunnel body, and the second considering a material of elastic behavior between the two structures, resulting in a flexible connection. The linear elastic material considered was neoprene, widely used in the construction of this type of structure. The geotechnical model used, the initial piezometric conditions and the proposed piezometric conditions to evaluate the long-term condition, as well as a summary of the tunnel and shaft characteristics and dimensions are presented. The Soft Soil Model was used to carry out the analyzes with finite element for the compressible strata. In the results analysis, emphasis on the relative deformations and stresses concentration in the elements of the connection for each hypothesis is placed. Finally, some advantages and disadvantages of each connection alternative are discussed to face the effect of subsidence in Mexico City are discussed.

Keywords. Tunnel-shaft connection, rigid, flexible, soft soils, regional subsidence.

1. Introduction

There is evidence of damage in tunnel-shaft connections built in soft clays in Mexico City (mentioned by References [1-5]). A clear example is what happened in the Casa Colorada Pumping Plant where there were structural problems because of the vertical differential displacements [5]. Therefore, it is important to resort to methods that consider more specific variables to the place under study and the structures involved and in this way to predict as closely as possible the settlements and the stresses distribution presented in the long term. An alternative to evaluate tunnel-shaft connections is the use of three-dimensional numerical methods, specifically, the finite element method (FEM).

[1] Corresponding Author, Departamento de Mecánica de Suelos, GEIC – CFE, Augusto Rodín No. 265, Col. Nochebuena, C. P. 03730, Ciudad de México; E-mail: jorge.guillen02@cfe.gob.mx.

In this document, the possible geotechnical behavior of a tunnel-shaft connection considering rigid and flexible coupling due to the effect of regional subsidence in Mexico City difficult soft soil conditions are evaluated. The three-dimensional finite element is used as the principal method of analysis, through which it is possible to observe the results of deformations and stresses accumulated in the elements subjected to the effect of subsidence.

The evaluated connection refers to a float type shaft of 16 m internal diameter, and a deep tunnel of 5 m internal diameter that connects to that shaft (entrance and exit). These structures are designed to be part of a deep pluvial drainage system in the soft clay zone of the former lake of Texcoco.

The objective of the article is to present the distribution of deformations and stresses in both types of connection (rigid and flexible), issuing comments and recommendations based on the comparison of obtained results.

2. Characteristics of the tunnel and shaft

2.1. General characteristics of the shaft

The shaft mentioned before is of the "floated" type, projected in this way due to the geotechnical conditions of the site and the necessary geometry for the drainage system. It has an internal diameter of 16 m, thickness of bottom slab of 1.50 m and structural walls of 0.60 m thick, the depth is 23.21 m to the level of the bottom slab.

It is composed of a grouted cut-off wall 0.80 m thick and 29.21 m deep as protection against deep seated failure and uplift forces. The annular space between the grouted cut-off wall and the structural wall is 0.50 m, this space is filled by mortar once the tank immersion process is finished. The tank is drowned in the bottom with mortar, forming another thickness of 3.50 m.

Figure 1 shows a geometric diagram of the shaft analyzed, it shows the dimensions and characteristics mentioned above.

2.2. General characteristics of the tunnel

The tunnel in the analysis consists of two tunnel linings: a primary lining consisting of a ring with 6 segmental lining (5 + "K") and a secondary lining formed by a continuous ring of reinforced concrete, this due to the geotechnical conditions of the site and the geometry necessary for the drainage system.

The inner diameter of the tunnel is 5 m. The primary segmental lining is 0.25 m thick, and the final lining is 0.30 m thick. The concrete projected for the segmental lining is of limestone aggregate (E = 14000√ [*f'c*]), while that of the definitive lining is basaltic aggregate (E = 11000√ [*f'c*]). For both the shaft and the tunnel, the structural concrete is designed with a f'c = 350 kg / cm^2.

It should be noted that the construction process of the tunnel is by mechanical methods of TBM type EPB (Earth Pressure Balance).

Figure 2 shows the geometry of the tunnel and its corresponding lining.

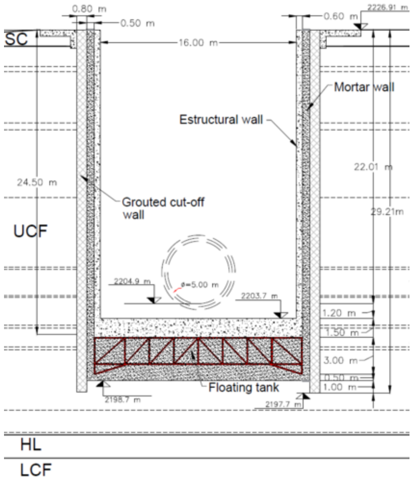

Figure 1. Geometric scheme of shaft.

