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# Effects of the Regional Subsidence on Tunnel-Shaft Connections, Considering Different Construction Procedures

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**Abstract.** We present the results obtained with 3D numerical modeling of rigid tunnel-shaft connections in soils subject to regional subsidence (HR). The results include the effects of two types of shafts: a) constructed by the flotation method and b) with Diaphragm wall. In each case, the mechanical response of the terrain was represented with the Hardening-Soil (HS) constitutive model. The greatest effects on the tunnel-shaft connection were observed in the modeling of shaft built with the Diaphragm wall technique.

**Keywords.** Rigid connections, floated shaft, diaphragm walls, Hardening soil.

## 1. Introduction

Currently, large underground works are carried out in the Valley of Mexico, mainly tunnels and shafts for purposes of transportation or sewerage networks. Constructing these structures constitutes a great geotechnical challenge, due to the subsoil characteristics of the lacustrine zone, including high compressibility, and to the consolidation processes to which it is subject. For the analysis of these structures, multiple analytical solutions are available. However, few results have been published regarding connections between shafts and tunnels. Traditionally, tunnels and shafts are analyzed and designed separately and the connection effects are not considered in any case.

For the subway system at Mexico City, 3D numerical modeling of tunnel-shaft connections in soft soils subject to the effect of regional subsidence (HR) was performed. The results of three cases with different types of connections were presented: shaft and tunnel structurally linked (rigid connection), shaft and tunnel disconnected (flexible connection) and ground improvement around the connection. The following was concluded: a) the highest concentrations of stress occur in the rigid connections, b) the flexible connections can cause extrusion of the ground inside the tunnel and the shaft and, c) the improvement of the terrain around the connection allows avoiding large concentrations of stress in the connection and extrusion of the ground. However, the soil improvement must cover a length over the tunnel of at least

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three times its diameter, in order to generate a transition that gradually follows the regional subsidence [1].

Another case related to connections, was presented in the study "The pumping plant Casa Colorada". This study included an analysis of the interaction between underground structures (tunnel-shaft) in a soil submitted to a consolidation process generated by pore water pressure drawdown (HR). A numerical model allowed obtaining displacements, strains and stresses, that were compared with the instrumentation results [2].

The parametric study presented in this contribution resorted to 3D numerical modeling of rigid connections in soils subjected to HR, considering the distance between the bottom of the shaft bottom and a hard layer CD. It was observed that the smaller this distance, the lower the concentration of stresses in the connection. For larger distances, the stress concentration increases in the connection, but decreases in the tunnel sections away from the shaft [3].

## 2. Case studies

Figure 1 shows the geometric and structural configurations of a shaft built respectively with the techniques of flotation [4] and perimeter Diaphragm wall. The properties of the structural elements for each shaft are presented in Tables 1 and 2. Figure 2 shows the finite element mesh used in the 3D numerical modeling for both cases, the stratigraphy of the site and the distribution of pore pressures in the field. The groundwater level (NAF) is 1.5m deep.

