Geotechnical behaviour of an instrumented urban tunnel built under difficult soft soil conditions

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ABSTRACT
A shallow urban tunnel for public transportation, built in difficult subsoil conditions with EPB tunnel boring machine, was instrumented to monitor its geotechnical behavior during construction. The parameters that define soil response were measured before, during and after the construction process. Herein the instrumentation used for the tunnel is described, as well as the implementation of new measurement systems. Relevant charts are shown.

Immediate tunnel deformations were monitored and used to verify the shield tunneling process. Using the gathered data, correlations were developed to assess the confining influence on the surrounding soil and to describe the stress state during TBM advance. Subsidence on nearby buildings was appraised and related to the grouting support effect.

Relevant conclusions regarding instrumentation, grouting and soil subsidence are provided.

RESUMEN
Se instrumentó un túnel de transporte público con poca cobertura, construido con máquina tuneladora EPB en suelo blando, para monitorear su comportamiento geotécnico durante la construcción. Se midieron los parámetros que definen la respuesta del suelo, antes, durante y después del proceso constructivo. En este artículo se describe la instrumentación usada para ese fin, así como la implementación de un sistema nuevo de medición. Se muestran las gráficas relevantes.

Se midieron las deformaciones inmediatas y se usaron para verificar el proceso de excavación. Con los datos reunidos, se desarrollaron correlaciones para evaluar la influencia del confinamiento en el suelo circundante y para describir el estado de esfuerzos durante el avance de la tuneladora. Se revisaron los asentamientos en edificios cercanos y se relacionaron con el efecto del relleno de soporte. Se incluyen conclusiones relevantes sobre instrumentación y asentamientos.

1 INTRODUCTION

Tunnels construction in urban environments represents a significant challenge due to subsidence phenomena and possible affections to surrounding structures. Since urban tunnels tend to be shallow for functional and economical reasons, affections on nearby buildings must be considered during design, construction and operation.

When designing an urban tunnel it is necessary to determinate the deformation and stresses applied to nearby structures, as well as the influence on the stress-displacement distribution in the vicinity of the opening.

However, mechanisms which control the tunnel-soil-structure interaction problem of overlying buildings and services are not well understood. Solution to that problem has been based on empirical explanations and green field analytical solutions but these approaches tend to simplify the problem and make several assumptions that might be not quite realistic.

In order to overcome these issues, geotechnical and structural instrumentation has become a mainstay for designers and constructors. Recently in Mexico new technologies to monitor tunnel behavior such as vibrating wire devices, strain gauges, resistive sensors, MEMS, and mechanical devices have been implemented. To manage these devices, electronic machines have proved to be very efficient on monitoring and processing data.

Tunnel instrumentation can offer information to check and optimize designs; it is useful to improve construction process regarding cost, quality and safety, and it is a tool to diagnose the cause of a problem in the project.

In this paper the instrumentation system of a transportation tunnel is described, and its results and advantages are presented.

2 TUNNEL INDUCED SETTLEMENTS AND BUILDING DAMGE

Evaluation of greenfield settlements can be done in different ways, for example empirical and analytical methods, laboratory and centrifuge testing or numerical modeling. In the same way, there are several procedures to evaluate building damage risk due to tunnel construction. Mair et al. (1996) proposed three stages: preliminary assessment, second stage assessment and detailed evaluation. First the greenfield settlements are evaluated to define whether they are or not in an acceptable range, if they are not admissible it is necessary to advance to the next stage; in the second stage the building is supposed to follow the greenfield settlement and the damage is studied, if it is not acceptable, a detailed evaluation is carried out, where several factors are checked: structural continuity, foundations, orientation of the building, soil-structure interaction and previous movements. If at this stage, the damage is not acceptable, protective measures are considered.

Many researchers have investigated the behavior of a TBM tunnel and the induced subsidence phenomena.

Subsequent sections will present results regarding this aspect and evaluation of the impact on structures.

