Construction of a Metro Tunnel in Mexico City with an EPB Shield

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ABSTRACT

The construction of the tunnel for Metro Line 12 represents a breakthrough and a challenge to Mexican engineering as this is the first great diameter mechanized tunnel to be bored under urban area and in the special soft soil conditions typical of Mexico City clays. It is a tunnel excavated by EPB TBM under very low covers and also subjected to regional subsidence phenomena. Along its way, the EPB shield runs below and next to important underground structures such as sewerage tunnels and river conductions, pile foundations for bridges, superficial Metro lines and underground crossways. The present paper discusses the excavation process of the first three sections of the tunnel, the first of which served as the learning curve of the process.

RESUMEN

La construcción del túnel de la Línea 12 del metro representa una gran innovación y un reto para la ingeniería mexicana ya que este es el primer tunel mecanizado de gran diámetro que se excava bajo una zona urbana y bajo las condiciones especiales de los suelos blandos típicos del Valle de México. Es un túnel de gran diámetro excavado con tuneladora EPB bajo pequeñas coberturas y que estará sujeto al fenómeno de consolidación regional. A lo largo de su trazo, el escudo EPB corre bajo y cerca de importantes estructuras subterráneas tales como conducciones de aguas negras y de ríos, pilas de cimentación de puentes, líneas superficiales de metro y pasos subterráneos. El artículo presenta el proceso de excavación de los primeros tres tramos de túnel, el primero de los cuales sirvió como curva de aprendizaje del proceso.

1 INTRODUCTION

In order to satisfy the high demand of efficient public transportation in Mexico City, on 2008 began the construction of Metro Line 12. This line links the Southeastern part of the city to the Western area, beginning at Tlahuac county and ending in Mixcoac area. It connects to the rest of the Metro System at lines 2,3,7 and 8 and it is expected to serve about 475 000 users per day.

Line 12 will be the largest of the Mexico City's Metro System, with a total length of 25.6 km, of which the first 2 km run superficial, followed by 11.6 km in an elevated viaduct and 2.7 km in a shallow cut and cover underground section which leads to the final tunneled section. The first 7445 meters of tunnel will be excavated by an Earth Pressure Balance TBM and the remaining 1.8 km will be excavated by NATM method.

The main purpose of constructing the last phase of Line 12 by means of a mechanized tunnel is avoiding the effects that an open excavation has on everyday life of the city. Due to the kind of soils encountered along the tunnel alignment, going from soft clayey soils to compact sandy-silty soils and even gravel with great dimension boulders, the selected excavation method was by means of an Earth Pressure Balance Shield (EPB). This method allows to equal the pressure of the excavated material inside the cutting chamber to the earth pressure at the excavation front, so that the disturbances on ground surface and nearby existing structures are minimized.

Line 12 tunnel has an excavation diameter of 10.20 m and an inner diameter of 9.11 m. The tunnel lining is made out of precast concrete segments of 40 cm thickness and 1.5 m length.

The present paper discusses the construction process used for the excavation of the tunnel of Line 12 by means of an EPB shield through the soft clayey soils typical of Mexico City Valley.

2 GEOTECHNICAL CONTEXT

2.1 Alignment of Line 12

Mexico City's Metro Line 12 runs from the south eastern part of the city (Tlahuac), an ancient lake zone, to the western area (Mixcoac), low hills zone. Along its way, different construction methods are utilized, beginning with the superficial, followed by the elevated viaduct and then an underground cut and cover shallow transition which gives way to the mechanically excavated tunnel, and finally an NATM tunnel, as shown in figure 1. The EPB bored tunnel begins at the area of Mexicaltzingo where Line 12 heads to the West toward its end at Mixcoac area.

2.2 Geotechnical profile of the tunnel

Line 12 runs through the three different geotechnical zones defined in Mexico City. It begins at the Lake Zone in Tlahuac and continues to the Northwest coming across rock outcrops which correspond to Hills Zone. At the beginning part of the tunnel there are also lacustrine deposits which, despite their lower depth, equally correspond to Lake Zone.