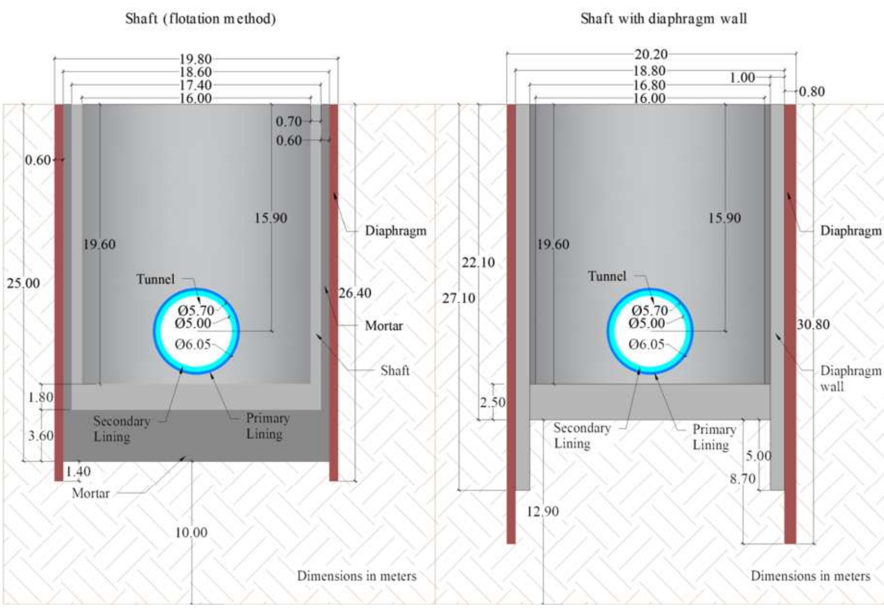


**Figure 1.** Geometric and structural configurations of shafts built with the techniques of flotation and Diaphragm wall.

Superficially, a dry crust (CS) approximately 1.50m thick is identified, formed of dried clays and silts. It is followed by an upper clayey formation (FAS), constituted by clays of high compressibility and very soft consistency. Below the FAS, a first hard layer (CD), formed by silts and dense sands is found. Below this is the lower clay formation (FAI), with clays of high plasticity and consistency from mild to medium. The boring depth made it possible to identify the upper stratified series (SES), constituted by intercalations of sands, clays and silts from firm to hard consistency and medium to dense compactness.

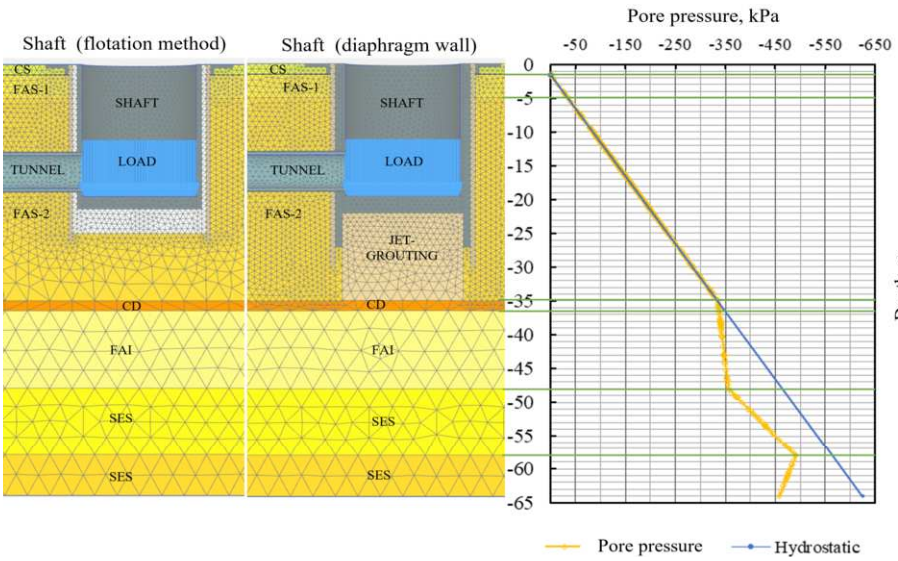


**Figure 2.** Cases of analysis with the geotechnical model and initial pore pressure.

The HS constitutive model (Table 3) was used for the numerical representation of the clay formations mechanical behavior. The firm strata were represented with the Mohr Coulomb (MC) constitutive model. All the construction stages corresponding to each construction procedure were modeled to obtain approximately the initial stress state (at the end of construction), for the long-term analysis of the tunnel-shaft connection. It was considered that the tunnels were built with tunnel boring machines and that they have a double lining. The external or "primary" lining (RP) is formed by rings of concrete segments and the "secondary" lining (RS) is a continuous element. Both linings were represented by volume elements. A reduction factor of the flexural stiffness ($\alpha$) was applied to consider the effect of the joints between the segments, which decreased the thickness of the volume elements used to represent the RP [5] (Table 2). The analysis stages are described in Table 4.

