Effect of the subsoil conditions in the seismic interaction between two underground stations connected by a circular section tunnel

Effet des conditions du sous-sol à l'interaction sismique entre deux stations de métro reliées par un tunnel de section circulaire

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ABSTRACT: The new Line 12 of the Mexico City subway presents several special situations related to geotechnical and seismic aspects. In this paper we analyze the influence of changes caused by variations in the properties and thickness of soil layers between two underground stations connected by a circular tunnel. For this purpose we discuss the accelerations, stresses and deformations generated in different elements of the underground structures and its variation along time. The results show that variations in the soil-structure response must be considered in design of this type of structures located in Mexico City.

RÉSUMÉ : La nouvelle ligne 12 du métro de Mexico présente plusieurs situations particulières liées aux aspects géotechniques et sismiques. Dans cet article, nous analysons l'influence des changements provoqués par les variations dans les propriétés et l'épaisseur des couches de sol entre deux stations de métro reliés par un tunnel circulaire. A cet effet, nous discutons des accélérations, des contraintes et des déformations générées dans les différents éléments des structures souterraines et sa variation au cours du temps. Les résultats montrent que les variations de la réponse du sol-structure doit être pris en compte dans la conception de ce type de structures situées dans la ville de Mexico.

KEYWORDS: Seismic interaction, subsidence phenomena, underground structures.

1 INTRODUCTION.

Certain areas of Mexico City are affected by regional subsidence and the amplification of earthquake ground motions. The first issue, caused by groundwater extraction from the underlying aquifer, induces changes in soil properties over time (Ovando et al., 2007). The consolidation process of soil strata caused by ground water extraction also modifies the seismic response of soil, the infrastructure works in the City (tunnels, bridges and buildings) may become more vulnerable to seismic events over time.

This study evaluates the evolution of seismic response a tunnel and two underground subway stations, caused by regional subsidence over a period of 50 years.

Analyses were performed using a three-dimensional finite difference model which comprises two underground subway stations, a tunnel section and the soil deposit. Acceleration, stress and displacement histories were determined at the tunnel station connections joints and those places where tunnel changes direction.

2 PROBLEM DEFINITION.

The Metro Line 12 is 24.5 km in length, and it passes through various geotechnical areas in which different geotechnical problems are presented. Some of these are related to stratigraphical variations along the line, regional subsidence and variation of the seismic response during the structures' life time.

Zapata and Parque de los Venados subway stations are located in the middle-west of Mexico City in the so called transition zone (NTC, 2004) where the thicknesses of soft clay strata do not exceed 20m. Both stations were built at a depth of 22 m approximately and are connected to 9m diameter circular tunnel. The studied area presents significant variations in the clay layers thicknesses. Soil deposits underlying The Zapata Station are formed by harder materials than those at the Parque de los Venados Station which was built over 15m thick compressible clay strata.

3 MATERIAL PROPERTIES

Soil properties of the studied area, were obtained from test on undisturbed samples obtained from three borings 15 to 20 m deep as well as from a cone penetration (CPT) and down-hole tests (see Figure 1).

Shear wave velocities at the Zapata Station were directly obtained from the down-hole test. Semiempirical correlations (Eq. 1) that relate CPT strength with shear wave velocity of soil (Ovando and Romo, 1991) were used for the characterization of soils in Parque de los Venados Station.

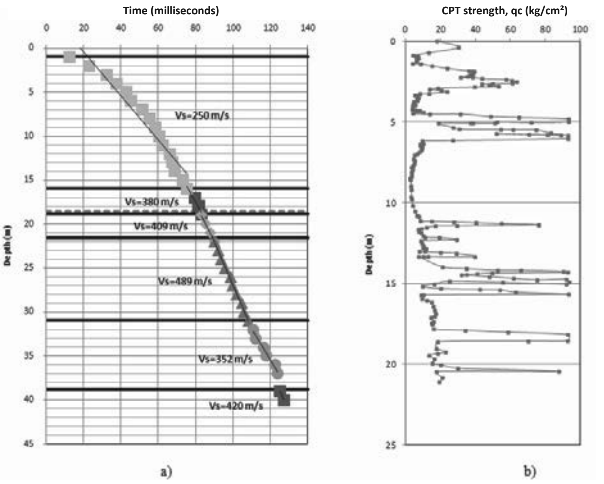

Figure 1. a) Down.Hole test results, in Zapata station. b) Cone penetration test results in Parque de los Venados station.

$$V_s = \eta \left[\frac{q_c}{N_{kh}\,\gamma_s} \right]^{0.5} \tag{1}$$

Where V_s has units of m/s, q_c is given in t/m^2 and γ s in t/m^3 (volumetric weight of soil), η and N_{KH} are typical values for soils from Mexico City.