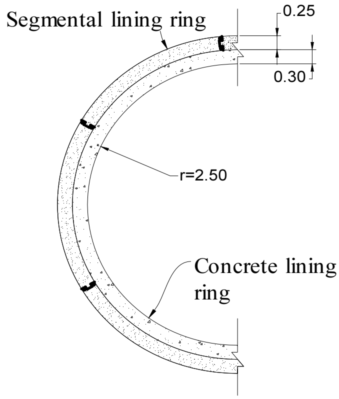

Figure 2. Geometric scheme of tunnel.

3. Geotechnical model

Based on several exploratory boring campaigns conducted in the area, information was gathered from laboratory tests and field tests to arrive at a stratigraphic interpretation of the analysis area. With the information mentioned above the geotechnical model of Table 1 was proposed assigning geomechanical properties to the different units according to their mechanical behavior and the type of analysis. The compressible strata (UCF2 and LCF) present parameters of the Soft-Soil constitutive model which was chosen for the analysis of long-term behavior. The remaining strata (SC, UCF1, HL) were modeled as Mohr-Coulomb type materials. Table 2 presents the nomenclature of Table 1.

4. General considerations for the 3D model

The idealized finite element three-dimensional model for the analyzes presented in this document represents the conditions of a shaft with the characteristics described in section 2.1, that shaft will have an entrance portal and an exit portal for the tunnel with characteristics mentioned in section 2.2. At the same time, in order to simulate a representative tunnel length (connected to the shaft), a length of 135 m was chosen from the shaft axis. This distance is enough to evaluate the behavior of the tunnel in an area away from the shaft.

Making use of the symmetry in the numerical modeling, the type section at the end represents half of the shaft, with a tunnel length of 135 m. Figure 3 represents a schematic of the represented model.

Based on the shaft scheme presented in Figure 1, some simplifications were made in the 3D model to facilitate the stages and calculation times. For the three-dimensional modeling, it was considered to combine the mortar wall (including the float tank) with the structural wall as a composite structure, which has a thickness of 1.10 m in the side wall and 5 m of the bottom slab, with volumetric weight (γ) and modulus of elasticity (E) equivalents. The weights of the slab lid, half cane and concrete bed (internal structures of the shaft) are replaced by a uniformly distributed load. The rim is discarded for the 3D model and the grouted cut-off wall is maintained with the same original characteristics. Figure 4 shows the idealized geometry of the shaft for 3D analysis.

Table 1. Geotechnical model for the long-term analysis.

Unit	Depth m	γ_m kN/m^3	c´ kPa	ϕ´ (°)	e_0 -	C_c -	C_r -	OCR -	$k_y = k_x$ m/day
SC	0 – 1.2	13.0	5	28	-	-	-	-	8.64E-01
UCF1	1.2 – 4.0	11.6	2	35	-	-	-	-	8.64E-03
UCF2	4.0 – 32.4	11.6	2	35	8.37	6.19	0.74	1.50	8.64E-05
HL	32.4 – 34.3	16.0	10	38	-	-	-	-	8.64E+01
LCF	34.3 – 49.3	11.9	2	35	6.07	4.46	0.66	1.40	8.64E-05

Table 2. Nomenclature of Table 1.

SC	Superficial crust	ϕ´	Effective internal friction angle
UCF	Upper clay formation	e_0	Initial void ratio
HL	Hard layer	C_c	Consolidation coefficient
LCF	Lower clay formation	C_r	Compressibility coefficient
γ_m	Saturated volumetric weight	OCR	Over-consolidation ratio
c´	Effective cohesion	$k_y = k_x$	Permeability on vertical and horizontal direction

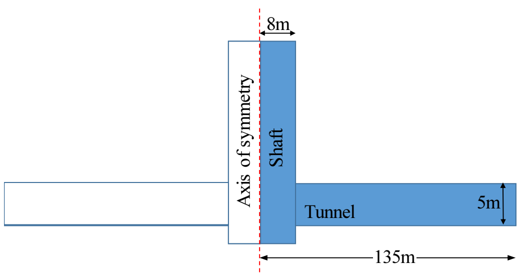

Figure 3. Scheme of the model represented in 3D analysis (use of symmetry).