**Table 1.** Elements for the construction of the shafts.

| Element | Material model | Material type | Thickness (m) | γ kN/m³ | E MPa | c kPa | ν |
|---|---|---|---|---|---|---|---|
| Diaphragm | Mohr-Coulomb | Non-porous | 0.6 / 0.8 | 14.00 | 64 | 500 | 0.20 |
| Mortar trench | Elastic-Linear | Non-porous | 0.60 | 20.00 | 13470 | - | 0.15 |
| Mortar | Elastic-Linear | Non-porous | 3.60 | 20.00 | 13470 | - | 0.15 |
| Wall shaft | Elastic-Linear | Non-porous | 0.7 / 1.0 | 24.00 | 26191.6 | - | 0.20 |
| Slab background | Elastic-Linear | Non-porous | 1.8 / 2.5 | 24.00 | 26191.6 | - | 0.20 |
| Jet grouting | Mohr-Coulomb | Non-porous | - | 13.00 | 100 | 1000 | 0.30 |

**Table 2.** Elements for the short and long term tunnel analysis.

| Lining | | Element type | f'c (MPa) | α | FR | E (MPa) | e (m) | ν - |
|---|---|---|---|---|---|---|---|---|
| Short term | Primary | Cluster | 35 | 0.30 | 1.00 | 7809 | 0.35 | 0.2 |
| | Secondary | Cluster | 50 | 1.00 | 1.00 | 31113 | 0.35 | 0.2 |
| Long term | Primary | Cluster | 35 | 0.30 | 0.57 | 4451 | 0.35 | 0.18 |
| | Secondary | Cluster | 50 | 1.00 | 0.57 | 17734 | 0.35 | 0.18 |

**Table 3.** Soil parameters for Hardening Soil model.

| Material | Depth (m) | | γ | c' | ϕ' | $e_0$ | $C_c$ | $C_r$ | OCR | $k_y$ | $K_0^{nc}$ | $\nu_{u'}$ | $E_{50}$ | $E_{eod}$ | $E_{ur}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | de | a | kN/m³ | kPa | ° | - | - | - | - | m/día | - | - | kPa | kPa | kPa |
| CS | 0.0 | 1.5 | 13.0 | 5.0 | 28 | - | - | - | - | 8.57E-01 | 0.53 | - | - | - | - |
| FAS-1 | 1.5 | 5.0 | 11.6 | 2.3 | 36 | 8.39 | 6.19 | 0.74 | 1.50 | 8.61E-03 | 0.43 | 0.33 | 925 | 415 | 6690 |
| FAS-2 | 5.0 | 35.0 | 11.6 | 2.0 | 35 | 8.43 | 6.26 | 0.81 | 1.48 | 8.58E-05 | 0.43 | 0.33 | 925 | 415 | 6690 |
| CD | 35.0 | 36.5 | 16.3 | 10.0 | 38 | - | - | - | - | 8.62E+01 | 0.38 | - | 20 | - | - |
| FAI | 36.5 | 48.0 | 12.0 | 2.5 | 35 | 6.10 | 4.45 | 0.67 | 1.20 | 8.59E-05 | 0.43 | 0.33 | 935 | 415 | 6700 |
| SES | 48.0 | 64.0 | 16.0 | 10.0 | 41 | - | - | - | - | 8.63E+00 | 0.33 | - | - | - | - |

