# Model for the determination of seismic interaction between tunnel and underground station

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LISBOA 2012

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**SUMMARY:**
Line 12 of Mexico City's subway is in its final construction phase. The project tunnel passes through different geological formations and important deposits of soft soils, whose properties and thicknesses vary sharply over short distances. In addition, these deposits are significantly affected by the phenomenon of regional subsidence. The aim of this study is to determine differential stresses and relative displacements that may occur in the interaction between a circular tunnel and a rectangular underground station when they are subjected to an earthquake. A three-dimensional finite difference model was formulated for this study to assess the influence of those stresses and relative displacements under seismic loading. The investigation considers the variation of material properties over time due to the phenomenon of regional subsidence.

*Keywords: Seismic interaction, Subsidence, Variation in seismic response, Water extraction*

## 1. INTRODUCTION

Certain areas of Mexico City are affected by regional subsidence and by seismic events in which incoming seismic waves display large amplifications as they traverse very soft clay deposits. The first issue is produced by groundwater extraction from the underlying aquifer, which induces effective stresses variation in the soil mass, accelerating the consolidation process of the highly compressive clays in the subsoil. On the other hand, these clays behave as nearly elastic materials with low damping values and these properties bring about large amplifications of seismic waves as they propagate through them. Finally, the variation in the soil properties caused by regional consolidation induces changes in the seismic response of soil deposit. Both these phenomena affect the behavior and the interaction of the structures built over or in these soils deposits.

Regional subsidence is due to the continuous and indiscriminate extraction of groundwater. This induces changes in the geotechnical properties of materials over time, and increments in effective stresses in the soil mass, thus accelerating the consolidation process of the soft clays. The process also modifies soil properties and, as a consequence, it also modifies the seismic response of structures through time.

This study evaluates the seismic interaction between the tunnel and an underground station in Mexico City's Line 12 subway. It includes an analysis of the influence of the maximum credible earthquake for the area of the project, considering staged construction as well as its short and long term conditions. The effect of the evolution of soils parameters due regional subsidence was evaluated.

Analyses were performed with a three-dimensional finite difference model, which comprises half the underground station, a tunnel section and the soil deposit. Soil material properties were obtained from the field data and laboratory tests. Finally, stress and displacement histories during seismic loading were determined at the tunnel-station joint.

## 2. PROBLEM DESCRIPTION

The Metro line 12, is 24.5 km long and traverses various areas that pose important geotechnical problems. Some of these are related to regional subsidence and the variation of the seismic response during the structures' life time. The site studied here is located in the so called transition zone where the thickness soft calys does not exceed 20m. The site is located close to one of the edges of the lake, where soft strata vary in thickness sharply and are also interspersed with coarser, harder materials (see Fig. 1).

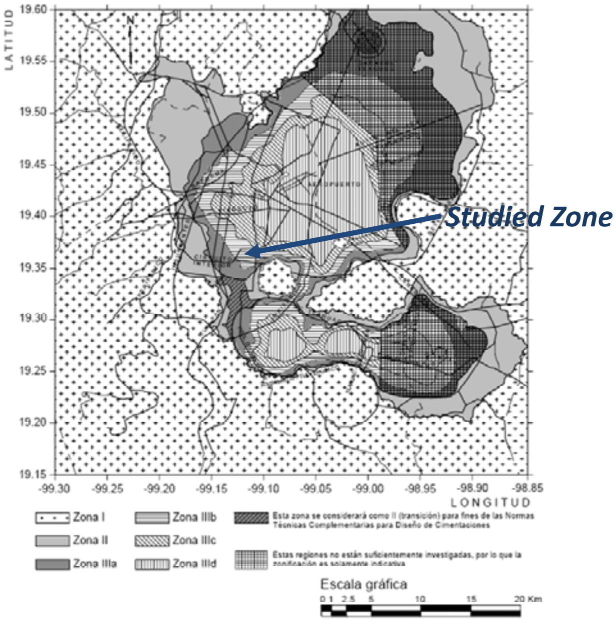


**Figure 1.** Seismic zoning of Mexico City. (NTC 2004). Location of the studied zone

## 3. DETERMINATION OF MATERIAL PROPERTIES

Material properties were determined by analyzing available information from standard (SPT) and cone penetration (CPT) tests, and from the testing of undisturbed samples 35 to 50 m deep. Data from a deep boring of 85 m deep, located 800 meters from the site were also considered to estimate the properties of the deeper materials (Fig 2).