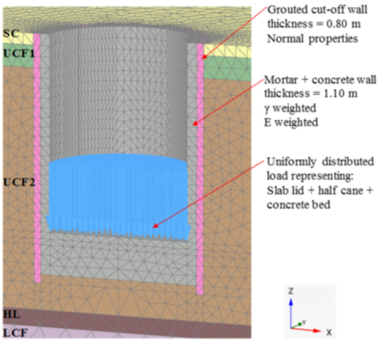

Figure 4. Geometric shaft arrangement for finite element 3D model.

For the tunnel a composite structure was also considered, with a thickness equivalent to the sum of both linings (primary and secondary) with concrete properties and an elastic modulus (E) weighted in long term conditions. Figure 5 shows the geometrical arrangement of the tunnel connected to the shaft for the 3D model.

For the evaluation of the stresses and deformations in the connection, all the structures and soil strata were considered as volumes (three-dimensional clusters) keeping continuity in all the elements, that is, they do not intervene interface elements, plates or beams.

Figure 6 presents the current, long-term piezometric conditions and their comparison with the hydrostatic pore pressure line. This piezometry is the one used in the analysis stages of finite element models.

The effect of the regional subsidence caused by the pumping will be represented by the change of initial pressures (green line Figure 6), to the pore pressure line in the long term (red line Figure 6), generating a pore pressure differential (Δu) and, at the same time, strong settlements due to this piezometric drawdown.

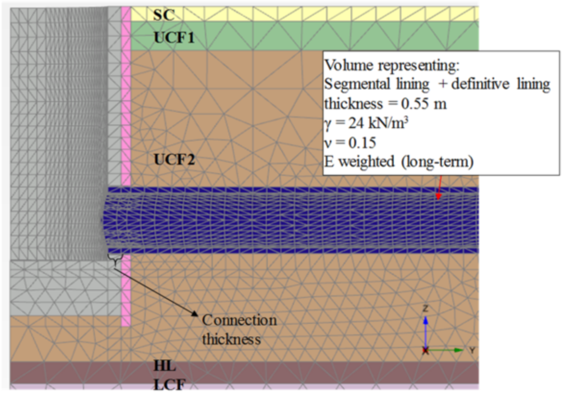

Figure 5. Tunnel-shaft geometric arrangement for finite element 3D model.

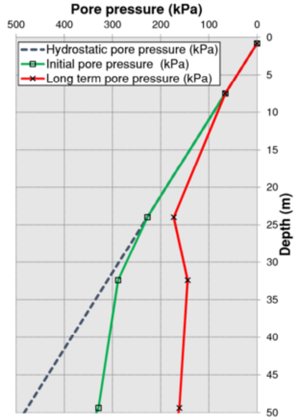

Figure 6. Pore pressure conditions used in the analysis.

5. Tunnel – shaft connection analysis in the long-term

The analysis carried out for the tunnel-shaft connection, considers as a "rigid" coupling, the concept in which the concrete volumes of the shaft (structural wall + mortar wall) are monolithically connected to the tunnel concrete (primary + final lining). On the other hand, the "flexible" coupling considers the concrete volumes of the shaft connected to the tunnel concrete by means of an interface material with elastic characteristics modeled as a neoprene ring with properties of linear elastic material, with a modulus of elasticity E = 2 MPa, a Poisson module ν = 0.499, and with a thickness of 10 cm (Figure 7).

The considered calculation stages were the following:

- Initial stage: initial conditions of the 3D model and piezometry.
- Complete shaft construction: grouted cut-off wall construction, concrete bottom slab and wall construction, addition of loads by half cane, slab lid and concrete bed, dry conditions for the shaft.
- Complete tunnel construction: construction of the equivalent lining (primary + definitive) on the entire length (135m). For the case of flexible coupling the 10 cm thick neoprene ring is added on the tunnel outer making contact with the wall of the shaft.
- Regional subsidence: application of long-term piezometry (100 years), displacements are reset to observe only the long-term effect.

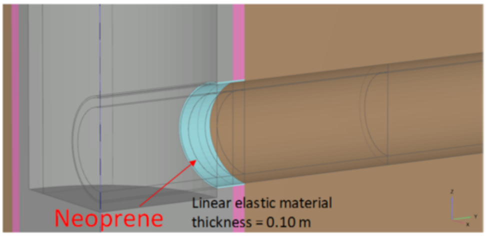

Figure 7. Modeling of neoprene ring in tunnel-shaft connection.

When performing the calculation steps previously indicated, the results of deformations generated in both types of connection are obtained. Figure 8 shows a comparison of the deformed meshes of the tunnel-shaft coupling types.