**Table 4.** Stages of analysis for the two types of construction process.

| Stages | Stages of the construction process of shaft: Flotation Method | Stages of the construction process of shaft: Diaphragm Wall Method |
|---|---|---|
| E-01 | Construction of exterior and interior mouth wall | Construction of exterior and interior mouth wall |
| E-02 | Excavation for perimeter diaphragm of self-setting slurry and placement of bentonite slurry | Excavation for perimeter diaphragm of self-setting slurry and placement of bentonite slurry |
| E-03 | Construction of perimeter diaphragm of self-setting slurry | Construction of perimeter diaphragm of self-setting slurry |
| E-04 | Annular excavation between self-setting slurry diaphragm and central core and placement of bentonite slurry | Excavation for Diaphragm wall |
| E-05 | Excavation of the core and placement of bentonite slurry | Construction for Diaphragm wall |
| E-06 | Construction and immersion of floated shaft, removal of bentonite slurry and placement of mortar in floating tank area and annular space between diaphragm and shaft. | Improvement with Jet Grouting at the bottom of the excavation |
| E-07 | Construction of exit portal | Shaft core excavation |
| E-08 | Construction of the primary lining, considering a reduction factor of the flexural stiffness, α = 0.3. | Construction of bottom slab and final lining |
| E-09 | Construction of secondary lining (RS), considering a decrease of the modulus of elasticity of the concrete due to plastic flow, FR = 0.57 | Construction of exit portal |
| E-10 | Total abatement of pore pressures in the field | Construction of the primary lining, considering a reduction factor of the flexural stiffness, α = 0.3. |
| E-11 | | Construction of the secondary lining (RS), considering a decrease of the modulus of elasticity of the concrete due to plastic flow, FR = 0.57 |
| E-12 | | Total abatement of pore pressures in the field |

## 3. Results and observations

Figure 3 shows the settlements of the soil surface and the apparent emersions induced by regional subsidence, for the two types of shafts. The shaft with the highest emersion value is that which is built with Diaphragm walls (table 5), because the screens and their walls are deeper than the walls and structural walls of the floated shaft. In addition, in the case of the Diaphragm Wall shaft, the improvement of the terrain by jet-grouting reaches the hard layer.

Figure 4 shows the deviatoric stresses due to the effect of regional subsidence, on the shaft-tunnel connections and for both types of shaft. The shaft-tunnel connection that presents higher deviatoric stresses is the shaft with Diaphragm walls. The above is due to the smaller emersion of the floating shaft. The deviatoric stresses were -22.8MPa for the Shafts with Diaphragm wall and -2.6MPa for the floating shafts.

Figure 5 shows the deviatoric stresses due to regional subsidence, induced in the secondary lining of the tunnel. In the case of shaft with Diaphragm walls, the greatest deviatoric stresses are observed on the secondary lining. This is due to the larger differential sinking between the connection and the tunnel, which is directly related to the greater emersion suffered by this type of shaft with respect to the floating shaft.

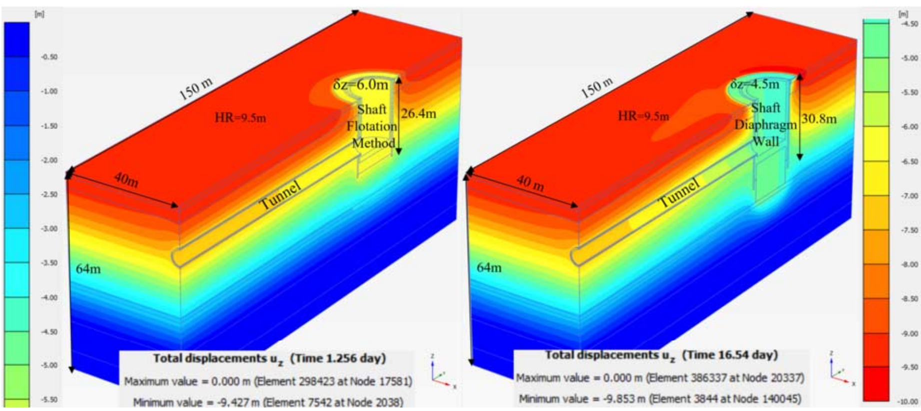


**Figure 3.** Apparent emersion due to regional subsidence, for the two types of shafts.

**Table 5.** Summary of results.

| Cases | Settlement max m | Emersion m | Shaft $q_{max}$ kPa | Tunnel $q_{max}$ kPa |
|---|---|---|---|---|
| Shaft Floated | 9.5 | 3.5 | -2597 | -11340.0 |
| Shaft Diaphragm wall | 9.5 | 5.00 | -22880.0 | -25600.0 |

## 4. Conclusions

Results of 3D numerical modeling performed for evaluating the behavior of rigid shaft-tunnel connections constructed in soft soils, subject to the effect of regional subsidence are presented. These connections correspond to shafts of equal depth but built using different techniques: Diaphragm walls and flotation method.