4 NUMERICAL MODEL

Numerical modelling was performed using the finite difference method, implemented in three dimensions in the analysis platform FLAC3D (ICG, 2009). The chosen platform applies the numerical method to geometry and arbitrary boundary conditions defined by the user with an external preprocessor (Romo et. al., 2005)

4.1 *Characteristics of the model*

The model of this site has two stations, which have 46 m wide by 190 m long. The stations reach a maximum depth of 22 m deep at their lower point from the surface. They are limited by two slurry trench walls in the transverse direction, which are supported at a depth of 28 m. The tunnel is 480 m long and 10 m in diameter and its crown is at a depth of 9.4 m. The model was conceived considering the layout plan of the section under consideration, including changes in the alignment of the tunnel which generate two horizontal curves, as presented in Fig.2.

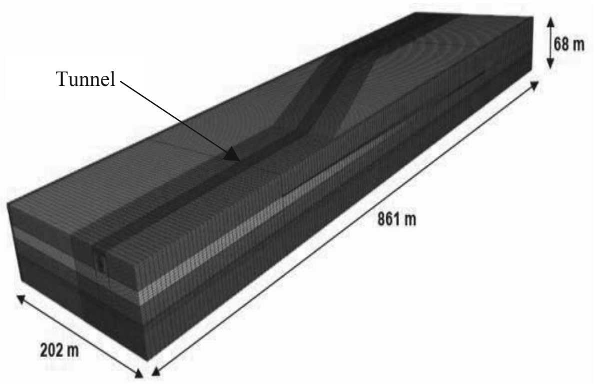

Figure 2. Isometric view of the three-dimensional model.

4.2 *Soil deposit model*

The three-dimensional finite difference model, consisting of 630,525 nodes and 608,004 elements which form mostly 8-node tetrahedral and the remaining correspond to 6 nodes wedges. The model has 202 m wide and 861 m long (see Fig. 2). With these dimensions it seeks to minimize the potential effects of refraction of waves in the half-space, in addition to dissipating boundaries are implemented for the same purpose.

The model consists of six layers. The first one corresponds to soft clay, the five remaining layers underlying are more compact, generating a significant contrast between the material stiffness.

4.3 *Detailed station and tunnel model*

The stations models have a top slab corresponding to the pedestrian circulation area, two Milan walls at sides of the platform area where the trains are parked.

To integrate the tunnel to the stations, it has concrete walls that connect the stations with the tunnel. The tunnel is made up of rings of 8 segments of 40 cm thick, which have a rotation (or phase) of 33° to each other. For modeling purposes, according to the hypothesis behavior of the elements, this covering is considered as a continuous stiffness properties equivalent to those of the original reinforcement.

5 SEISMIC ENNVIROMENT

The seismic environment at the site was determined in terms of acceleration spectra envelopes obtained from accelerations recorded in the vicinity of the site. Finally, the surface spectrum was scaled by the seismic coefficient specified in the Mexico City Building Code (NTC, 2004). This meets statutory provisions (see Fig. 3)

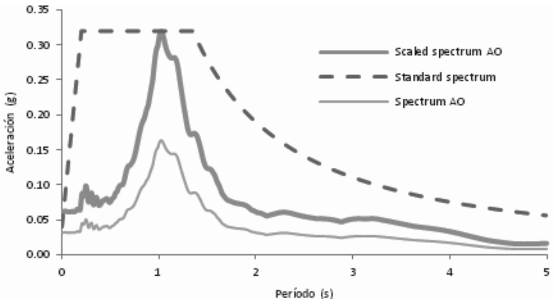

Figure 3. Comparative spectra.

The scaled spectrum was deconvolutioned at the model base by means of a probabilistic analysis. To the end we generate 25 random site profiles. The analysis was made take the spectrum corresponding to the mean plus one standard deviation in order to cover the range of uncertainty inherent to this type of study.

The resulting spectrum is taken as the objective function to generate a synthetic earthquake, which serves as a basis for analyses in time domain.

6 EVOLUTION OF THE SEISMIC RESPONSE DUE TO REGIONAL SUBSIDENCE

Regional subsidence in Mexico City induces changes in pore pressure that increase effective stresses. As a result, the static and dynamic properties of the soil are modified and therefore, the seismic response.