3 PROJECT DESCRIPTION

A subway line will be constructed having different solutions throughout its total route: an elevated solution, a superficial solution and an underground solution. The present paper focuses only on the underground section which from here on will be referred to as Metro project. This project consists of a 7.4 km long TBM-EPB shield tunnel excavation with the biggest diameter used in Latin America, 10.19 meters. This tunnel is built in clay and sandy silts with a thin coverage, ranging from 8.0 to 13.0 m, in the middle of an overpopulated city.

Along the excavation the tunnel crosses some critical zones like disposal water tubes, urban bridges foundations, edifications and its installations, subway stations of the Mexico Metro System and other tunnels.

Given the relevance and difficulty of this project, an instrumentation system was designed to properly monitor structures behavior and identify any possible risk with the aim of implementing protective measures.

3.1 Objectives of the instrumentation system

The decision of installing an instrumentation system was based on the following objectives: measurement of geotechnical and structural behavior of all the structures that are part of the subway, before, during and after the construction, optimization of design parameters and construction processes, determination of risk criterion, and detection of atypical behaviors.

As it has been pointed out, the line crosses several important structures, which represents a potential risk. Hence, monitoring of TBM behavior is fundamental to assess any likely damage.

Selection of used devices to instrument the tunnel section of the Metro project was made to meet the established objectives.

3.2 Instrumentation description

The instruments used for this project can be divided into two groups: instruments used to monitor the tunnel behaviour and instruments used to measure the response of neighbour soil and structures, to tunnel construction. In the following sections a brief description of those instruments, is presented.

3.2.1 Tunnel instrumentation

Externally, a pair of total earth pressure cells was installed in the tunnel walls to measure horizontal soil stresses and pore pressure variation. Two vibrating wire piezometers were located in crown and bench sections to monitor the pore pressure variation along with an inclinometer with magnetic extensometer to obtain horizontal and vertical displacements that will be generated at TBM pass (Figure 1).

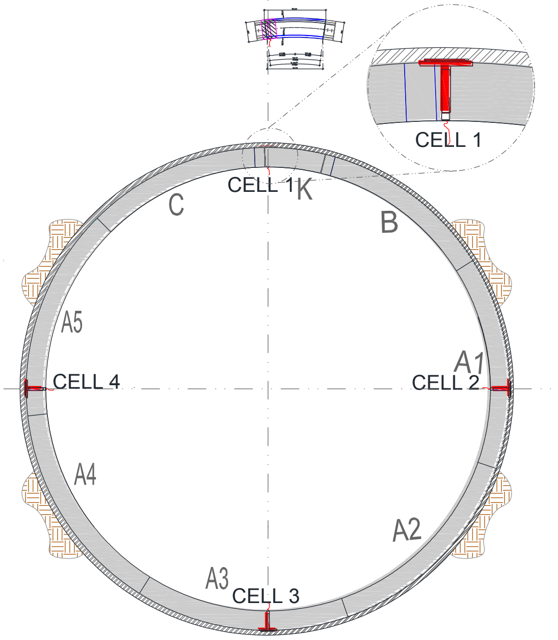

Figure 1. Pressure cells in the tunnel perimeter

In each selected section, one ring was instrumented with pressure cells in perpendicular position to obtain the magnitude and distribution of confinement soil stresses around the tunnel section.

In the inside, a topographical system with composite section was installed to monitor the segmental concrete lining behavior of the TBM tunnel.

For convergence and divergence measurement immediately after the placement of the ring and in the TBM train section, the conventional topography was not enough due to the reduced space of TBM installation itself. To prevail over this problem, an automatic measurement of convergence and divergence system was proposed with inclination sensors called tiltmeters. This system was specially developed for the Metro project and it is a unique system in Mexico. It comprises six interconnected tiltmeters monitored by a datalogger and managed by specialized software (Figure 2).