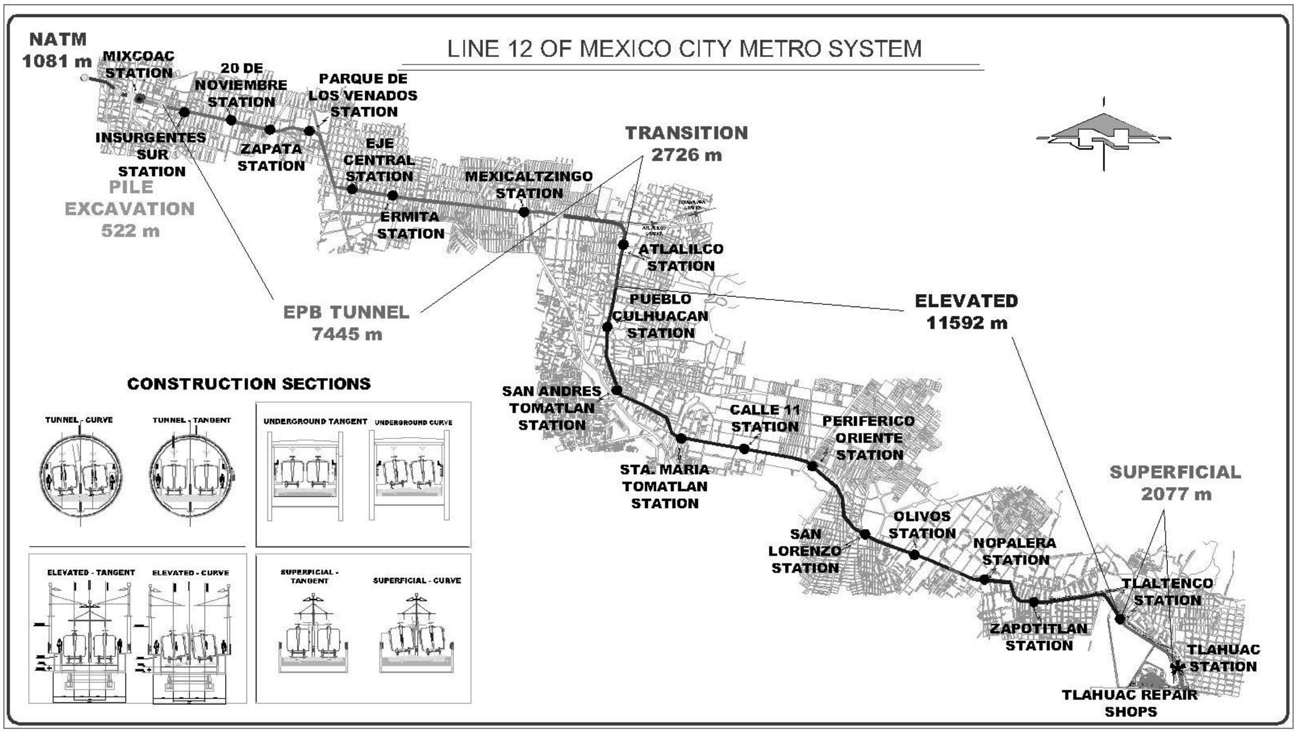

Figure 1. Mexico City’s Metro Line 12.

As the tunnel continues to the West, the clayey deposits decrease their depth and the tunnel gets into the Transition Zone to finally meet the Hills Zone, figure 2.