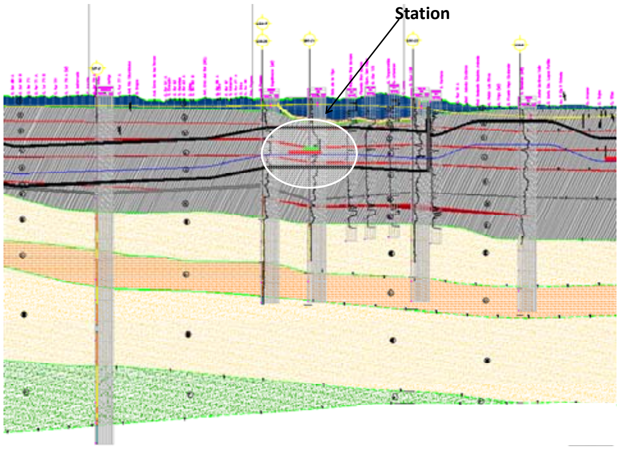


**Figure 2.** Stratigraphic profile

### 3.1. Geotechnical exploration

CPT results show that the penetration resistance of the very soft soils is nearly constant over the entire depth of the boring ($q_c$ = 43 kPa on average). Harder soils, lenses of compact sand and silty clay intersperse the clays ($q_c$ = 10, 000 kPa or more).

Shear wave velocities were determined with a semiempirical expression that relates $q_c$, with $V_s$. (Ovando and Romo, 1991):

$$V_s = \eta \left[ \frac{q_c}{N_{kh}\ \gamma_s} \right]^{0.5} \tag{3.1}$$

Where $V_s$ is in m/s, $q_c$ is given in t/m$^2$ and $\gamma$ s in t/m$^3$ (volumetric weight of soil).Typical values $\eta$ and $N_{\mathrm{KH}}$ for soils from Mexico City are reported in Ovando and Romo, 1991.

For the clay layers and the silty-clays we used $N_{\mathrm{KH}}$ = 9.5 and $\eta$ = 26.40. The calculated shear wave velocity profile is shown in Fig. 3.

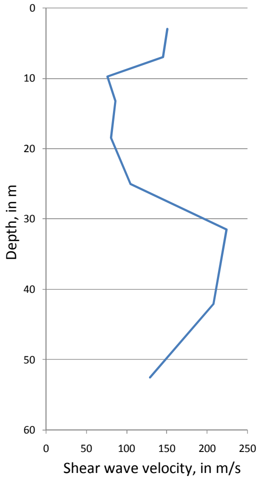


**Figure 3.** Wave velocity profile

## 4. MATHEMATICAL MODEL FORMULATION

Numerical modeling was performed using the finite difference method, implemented into the three dimensional analysis platform FLAC3D (ICG, 2009).

### 4.1. Characteristics of the model

The model of the Mexicaltzingo subway station is 46 m wide and 190 m long. The station reaches 22 m deep at its farthest point from the surface. Two slurry trench walls, 28 m deep, confine it in the transverse. The tunnel is 190 m long and 10 m in diameter, and its crown is at a depth of 9.4 m. Figures 4 and 5 illustrate longitudinal and cross sections.

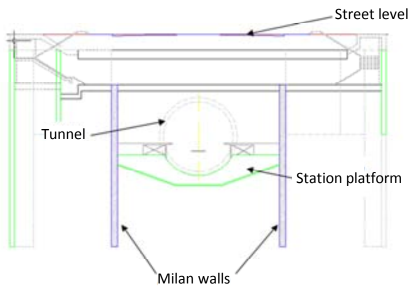


**Figure 4.** Cross section of Mexicaltzingo station

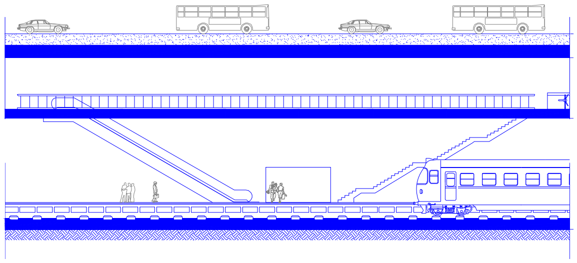


**Figure 5.** Longitudinal section of Mexicaltzingo station

## 4.2. Soil deposit model

The three-dimensional finite difference model has 305.696 nodes (see Figs 6 and 7) which form, mostly, 8-node tetrahedral elements; the remaining elements correspond to 6 nodes wedges. The model is 246 m wide and 380 m long. These dimensions reduce the potential effects of wave refraction waves in the half-space; additionally, dissipating boundaries were implemented for the same purpose.