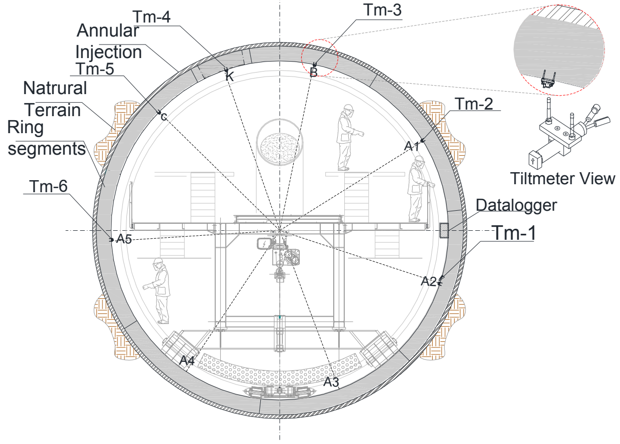

Figure 2. Convergence and divergence system

3.2.2 Instrumentation in the nearby area and structures

The external instrumentation consists of superficial references along the tunnel axis based on level banks to identify displacements, collimation lines with superficial level banks distributed transversely to the tunnel advance axis, benchmarks, and vertical plumb levels installed in neighbor edifications.

In the critical zones instrumentation stations were built. Instruments were selected depending on the type of structure. In some cases rod extensometers, inclinometers and piezometers were installed to verify the ground mass and water behavior at different depths. For example, to monitor disposal water collectors, a multiple point extensometer was used and 2 anchors were projected, the first to the collector crown and the other one to the bench. Besides, two vibrating wire piezometers were placed in the collector bench to identify some atypical water flow and detect any fugue.

Throughout the tunnel piezometers, inclinometers, tiltmeters, extensometers and pressure cells were installed. These instruments were used to properly define the initial and final state of the surrounding soil and structures.

4 BRIDGE AND SEWER TUNNELS RESPONSE TO TBM TUNNEL CONSTRUCTION

Figure 3 shows an instrumented subway station where the TBM pass under sewer tubes, next to a bridge deep foundation and near to urban installations.

The instrumentation system is presented therein and it consists of open and vibrating wire piezometers which were collocated in the bench of sewer tubes to monitor any pore pressure increment due to filtrations or little cracking in the structures. There is an inclinometer with magnetic extensometer collocated in the bridge piles to measure the horizontal and vertical deformation and tiltmeters were placed in columns to measure the inclination, both measurements during the TBM pass. In this way it was pretended to evaluate the impact on the foundation. Besides, pressure cells were installed to observe the change in the ground state of stresses.