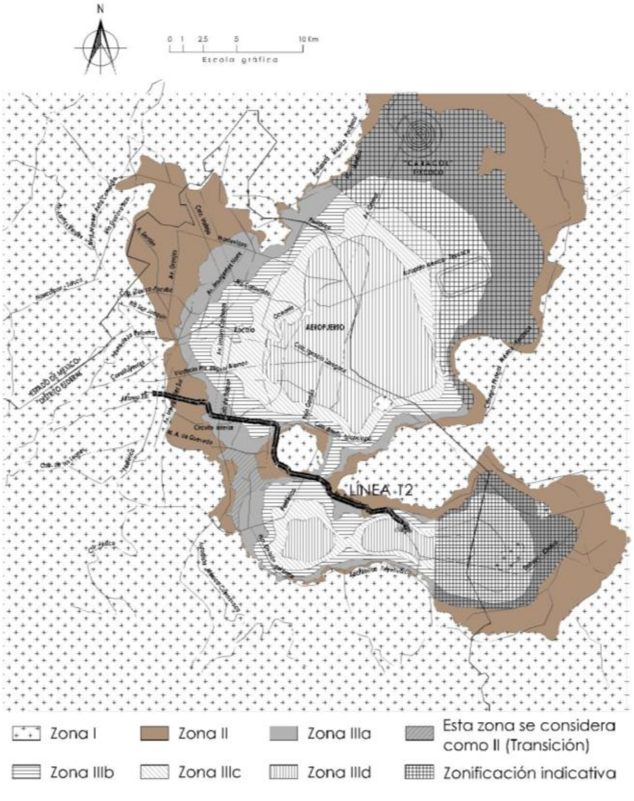

Figure 2. Line 12 on Mexico City’s geotecnnical zones.

At its first part, the tunnel is excavated inside a stratigraphy composed mainly by soft clayey soils with high water contents, high plasticity and low strength interbedded by sand lenses and volcanic ash. Above these soft clays there is a firm clayey sand stratum and at the top there is the superficial crust of silty-sandy material.

Towards the West, the tunnel gets into the deep deposits of silty sands, sandy silts and sands with isolated gravel. At the middle part, their ascending profile makes the tunnel lay over these hard deposits. Towards the exit shaft, the tunnel will be completely excavated in sands and silts of the Hills zone, meeting at its pace even great dimension boulders which the TBM is able to excavate.

It is important to mention that the clayey strata into which the tunnel runs at it is initial part are subjected, as the rest of the Mexico City’s clayey soil, to regional subsidence due to water extraction. The watertable was found at 2 to 3 meters depth, from where the piezometric distribution is hidrostatic down to 11 to 15 m depth. At greater depths the piezometric curves start to lower and when reaching the deep hard deposits, the pore pressure becomes practically null.

The stratigraphic profile of the underground part of Line 12 is shown on figure 3, taken from “PERFIL ESTRATIGRÁFICO DEFINITIVO DESDE EJE 3 ORIENTE HASTA MIXCOAC” (2009).

3 PREVIOUS THEORETICAL STUDIES

Besides the geotechnical research campaign carried out to identify the types and properties of the underground that the tunnel would run through as it crosses the urban area, there were some other studies needed prior to the excavation of the tunnel, which consist mainly on the calculation of the face-support pressures and the calculation of the expected settlements on surface induced by the TBM excavation.

3.1 Calculation of the face-support pressure

Before the start of the excavation with the TBM it is necessary to know the pressures needed inside the excavation chamber in order to equilibrate the earth pressures at the excavation front. The calculation of such pressures was made through analytical semi-empiric methods proposed by different authors:

a) Approximate solution for ground with own weight (Kolymbas, 2008)
b) Criterion according to the bound theorems, lower bound theorem (Kolymbas, 2008)
c) Earth pressure at rest criterion:

$$p=k0\gamma z=(1-\sin\phi)\gamma z \qquad [1]$$

d) Observational criterion:

$$p=0.75\gamma z \qquad [2]$$

The pressures calculated by these methods would define the range into which the support pressures would vary and the exact value would be adjusted according to the results of the measurements of the instrumentation installed along the tunnel alignment, so that the lesser surface movements are induced at the TBM front.

3.2 Calculation of the expected settlements

Aditional to the face-support pressures calculation it is necessary to calculate the maximum expected settlements due to the TBM passing, as a control parameter during the excavation process. For this purpose there exist different numerical and semi-analytical methods based mainly on experience. The calculation of the expected settlements due to the TBM excavation of the tunnel for Metro Line 12 was made through the use of two theoretical criteria:

a) Criterion by Kolymbas (2008)
b) Criterion by Attewell and Woodman (1982)

4 DESIGN OF THE SEGMENT RINGS

The project of the tunnel for Metro Line 12 consists of a precast reinforced concrete segmented lining made out of universal rings, which means that with a unique ring geometry, placed at 14 different positions it is possible to follow the curves or tangents of the project alignment.