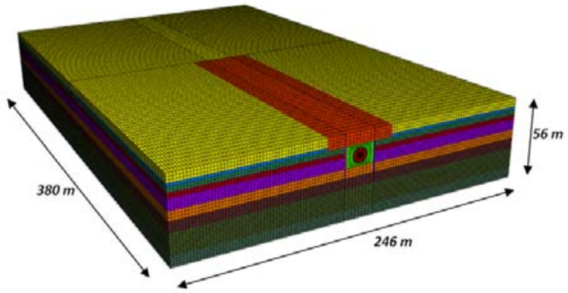


**Figure 6.** Tree-dimensional model nodes 305 696.

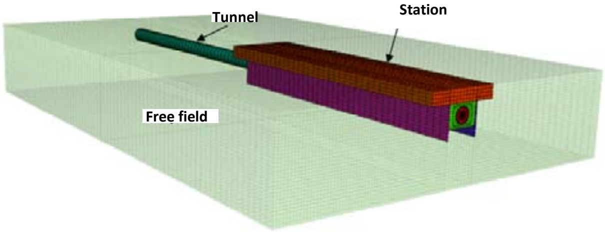


**Figure 7.** Three-dimensional finite difference model. Semitransparent view of the station location with respect to the tank floor.

## 4.3 Station mode in detail

The station was modeled taking into account its most relevant geometrical characteristics to enable the analyses of the evolution of the station-tunnel interaction during the structure's life.

The station model has a top slab corresponding to the pedestrian circulation area and two slurry trench walls limit the train's parking zone (see Fig.8). S concrete slab is used to integrate the circular tunnel to the station.

## 4.4. Detailed tunnel model

The tunnel, an 8 segment ring, is 40 cm thick; segments have a rotation (or phase) of 33° with respect to each other (see Fig. 9). The ring was modelled as a continuous element, having an equivalent stiffness for each excavation stage.

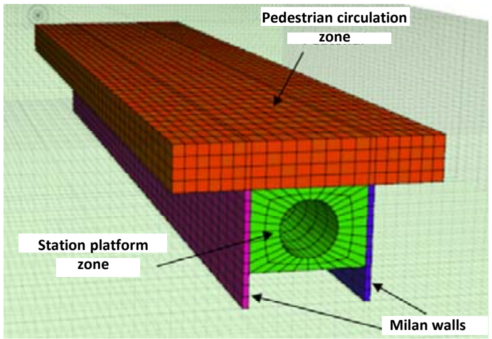


**Figure 8.** Front view of the station model.

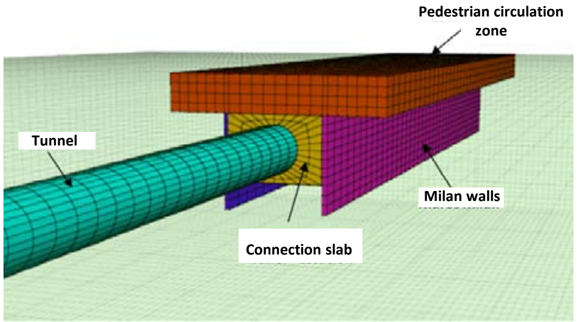


**Figure 9.** Tunnel-station integration

### 4.5. Soil characterization

The model consists of 9 horizontal layers defined from field information and laboratory tests (see Table 4.1).

**Table 4.1.** Model of the stratigraphic characteristics and material properties.

| Layer | Soil type | Depth (m) | Thickness (m) | $\gamma$ (t/m$^3$) | $\nu$ | $V_s$ (m/s) | $G_{máx}$ (t/m$^2$) | $K$ (t/m$^2$) |
|---|---|---|---|---|---|---|---|---|
| 1 | Filler | 0.00 – 6.00 | 6.0 | 1.49 | 0.35 | 151.3 | 4099.7 | 8882.8 |
| 2 | Sandy clay | 6.00 – 8.00 | 2.0 | 1.16 | 0.35 | 145.3 | 2762.4 | 5985.1 |
| 3 | Clay | 8.00 - 11.50 | 3.5 | 1.16 | 0.35 | 76.6 | 803.4 | 1740.8 |
| 4 | Clay | 11.50 – 15.00 | 3.5 | 1.16 | 0.35 | 86.9 | 1104.1 | 2392.3 |
| 5 | Clay | 15.00 – 22.00 | 7.0 | 1.16 | 0.35 | 81.3 | 794.1 | 1720.5 |
| 6 | Clay | 22.00 – 28.00 | 6.0 | 1.16 | 0.35 | 105.4 | 1345.9 | 2916 |
| 7 | Silty sand | 28.00 – 35.00 | 7.0 | 1.78 | 0.35 | 224.7 | 4698.5 | 10180.2 |
| 8 | Clay | 35.00 – 49.00 | 14.0 | 1.80 | 0.35 | 209 | 4375.1 | 9479.3 |
| 9 | Silty sand | 49.00 – 56.00 | 7.0 | 1.80 | 0.35 | 129.5 | 3076.9 | 6666.7 |