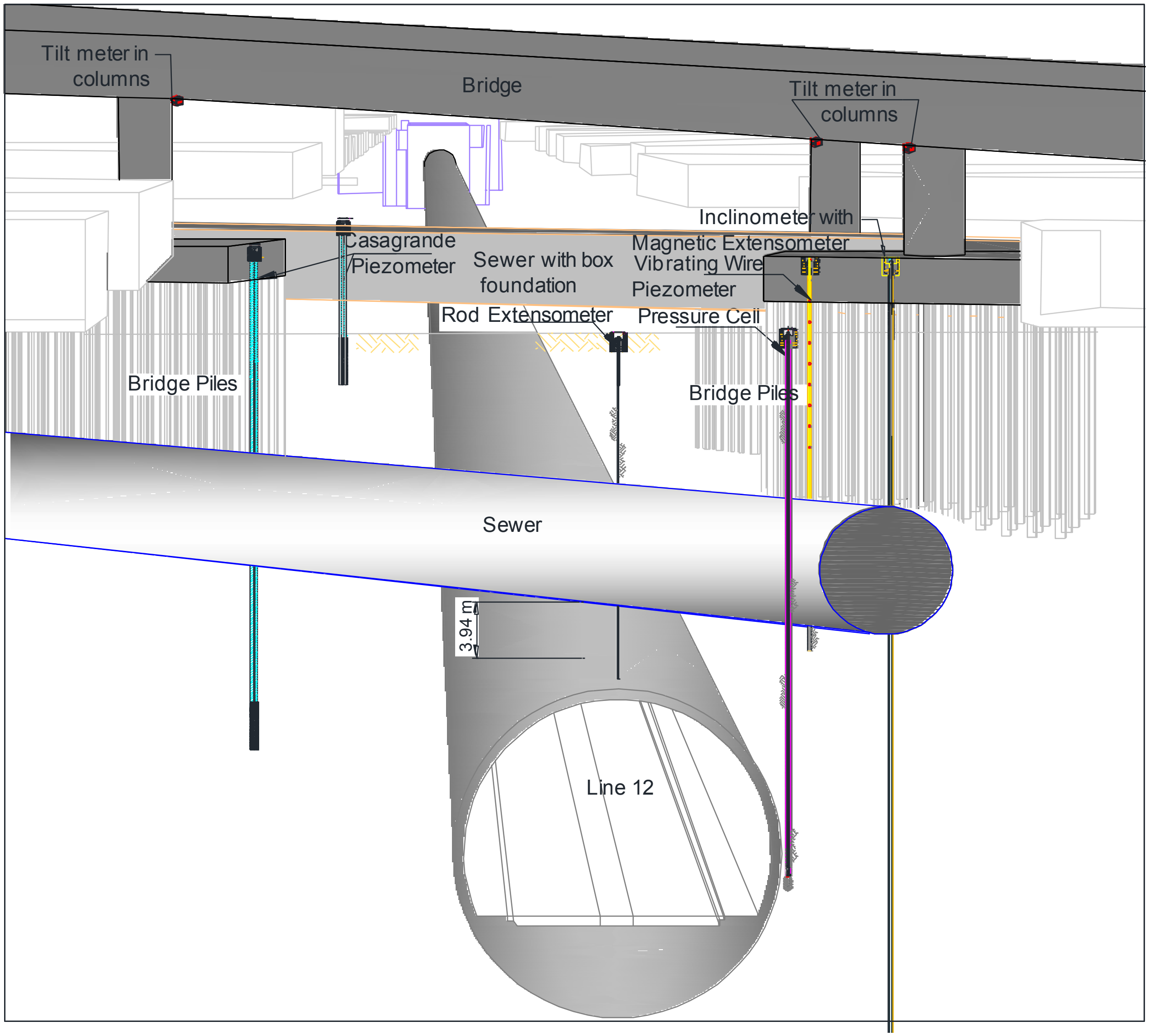

Figure 3. Instrumentation system of the tunnel junction with sewers and a bridge foundation

A typical preparation of the extensometers is presented in Figure 4, where the installation is described schematically. A borehole of 4.5 in diameter is made and an appropriate PVC casing is placed to protect the instrument.

All these instruments were connected to a common datalogger to the automatic measurement and get the information as quickly and clearest as possible, to be able to make appropriate decisions.