The shaft built with Diaphragm walls was the one that presented greater emersion, because its Diaphragm walls are deeper. In addition, for this case of study, the soil improvement that is required to avoid certain types of failures during its construction, reached the hard layer. The greater emersion caused greater differential settlements between the tunnel-shaft connection and the tunnel itself, generating greater deviatoric stresses both in the connection and in the final lining of the tunnel.

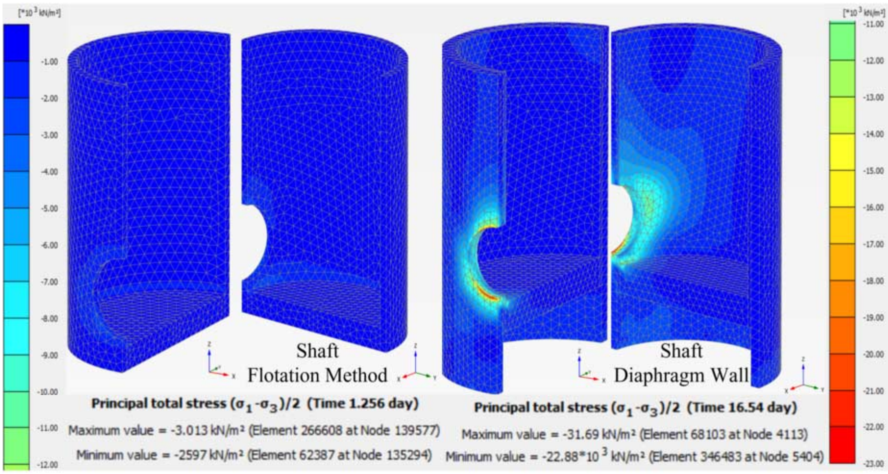


**Figure 4.** Deviatoric stresses in the tunnel-shaft connection, for both types of shafts.

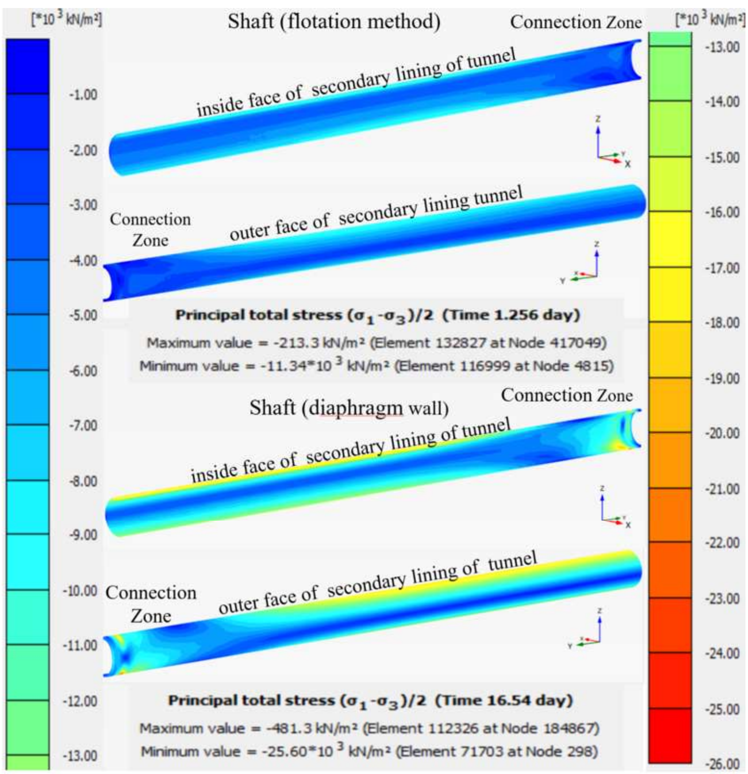


**Figure 5.** Deviatoric stresses in the tunnel, for the two types of shafts.

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