$\gamma$ is the volumetric weight of the soil, $v$ is Poisson's ratio, $V_s$ is the shear wave velocity, $G_{max}$ is the maximum modulus and $K$ is the bulk modulus.

## 5. DEFINITION OF THE SEISMIC ENVIRONMENT

The location of the site under study corresponds to Zone IIIB, according to the local building code (NTC2004). The free field spectrum in rock is shown in Fig 10.

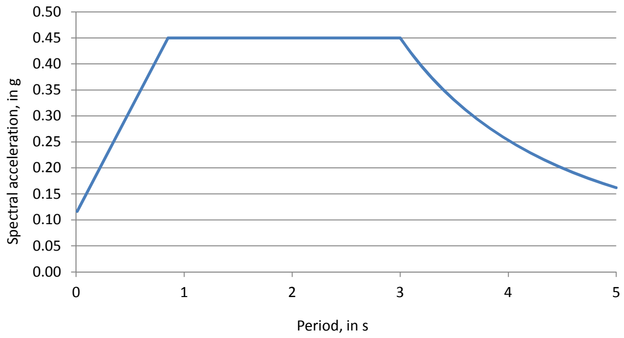


**Figure 10.** Spectrum regulatory zone IIIB

This spectrum, which is the basis for the seismic analysis, was first deconvolved to the model base. Deconvolution involved the passage of this spectrum through a stratified free field using 25 soil profiles randomly generated within the range of about one standard deviation of the profile defined from the soil mechanics studies (probabilistic analysis of the shear velocity variation). Finally, the motions used in the analysis were taken from the mean spectrum plus one standard deviation in order to cover the range of uncertainty inherent to this type of study (see Fig. 11). The resulting spectrum is the objective function (see Fig. 12) we used to generate a synthetic earthquake representative to the zone characteristics (see Fig. 13), which serves as a basis for analyses in time domain.

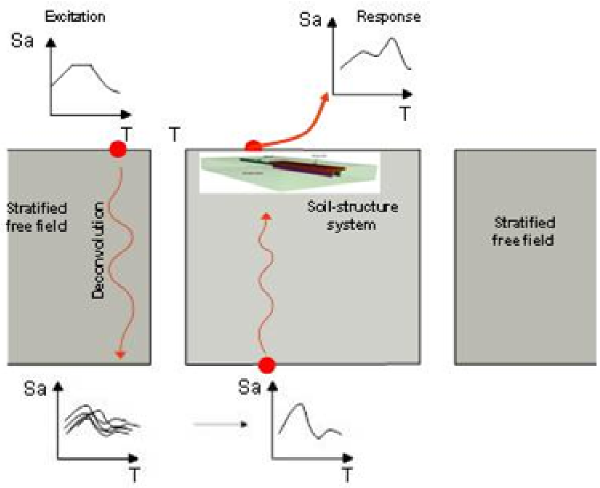
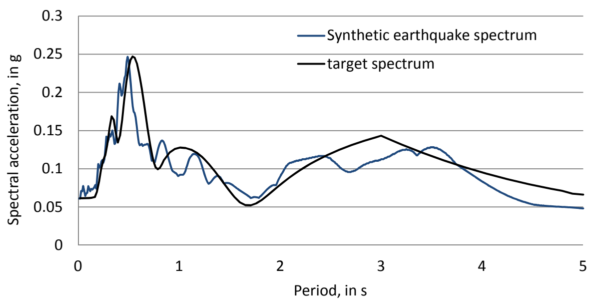