6.1 *Pore Pressure distribution*

The variation of pore pressure distribution due to regional subsidence was analyzed using a one-dimensional model of soil consolidation. The model we used, considers the soil as an elasto-viscous-plastic material in which primary and secondary consolidation are coupled. The model was originally proposed by Yin and Graham (1996) and implemented by Ovando and Ossa (2004) to evaluate regional subsidence caused by water pumping. The analysis of the variation of pore pressure distribution due to regional subsidence considered a period of 50 years. The studied site was modeled taking into account that compressible deposits are confined by permeable soil layers.

The initial piezometric conditions and the pore pressure depletion rates at the permeable boundaries were estimated from piezometric stations located near to the studied site.

Evolution of the pore pressure distribution in the studied site is presented in Figure 4a.

6.2 *CPT strength and shear wave velocity*

CPT strength depends on the shear strength of the soil. On the other hand, the relationship between vertical stress and shear strength of normally consolidated soil (clay condition representative of the Valley of Mexico) is constant, leading to assume that changes in effective stress due to groundwater extraction induces changes in the values of CPT strength. This can be represented by Eq 2 as follows:

$$q_c(t)=N_\sigma \sigma'_v(t) = N_\sigma(\sigma'_{v0}(t)+\Delta u(t)) \qquad (2)$$

Where N_σ (Santoyo et al., 1989) is a correlation factor ($N_\sigma \approx 5.5$) and $\sigma'_{v0(t)}$ is the initial effective vertical stress. The factor $\Delta u(t)$ represents the variation of pore pressure at the period under consideration. Evolution of shear wave velocity was estimated from equation 1, taking into account the changes in CPT strength over time. Evolution of these two parameters due regional subsidence is presented in Fig.4b y 4c.

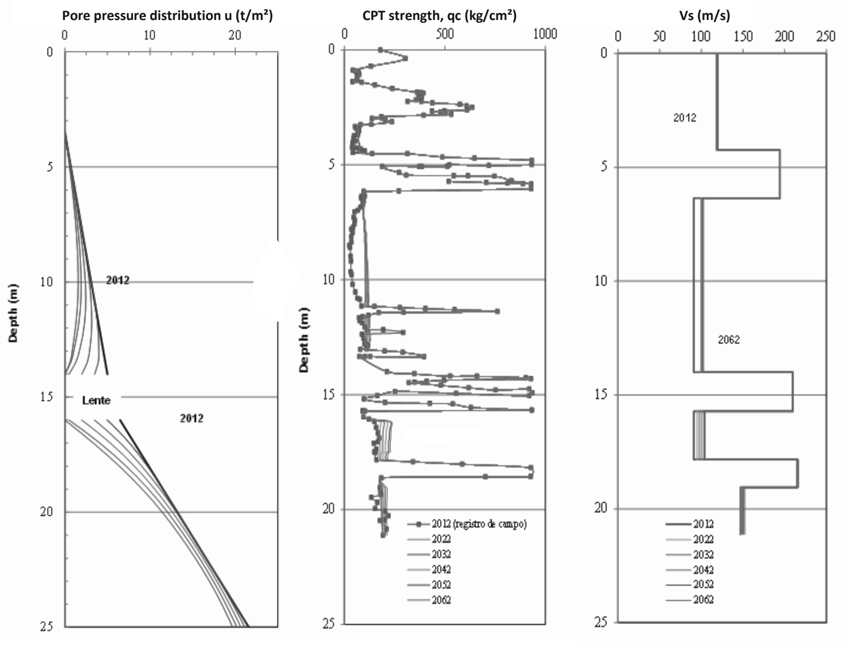

Figure 4. Evolution of a) Pore pressure distribution, b) CPT Strength. c) Shear wave velocity, due regional subsidence.

7 ANALYSIS OF RESULTS

In the seismic analyses three scenarios were evaluated. The first corresponds for the present time, the second to 30 years in the future and the last one 50 years. These analyses were performed modifying the soil properties according to the proposed model explained at previous section. We analyze the resulting histories of acceleration, force and displacement.

Eight monitoring points were fixed along the tunnel, in areas considered critical. These areas are the joints of tunnel and the stations and the zones where tunnel changes its direction (Elbow 1 and 2) (Figure 5). The monitoring points are located in sections of the upper and lower parts of the tunnel.

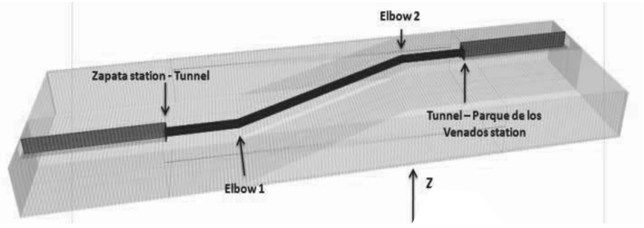

Figure 5. Location of monitoring zones.