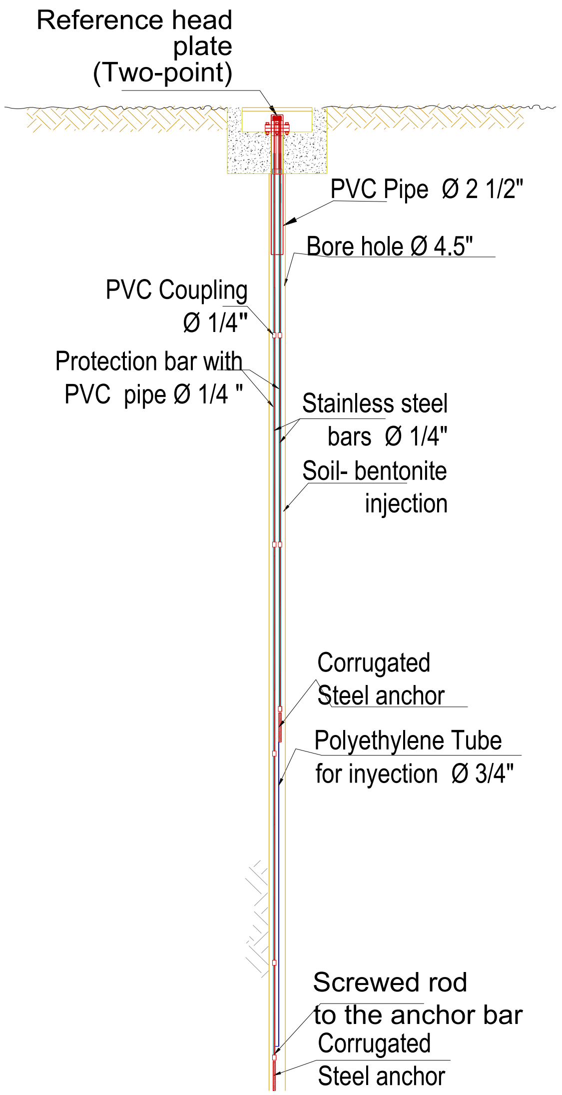

Figure 4. Rod extensometer installation

5 MEASUREMENT OF PARAMETERS

Using the instrumentation described on section 4, the measurement of relevant parameters was carried on. Figure 4 shows the change in total horizontal stress and pore pressures during the construction process.

As it can be seeen, the TBM passed on September 27 and there was a 62% pressure increment that was estabilized four months later. It is observed that the curve returns to normal state of stresses after the TBM pass.

These data along with pore pressure was used to properly define the relation between horizontal and vertical effective stresses, K_0. This parameter was found to be between 0.58 and 0.72 in static conditions and was used to define numerical models to design the segmental concrete lining. During the TBM pass due to the sudden increment of pore pressure and instability of the equipments for the belligerent change, the K_0 value ranged from 0.03 to 0.33.

This parameter results very important when modeling the tunneling process and have a significant impact on the mechanic elements that lead to a certain steel amount on the concrete segments. Hence, measurement of this parameter led to important savings on the lining.

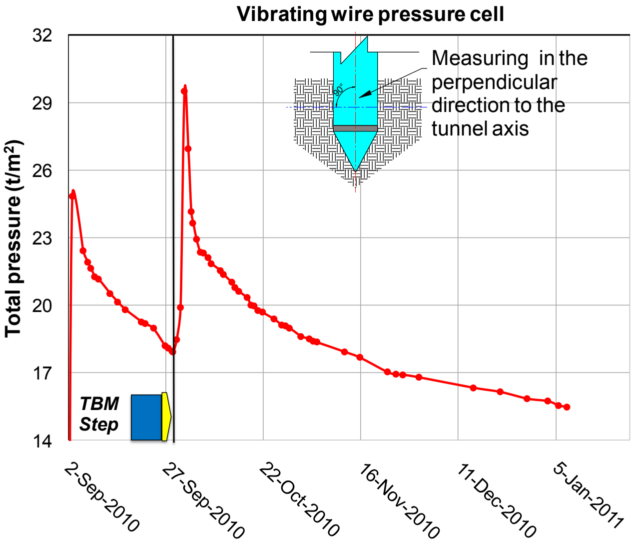

Figure 4. Total pressure during the tunnel construction

Pore pressure distribution and variation is presented in Figure 5. As well as the total pressure, there is a significant increment during the TBM pass and after that, the excess pore pressure is dissipated and three months later, it finally stabilizes, reaching a 5 t/m^2 at 17.10 m which clearly shows the low pore pressure in the Mexico City Valley.