The segment ring is made out of 7 segments plus a key (7+1 system). The ring has an outer diameter of 9.91 m and an inner diameter of 9.11 m, with a segment thickness of 40 cm. The ring length is 1.50 m.

The excavated diameter is 10.20 m, corresponding to the diameter of the cutting head of the EPB shield. The tail void created between the excavated soil and the segment lining has a 14.5 cm theoretical thickness and is filled out with the grout injection through the TBM tail.

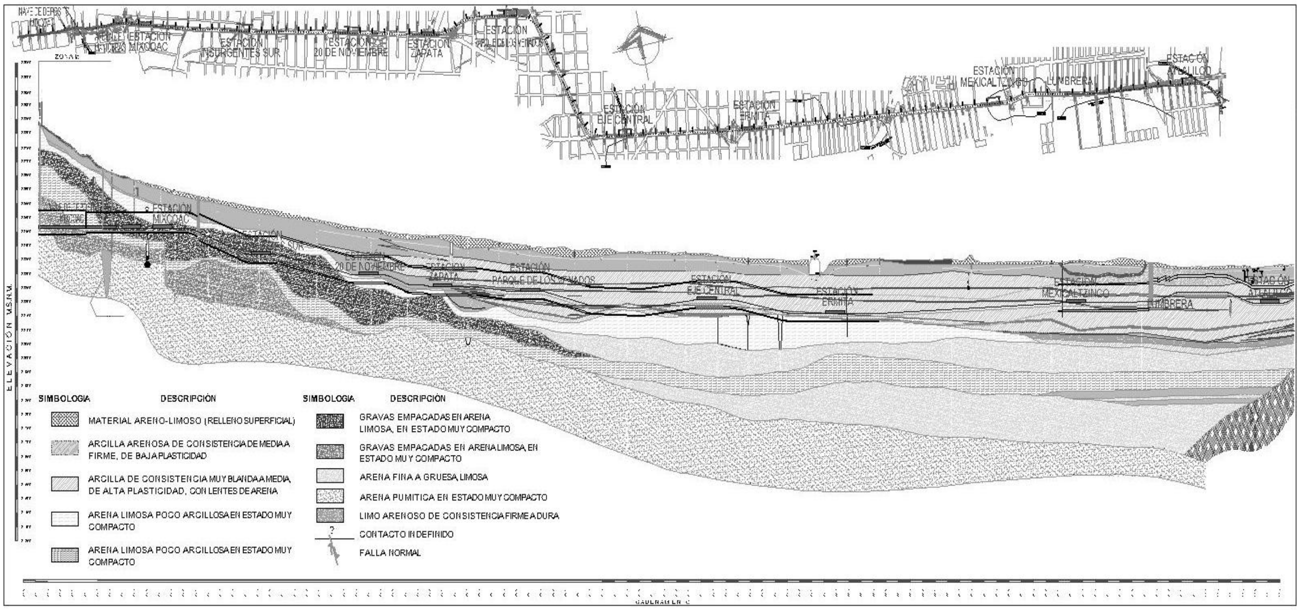

Figure 3. Stratigraphic profile of the underground section of Metro Line 12.

For the structural design of the reinforced concrete segments, it was necessary to take into consideration the long term effect of regional subsidence over the tunnel, which modifies the current stress state and increases the vertical loads over the tunnel.

5 EXCAVATION PROCEDURE

5.1 Functioning principle of an EPB TBM

EPB TBM's are based upon the principle of equilibrium between the earth pressure at the excavation front and the pressure of the excavated material inside the excavation chamber. This way the disturbance and movements induced on the surroundings by the tunneling process should be minimum.