**Figure 11.** Schematic representation of the deconvolution procedure, excitation and response of the model in



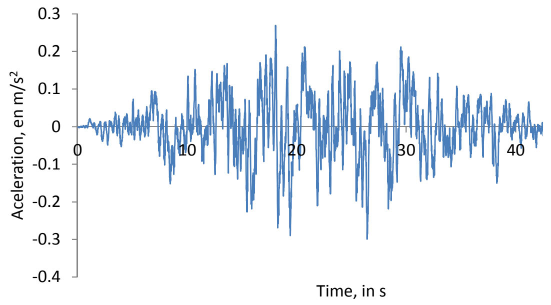


**Figure 12.** Resulting spectrum of the synthetic signal.

**Figure 13.** Synthetic earthquake

# 6. EVOLUTION OF SEISMIC RESPONSE DUE TO REGIONAL SUBSIDENCE

Extraction of groundwater generates changes in pore pressure, increasing the effective stress, causing an effective overload on the soil, which increases the consolidation process. As a result, the static and dynamic properties of the soil changes, and therefore the seismic response (Ovando et al., 2007).

## 6.1. General conditions

CPT penetrarion resistance depends on the soil's shear strength. On the other hand, the relationship between vertical stress and shear strength of normally consolidated clay (this condition is representative of the valley of Mexico) is constant from which it follows that changes in effective stress due to the groundwater extraction induces changes in the values qc. This can be represented by Eq. 6.1.

$$q_c\,(t)=N_\sigma \sigma'_v(t) = N_\sigma(\sigma'_{v0}(t)+\Delta u(t)) \qquad (6.1)$$

Where $N_\sigma$(Santoyo et al., 1989) is a correlation factor ($N_\sigma = 5.5$) and $\sigma\,'_{v0}(t)$ is the initial vertical effective stress. The factor $\Delta u(t)$ represents the pore pressure reduction at the period under consideration due to water extraction from the aquifer.

To analyze the variation in distribution of pore pressure due to regional subsidence process can be performed using one-dimensional models of soil consolidation. In this study, such variations were estimated using a model that considers the soil as an elastic material and viscoplastic, and suppose that that primary and secondary consolidation process occurs in a coupled way. The model was originally proposed by Yin and Graham (1996) and implemented by Ovando and Ossa (2004) to evaluate the regional subsidence caused by water pumping.

## 6.2. Evolution of the seismic response of Mexicaltzingo site

### *6.2.1. Evolution of pore pressure distributions*

The analysis of the variation pore pressure distributions due to regional subsidence considered a 50 years period. The study site was modeled considering compressible deposits defined in Table 4.1, that are confined by permeable soil layers. The initial piezometric conditions adopted for such analysis is the record for the month of November 2008 at a station located near the site. Pore pressure depletion rates at the permeable boundaries were estimated from records of neighboring piezometric (Table 6.1).

**Table 4.2.** Groundwater extraction rate in compressible strata boundaries

| Depth (m) | Groundwater extraction rate (t/m²/año) |
|---|---|
| 8.0 | 0.09 |
| 26.0 | 0.24 |
| 30.0 | 0.24 |
| 33.0 | 0.30 |

Evolution of pore pressure distributions at the Mexicaltzingo station are shown in Fig. 14. In these analyses time dependent pore pressures were calculated with a model that assumes that the compressible clay is an elasto-vicours-plastic soilid (Yin and Graham, 1996

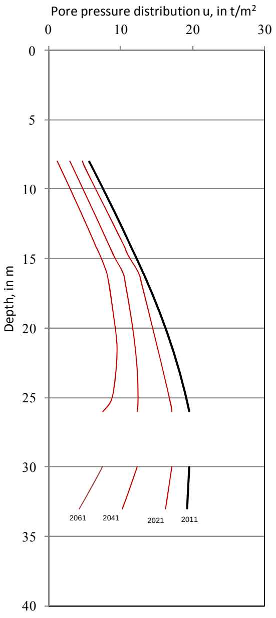
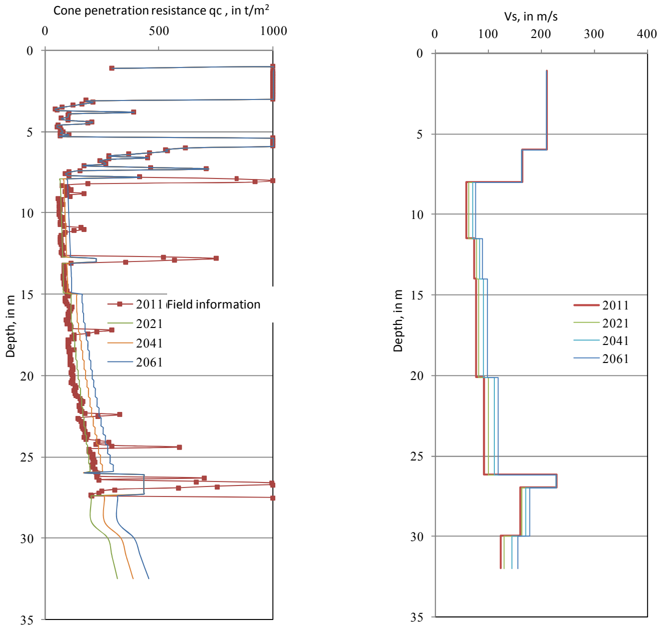