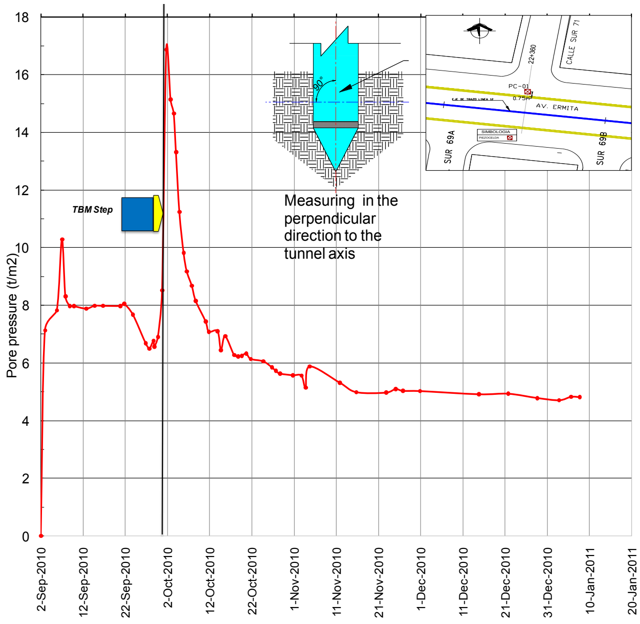

Figure 5. Pore pressure variation with time

Settlement measured with rod extensometer is depicted in Figure 6. A maximum 0.040 m settlement is observed one month later after the TBM pass, but it can be appreciated that such setllement has estabilized. This extensometers, located on the sewer tube at different depths, show how the sewer moves uniformly, as both sensors register similar displacements.

This settlement was also evaluated using a 2D finite element model that simulated the tunnel opening and constructions. In such model a 3.6 cm settlement was found

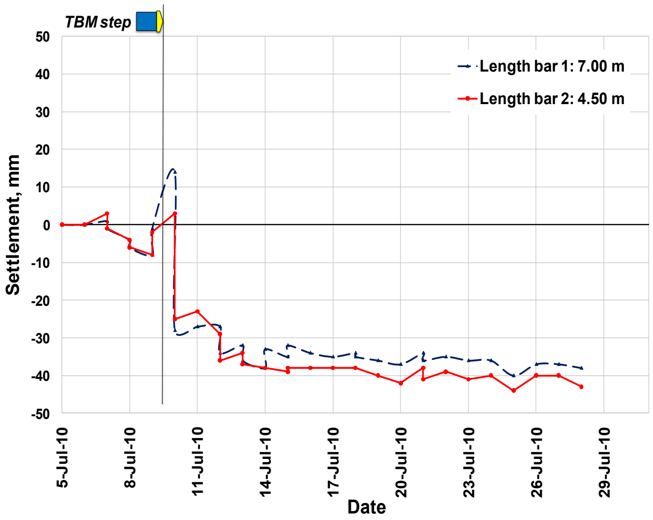

Figure 6. Settlement measured with rod extensometer

Convergences and divergences were also measured in this zone. Figure 7 shows the measurements taken on the 998 ring. A 0.019 m vertical displacements is observed at the crown and a 0.015 m horizontal displacement was registered at the walls.

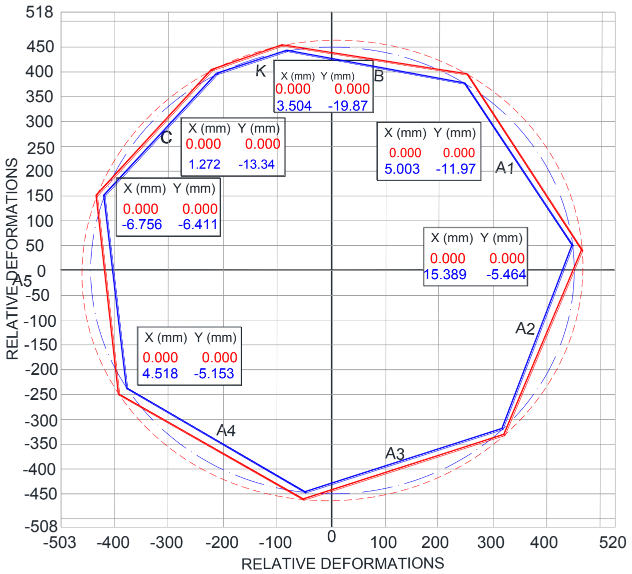

Figure 7. Convergences and divergences measured on the tunnel

Direction of displacements confirm that the tunnel is getting an oval shape after installation.