The control of the pressure inside the cutting chamber during TBM advance is achieved through the control of the advance rate and the control of the velocity of extraction of excavated material through the screw conveyor.

5.2 Assembly of the EPB-TBM

The excavation process of the tunnel of Metro Line 12 began with the assembly of the TBM at the working site. Usually, a pre-assembly takes place at the factory, previous to its shipment to the site. For the case of Line 12, it was necessary to carry out the first assembly of the EPB directly on site in order to optimize the tight times of the working program.

5.3 Two-component grouting system

During the excavation with a TBM, a void space between the segment ring and the excavated soil is created due to the difference in exterior diameters between the TBM and the precast segment ring. In order to reduce surface settlement induced by the tunneling process, it is necessary to fill the tail void by the injection of grout through conduits located at the shield's tail.

The two-component grouting system allows to combine a mortar or grout (which can contain a retarding admixture) with an accelerating agent directly at the shield's tail. The two-component mix flows through a short distance towards the end of the tail to the void to be filled. It is then when stabilization and setting of the two-component mix take place in a very short time.

The piping system of the two-component injection is made out of two lines, one for each component (A or 1 and B or 2). Both liquids will be mixed at the end part of the tail and the two-component mix (A+B) will penetrate into the tail void. Each line has a flow and pressure measuring device.

The two-component injection of the tail void is carried out simultaneously to the excavation along the tunnel. Line 12 TBM performs the fill grouting through two points located at the top section of the tailshield so that the grout gets to the whole perimeter of the void.

The fill grouting control is made on the basis of the grouted volume and the grouting pressure. It is common practice to grout a larger volume than the theoretical volume of the tail void due to possible overexcavation or grout losses, this way the excess volume will guarantee the correct filling of the tail void. For the grouting control of the two-component mix at Line 12, two criteria were used, grouting would stop when any of the following conditions was met:

a) The real grouted volume is equal to the theoretical volume plus 15%.
b) The grout pressure reaches the support pressure applied at the lower part of the shield front.

6 GEOTECHNICAL INSTRUMENTATION

6.1 Installed instrumentation

Geotechnical instrumentation represents an essential part of the tunneling process, as it is useful in the verification of the effects of excavation in the underground, on surface and over the neighboring structures to the tunnel.

There are many variables that can be measured during the TBM advance. Nevertheless, the most important ones are the deformations or displacements that the excavation induces on the ground surface. Also, with the previously calculated settlement it is possible to control more efficiently the excavation process.

For the instrumentation of Line 12 tunnel, many variables were considered for monitoring, of which the main ones are:

a) Surface movements at the excavation front, in order to control the face support pressures.
b) Surface settlements of the tunnel axis over the TBM alignment for the control of the two-component grouting.

Both of these variables are measured by surveying methods through reference points placed on surface over the tunnel axis.

The following parameters were also monitored:

1. Vertical and horizontal displacements of important structures due to the tunneling process. Special care was taken when monitoring an old church (San Marcos Mexicaltzingo) which already showed some differential settlement, the tunnel passage below two sewer conductions and Churubusco bridge, and the excavation under a superficial metro Line.
2. Vertical displacements of sections transverse to the tunnel axis at surface.
3. Convergences inside the segment rings, every 20 m by surveying methods and at selected sections by automatic measurements.
4. Variation of the horizontal diameter of every segment ring.

Some special points along the tunnel alignment were selected to place instrumentation sections in order to measure the soil-tunnel interaction. Those sections have instrumented rings containing pressure cells as well as piezocells, piezometers and inclinometers inside the ground. All of it serves to better study the effect of the TBM advance and lining placement on the ground, as well as the medium term interaction between the soil and the tunnel.

6.2 Special instrumentation at important crosses

Along the tunnel alignment, there are some special sections where Line 12 crosses important structures or facilities. At these sections it is important to monitor ground and structure displacements during the TBM cross, therefore special instrumentation sections were installed at these points in order to implement any measure required for the tunneling process not to affect any important structure.