7.1 *Evolution of the acceleration response*

The resulting acceleration spectra show that the maximum acceleration decreases with time (see Fig. 6). Table 1 shows that acceleration reductions at each monitored zone are different over 50 years, indicating clearly that the variation in the resulting accelerations will be unique at each site.

Table 1. Variation of the acceleration magnitude between 2012 - 2062

Monitoring zone	*Reduction of the acceleration magnitude*
Zapata station - Tunnel	17.0
Elbow 1	17.0
Elbow 2	13.0
Tunnel – Parque de los Venados station	4.5

Ours results also show that the site dominant period is located at 1.12 s and that it presents a small decrease of less than 0.01 s over the 50 year period. This is due to the fact that soil properties at the site; do not vary significantly along time.

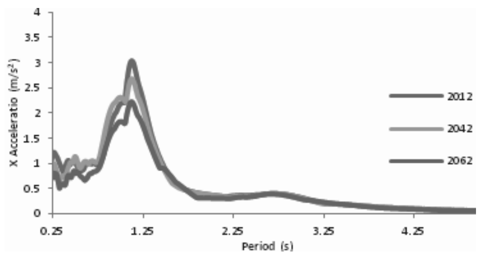

Figure 6. Evolution of the acceleration spectra over time. Case of Elbow 1 in X direction.

7.2 *Evolution of the relative displacements*

Relative displacements between 2012 and 2042 do not vary significantly but increase sharply between 2042 and 2062 where we estimated an increase of 32% on this period of time (see Fig. 7).

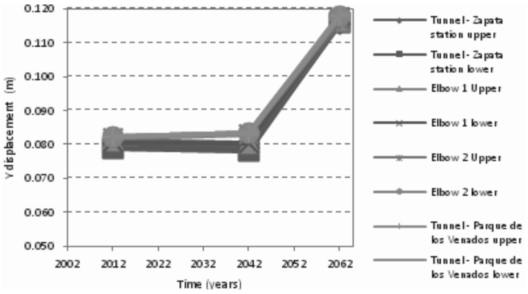

Figure 7. Evolution of the displacementover time.

7.2.1 *Evolution of normal stress*

Normal stresses at the connection of the tunnel with the Zapata Station increase around 30 to 40% over the 2042-2062. These increases occur at elbow zones; especially those on soft deposits of greater thickness (see Fig. 8).

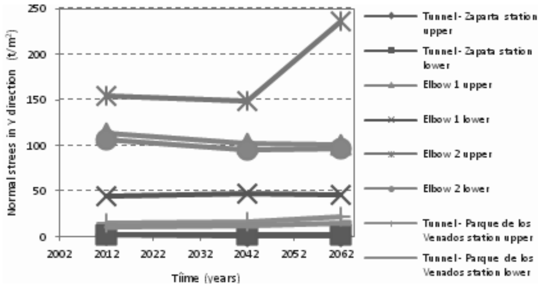

Figure 8. Evolution of the normal stresses over time. Case of Y direction.

7.2.2 *Evolution of shear stress*

The shear stresses increase around 30 to 60% for the 2042-2062 period of analysis, only in the connections supported on thicker soft material, as are elbow 2 and Tunnel- Parque de los Venados station zone. Shear stresses remain constant with time at other connections upon the occurrence of seismic events (see Fig. 9).

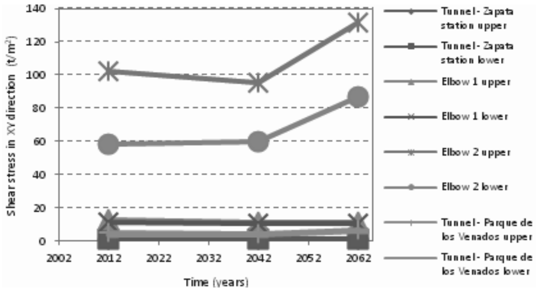

Figure 9. Evolution of the shear stresses over time. Case of XY shear stress.

8 CONCLUSIONS

We calculate static and dynamic displacements, accelerations and stresses over 50 year period.

Regarding displacements, our results show that these will be admissible and should not promote damages and difficulties on the section of Metro Line 12 studied here.

Shear and normal stresses will increase in the future at section of the tunnel supported by the thicker clay strata or at section where the direction of the tunnel changes. The structure design of these stations must account for these changes bearing in mind that estimated stress increments in the future can be far from negligible.

9 REFERENCES

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