Figure 8 shows the deformation of each segment during time. H and V stand for horizontal and vertical displacement. A, B, C and K represent each concrete segment of the ring, also shown on Figure 7.

This figure enforces the idea of the ovalization being suffered by the tunnel with time. It is importan to mention that such measurements were registered during 3 months.

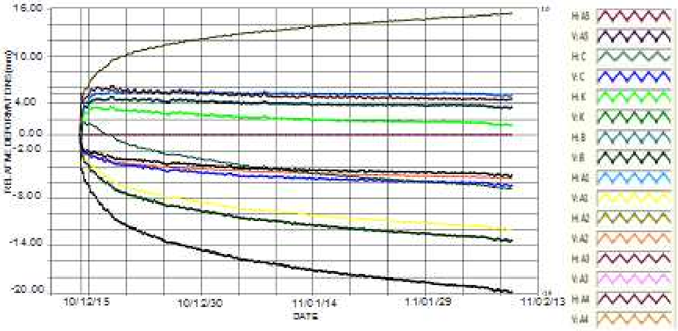

Figure 8. Relative deformation of concrete segments

A previous numerical model was used to predict the displacements suffered by the tunnel at short-term conditions, keeping the grouting force as a variable. Using this results it was possible to establish a value for this force to match these displacements.

Another noteworthy aspect of these measurements, compared with long-term analyses, is the fact that elastic deformations in the tunnel represent an important component of the total deformation (Aguilar et al., 2010). Particularly, this tunnel was designed to withstand a 5 cm total deformation, although its deformation can reach 10 cm.

These displacements were used to perform longitudinal analysis of tunnels, as the one described by Bonnier et al. (2002) to found mechanic elements and its real distribution throughout the longitudinal direction. Results from such analyses were used to callibrate numerical models and to enhance design of the segmental concrete lining. Outcome of those analyses will be presented in later works.

Insturmentation used for piles and columns showed that TBM pass did not cause significant effects on the structure and displacementes were found to be within an acceptable range defined by common building codes.

Regarding the bridge behavior, tiltmeters were installed on the columns, as mentioned before. Such inclinations did not exceed 3 cm that is a rough approximation to standard limits.

Figure 9 shows the displacement measured on the bridge columns. In the right upper corner, the direction of measurements is observed. The bidirectional displacements measured in the bridge columns during TBM pass, were not important to bridge structural security. Using these results and measurements of the neigbour soil mass as a first approach, it was decided to adjust the face pressures, velocity and injection volumes during the advancement of the TBM to protect the structure and in the figures it can be observed that the tunnel construction did not cause any damage.