The instrumentation included at this sections was: inclinometers and piezometers inside the ground, tiltmeters at superficial structures, pressure cells and tiltmeters at selected rings, superficial references forming a closed reticle and additional transverse superficial sections.

7 EXCAVATION FROM THE LAUNCHING SHAFT TO EJE CENTRAL STATION

7.1 Launching Shaft to Mexicaltzingo Station

The tunnel excavation started at the launching shaft towards Mexicaltzingo Station, the shield's first stop along its algnment. This first section represented the beginning of the TBM excavation process and the learning curve for the crew, so during this first section many details of the process and the machine itself were calibrated.

The first section of the tunnel corresponds to the lowest cover zone, from 7 at the shaft to 8 m when reaching the station (lower than the TBM diameter). Also at this section there are two 250 radius curves (the minimum operational radius in the line) just before reaching the station.

This first zone has also very special geotechnical conditions, as above the tunnel there is an ancient fill due to a prehispanic settlement and due to the filling of the ancient La Viga Channel. These fills have caused a more rapid consolidation of the soil, so the material excavated was a clay with lower water contents than those of the typical clays of Mexico City Valley and with a tendency to crack.

7.2 Mexicaltzingo Station to Ermita Station

The second section of the tunnel starts at Mexicaltzingo Station and finishes at Ermita Station. The difficulties encountered for the excavation of this tunnel section were related to the existing structures along the TBM alignment. At one singular intersection the machine had to bore between the Churubusco Bridge foundation piles and below two underground sewer tunnels of different diameters and at different depths. This intersection is shown in figure 4. At this point, a special monitoring section was installed including all the instrumentation previously mentioned, and the excavation control was taken more strictly, limiting the fluctuation of the applied front pressures to half of the usual.

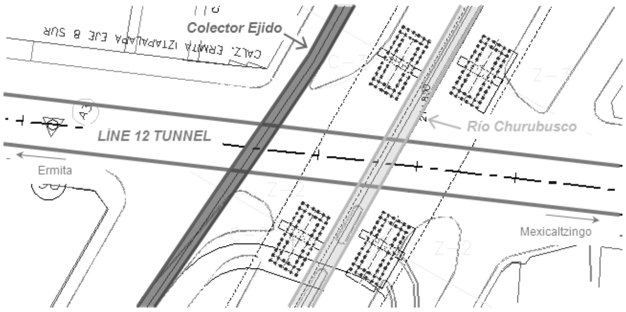

Figure 4. Line 12 tunnel crossing below Rio Churubusco sewer conduction and bridge.

At this section the tunnel cover varies from 8 to 15 m depth and at some lengths the tunnel rests over the hard deposits below the lacustrine clays. The material encountered decreased its water content progessively as the TBM advanced to the West towards Ermita Station.

The Mexicaltzingo-Ermita section is the longest of the underground section of Line 12, with an approximate length of 1800 m.

The efficiency of the tunneling process at the Mexicaltzingo-Ermita section was deeply improved with respect to the previous section.

7.3 Ermita Station to Eje-Central Station

The Ermita-Eje Central section of the tunnel is practically a tangent line joining both stations, so that there were no major difficulties to be dealt with at the excavation of this section. There was only the passage of the TBM below the superficial Metro Line 2, which connects Line 12 at Ermita Station. For this passage there was also a limit for the possible fluctuation of applied support pressures to better control the effects of tunneling on the structure of Line 2.

This section of the tunnel develops under low covers (7 to 12 m) and partially resting over the hard sandy deposits. The material excavated showed less water content than the previous and a significant content of sand.

7.4 Results of monitoring

On figure 5, the results of the monitoring of superficial vertical displacements along the tunnel axis are shown for the Shaft-Mexicaltzingo section. These measurements were made twice a day during the TBM functioning in order to have a more precise control of the excavation. The positive displacements at the excavation front had a maximum of 2.5 cm and the maximum settlement once the TBM had passed was 8.5 cm, 4 cm above the expected. The movements at the excavation front were considered acceptable so the support pressure control was satisfactory. The settlements behind the TBM were above the expected so the tail void injection process was reviewed and improved in order to limit these displacements.