Considering a reference point in the tunnel key in the connection (red dot in Figure 8) and a point in the tunnel key furthest in horizontal distance (green dot in Figure 8), we can see that the vertical differential displacements ($\Delta\delta z$) in the flexible connection are larger than the differentials in the rigid connection, that is, the flexible connection allows 4 cm more displacement than the rigid one. On the other hand, Figure 8a describes a deformation in the form of "S" or with two inflection points due to the effect of the stiffness provided by the monolithic connection between shaft and tunnel. Figure 8b describes a slope from the start of the connection due to the degree of freedom offered by the neoprene ring. The green point in Figure 8 results with the same displacement value for both types of connection, this is an expected result since at a tunnel point away from the shaft the tunnel subsidence is equal to that of the regional subsidence in free field in that depth.

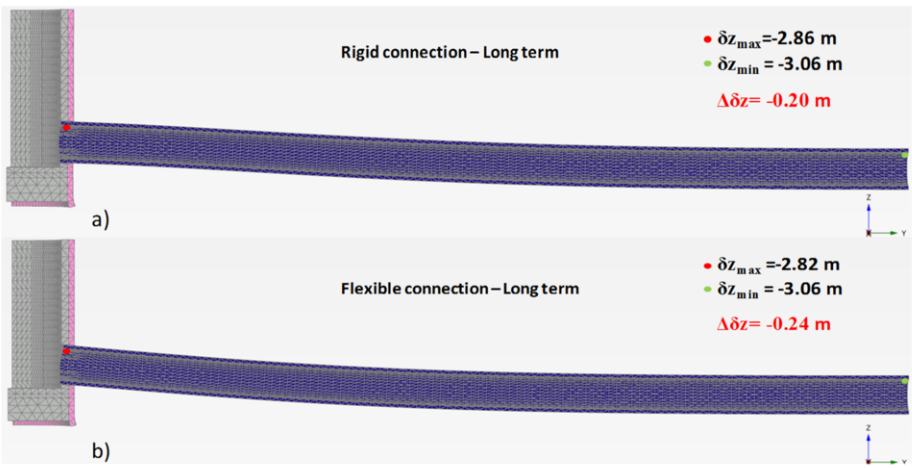

Figure 8. Deformed mesh of the tunnel-shaft combination scaled 20 times, includes value of maximum vertical displacements in the key of tunnel for the case: a) rigid connection; b) flexible connection.

The results of stress concentration in the specific area of the tunnel-shaft connection for both types of couplings are presented in Figures 9, 10 and 11. Figure 9 shows the results of effective vertical stresses (σ'_{zz}); it can be seen that, in the case of the rigid connection (Figure 11a), the stress concentration is larger than the flexible connection (Figure 11b). It is also observed that, with the rigid connection, the vertical stresses to compression and tension are concentrated in the key and counter-key respectively, in the inner part of the connection and vice versa, in the outer part of the connection (tension in key and compression in counter-key); in the case of flexible connection these stresses are released, and minor stresses are distributed in gable, key and counter-key. The stresses magnitudes in the rigid connection oscillate between 8,300 and -9,500 kPa, while in the flexible one they obtain from 2,300 kPa in tension up to -4,100 kPa in compression.

Figure 10 shows the results of effective horizontal stresses (σ'_{yy}), that is, stresses in the direction of tunnel length; it is appreciated, as in Figure 9, that in the case of the rigid connection (Figure 10a) the stress concentration is larger than the flexible connection (Figure 10b). The magnitudes of stresses in the rigid connection oscillate from $15\text{x}10^3$

kPa in tension and $-15.8x10^3$ kPa in compression, while in the flexible one they obtain values from $11x10^3$ kPa in tension up to $-1x10^3$ kPa in compression.

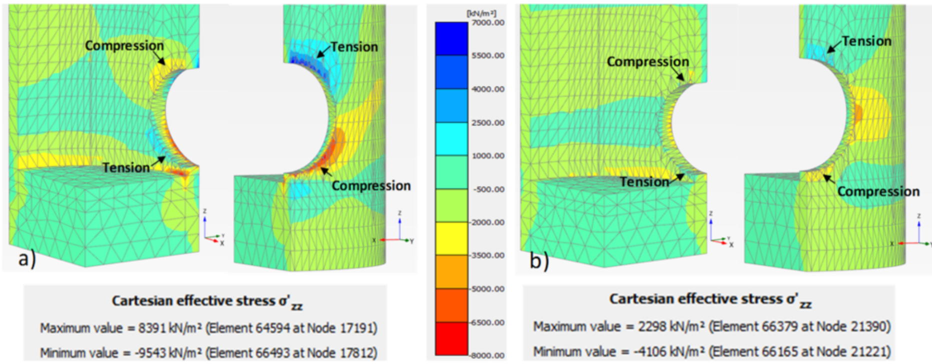

Figure 9. Results of vertical stresses (σ'_{zz}) in tunnel-shaft connection for the case: a) rigid connection; b) flexible connection.