**Figure 14.** Evolution of the distribution of pore pressure due to regional subsidence.

### *6.2.2. Cone penetration resistance and shear wave velocity*

Taking into account the calculated pore pressure decrements, resulting from the analysis above and using Equation 6.1, we calculated the evolution of cone penetration resistance and shear wave velocity for a period of 50 years, as illustrated in Fig. 15.



a) b)

**Figure 15.** Evolution of a) Point resistance, b) Shear wave velocity, for a period of 50 years

## 7. ANALYSIS OF RESULTS

We evaluated two possible scenarios for the seismic analysis. The first one considers the condition at the end of construction. The second is a long term condition, 50 years afterwards. Stress histories and resulting displacements from the synthetic earthquake generated for this evaluation were analyzed varying the properties of geomaterials, as described in the previous chapter.

### 7.1. Earthquake induced displacement

Figure 16 shows the resulting earthquake induced displacements in the element connecting the station to the tunnel. The movements correspond to years 2011 and 2061. It can be seen in this figure that the resulting shifts in the connecting element are practically the same in the two analyses. This is so because the union is sufficiently rigid and has an adequate structural design.

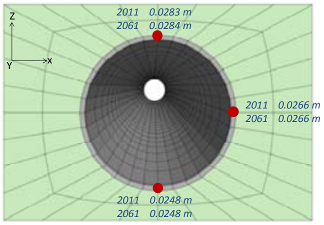


**Figure 16.** Displacements resulting from the quake for the years 2011and 2061

### 7.2. Stresses induced by earthquake

The results show a tendency to reduce shear forces in 2061. This is a consequence of the stiffening of the soil due to regional subsidence. Indeed, the soils' shear moduli increase and therefore the flexibility of the whole soil-structure decreases, causing a reduction of stresses. The graphs in Figures 17 and 18 show the resulting shear stresses along two perpendicular directions.

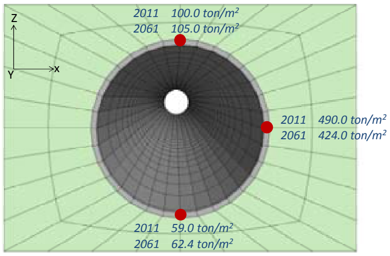


**Figure 17.** Shear $\sigma_{XZ}$, for the years 2011 and 2061.

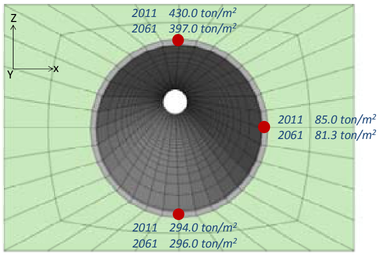


**Figure 18.** Shear $\sigma_{XY}$, for the years 2011 and 2061.

Some of the initial stresses turned out to higher than the maximum allowable stress, but it is necessary to consider that these are transient conditions and will not necessarily cause damage. Nonetheless, it is important that the structural design be revised taking into account these stresses.

## 8. CONCLUSIONS

Pore pressure depletion in the soils that underlie Mexico city´s Line 12 subway induce effective stress increments and changes in the dynamic properties that cannot be ignored. Hardening of the clays reduces the site dominant period. It is convenient to revise periodically the seismic response of the most relevant structures along the axis of the line 12.

Static and dynamic displacements calculated with the numerical model turned out to be The resulting admissible and should not lead to damage or difficulties in the operation of the metro line 12 and, specifically, of Mexicaltzingo Station.

Seismically induced shear stresses exceeded permissible values in some areas of the tunnel-station interface. Since these stresses are transient, they may not induce major damage to structures but a structural design revision must be performed, taking into account this possibility.

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