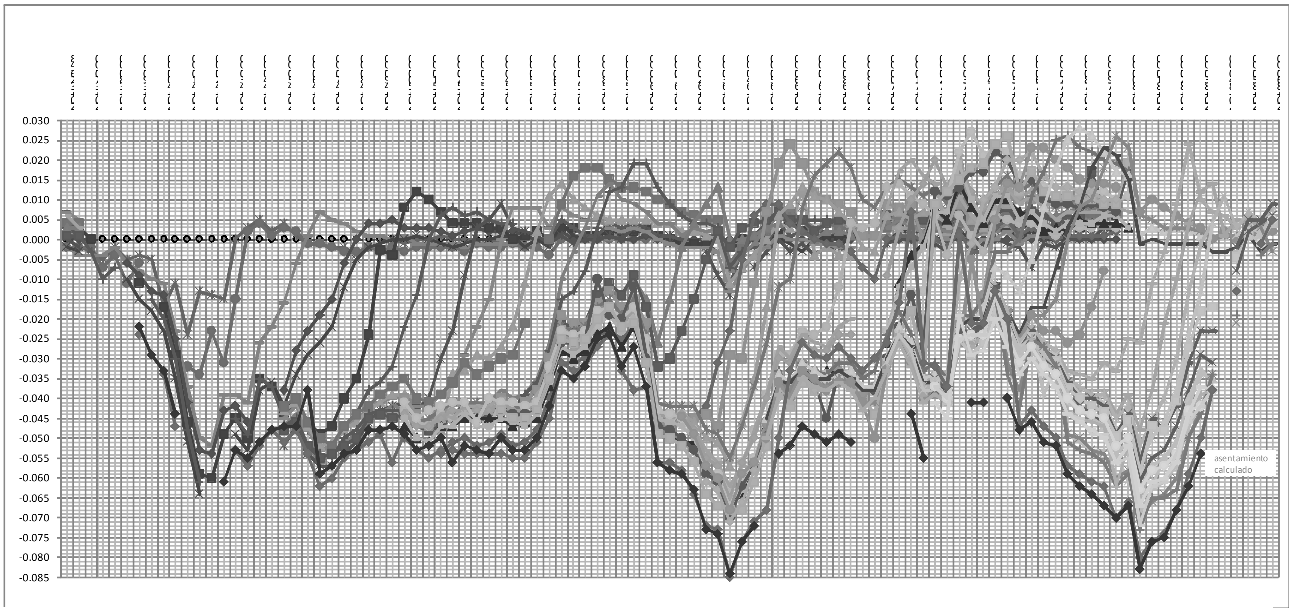

Figure 5. Evolution of vertical displacements during the TBM advance. Launching shaft to Mexicaltzingo Station.

The vertical displacements registered at the next two excavated sections are shown respectively on figures 6 and 7. After the learning curve of the excavation of line 12, the excavation process developed with better results and this can be noted on the surface settlements registered at the next two sections. The settlements at Mexicaltzingo-Ermita were below and sometimes close to the expected and at Ermita-Eje Central were always minor than those calculated.

The convergences registered by the automatic and traditional methods and the variation of the horizontal diameters showed a maximum increase of 2.5 cm of the horizontal diameter of the rings, with a mean value of 1.0 cm.

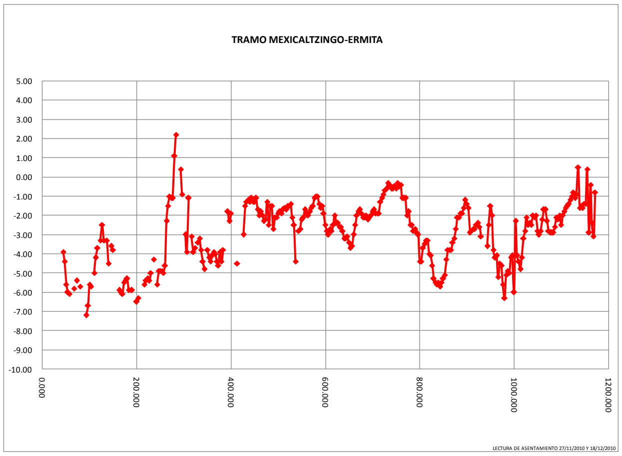

Figure 6. Surface settlements (cm) at the Mexicaltzingo-Ermita section after the excavation.