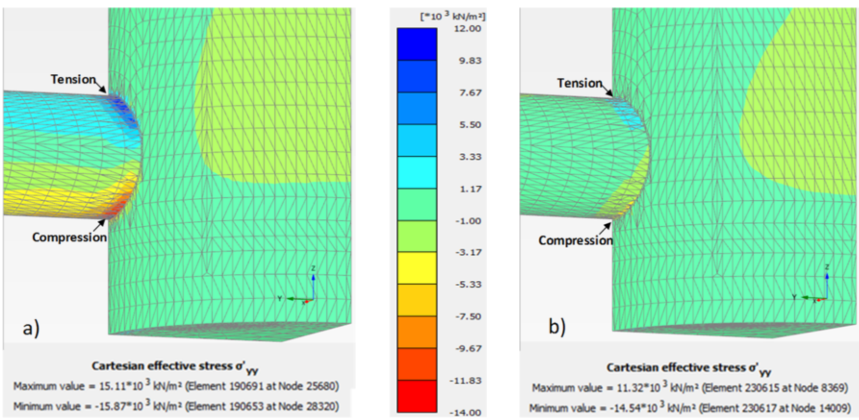

Figure 10. Results of horizontal stresses (σ'_{yy}) in tunnel-shaft connection for the case: a) rigid connection; b) flexible connection.

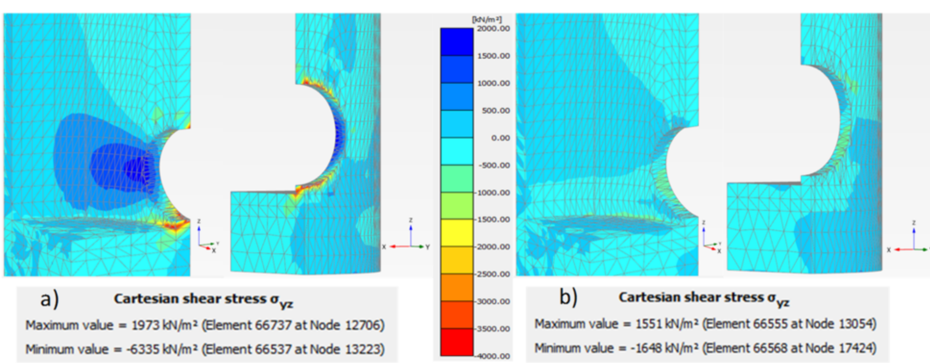

Figure 11. Results of shear stress (σ_{yz}) in tunnel-shaft connection for the case: a) rigid connection; b) flexible connection.

Figure 11 shows the results of shear stresses (σ_{yz}), that is, stresses generated in the transverse direction of the connection. When comparing the stresses with the same graphical scale just by observing the color scale, the rigid connection (Figure 11a) generates a higher concentration of shear stress than the flexible connection (Figure 11b). The shear stress magnitudes in the rigid connection fluctuate between 1,900 kPa in the positive direction and -6,000 kPa in the negative direction, while in the flexible, values are obtained from 1,500 kPa in the positive direction to -1,600 in the negative direction.

6. Conclusions and recommendations

Based on the observed results of the long-term analysis, the following can be concluded:

- The flexible connection allows an additional 0.04 m of displacement compared to the rigid connection, there is a 20% increase in the displacement of the flexible connection to the rigid connection.
- Allowing these displacements with the flexible connection the stresses compared to the rigid connection are reduced with the following percentages:
    - Effective vertical stresses, σ'_{zz}: 73% in tension and 57% in compression.
    - Effective horizontal stresses, σ'_{yy}: 25% in tension and 8% in compression.
    - Shear stress, σ_{yz}: 21% in positive direction and 74% in negative direction.

The simplified numerical modeling presented in this article, allows to observe a significant reduction in the stresses generated in the tunnel-shaft connection with flexible coupling with respect to the rigid one, in exchange for admitting minimum vertical displacements.

The results obtained represent numerically the advantage with the choice of flexible connections in tunnel projects; however it is necessary to study thoroughly and put into practice the appropriate construction processes to contemplate a flexible type connection.

Nowadays the soil improvement zone is the most usual for the tunnel-shaft connection entrance; however if this subject is further investigated we can optimize the area of improvement or even replace it with a flexible connection.

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