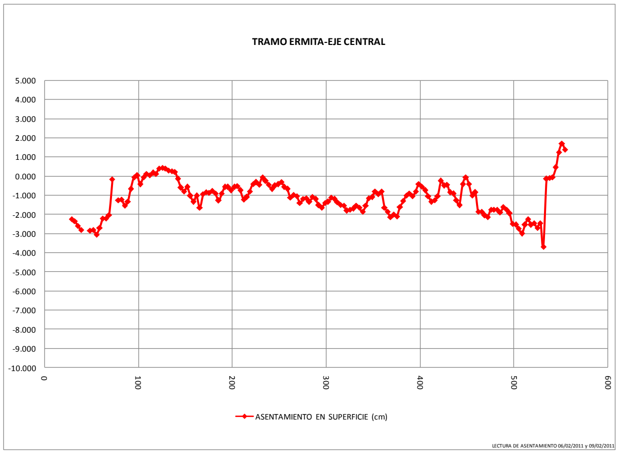

Figure 7. Surface settlements (cm) at the Ermita-Eje Central section after the excavation.

7.5 Adjustments to the excavation process

The results of monitoring allowed to calibrate the support pressures applied throughout the excavation, which kept being very close to those calculated.

According to the settlements measured during the first section excavation, some measures needed to be taken to decrease and minimize the induced surface settlements. The zone where the maximum settlements presented corresponds to the period of excavation during which the tail void injection system had some trouble, as the sand included in the mortar mix caused the valves to fail and the fill may have not been well distributed into the tail void. Therefore at this point the sand was taken off the mix, turning it into a grout which kept the same setting time as the previous mix but with a better consistency and viscosity. With this change, the settlements on surface decreased to the expected range of values.

The rest of the instrumentation did not show any significant effects of tunneling over the surrounding ground or structures, not even at the crossing below Churubusco Bridge and the nearby underground conductions or below Metro Line 2. All of this reflects a satisfactory control of the excavation process and shows how instrumentation is an essential support in order to carry out this control properly.

8 CONCLUSIONS

For the excavation of the underground section of Metro Line 12, mechanized excavation by means of an EPB shield was chosen because this method provides better results in the typical clayey Mexico City soils and also produces the less disturbances inside the ground and to superficial structures and the everyday life of the population.

The EPB TBM functions on the principle of equaling the pressure at the excavation front with the pressurization of the excavated material inside the excavation chamber of the machine.

Line 12 tunnel crosses the three different geotechnical zones of Mexico City soil, beginning in the Lake zone which is known for its soft clayey soil with high plasticity, high water content and low strength also subjected to regional subsidence. It continues to the transition zone where at time it reaches the hard silty-sandy deposits below the soft clays.

This tunnel is a great diameter tunnel, 10.20 m excavation diameter and 9.11 m inner diameter, with very low covers (at times lower than the TBM diameter), specially at the starting section which was precisely the learning curve of the process.

Though the installed instrumentation and the control of the excavation parameters it was possible to calibrate the process in order to cause the least disturbances to the surrounding environment. Only at two singular points at the first excavated section the calculated settlements were exceeded, so the parameter control is considered to be satisfactory. The face-support pressures were at all times properly controlled so that no significant displacements were noticed at the excavation front.

Through the excavation of the first section, which corresponded to the learning curve, it was possible to calibrate the electromechanical components of the shield itself, the excavation process and its supplementary processes as well as the theoretical calculations made prior to the start. By the end of the excavation of the first section, the whole process was better controlled and this could be noticed through the decrease of the induced settlements to values lower than those expected, and through the increase of the efficiency of the excavation to practically the double.

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