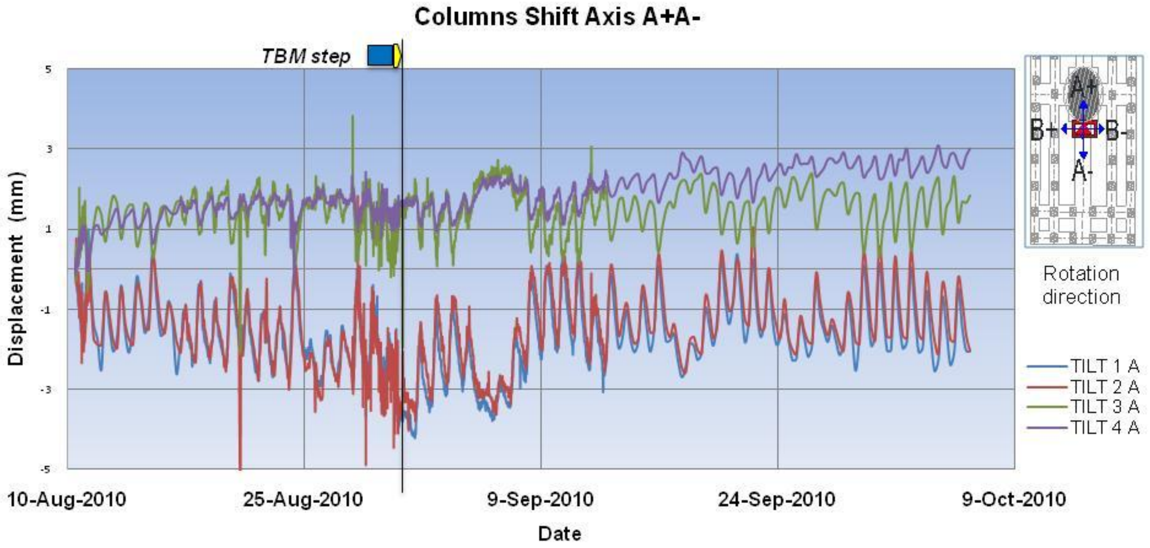

Figure 9. Columns inclination

6 SOIL BEHAVIOR

Soil behavior was defined by the parameters presented on section 5: total stress, pore pressures and displacements. Considering the face pressures developed by the TBM, a correlation between TBM advance and settlement profile was made. Figure 10 presents the transverse settlements. The initial reading shows a stabilized line that starts to grow as the TBM gets closer; a 0.025 m settlement is reached during the TBM step, and the last reading shows a 0.027 m settlement.

It can be seen that settlement decreases as the tunnel axis gets further, however this behavior meets the theoretical deformation that can be expected during TBM tunnel construction and can be related to the longitudinal settlement.

As described in Bonnier et al. (2002) it is possible to estimate the longitudinal settlements from the transversal settlements, such procedure led to 4.2 cm and the measured longitudinal settlement measured with topography was found to be 3.7 cm. Hence, the information gathered from this instrumented section was used to calibrate the numerical methods for the following sections.

Soil performance during and after pass of the TBM, was monitored and controlled through continuous processing of the gathered data. As seen before, it is possible to use the greenfield settlement as a first approach to measure the influence of tunnel boring on nearby buildings and structures.

information was used to assess any possible damage on the surrounding structures and although settlements were registered, there was no significant affection to the sewers or the bridge.

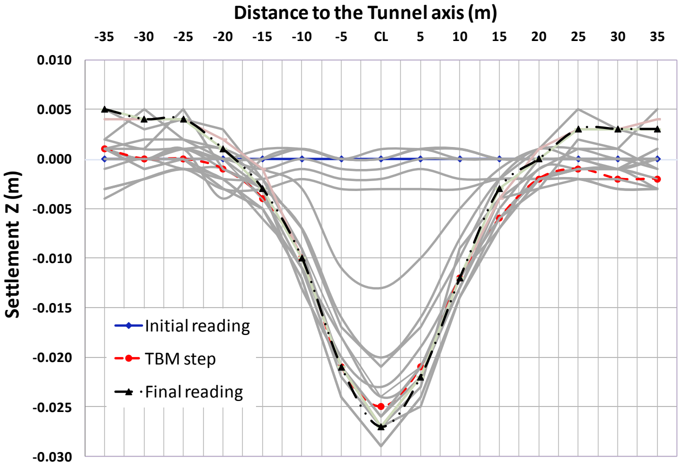

Figure 10. Transverse settlements

As the TBM advanced, the face pressures were also calibrated using the longitudinal and transverse settlements, to avoid significant settlements behind the TBM and expansions at the front of it.

Using this data it was found that face-pressures calculated using the at-rest lateral earth pressures approach, seemed to be the most accurate analytical method. The best estimate for the K_0 value was found to be 0.75 for the analytical face-pressure analysis.

Settlements measured in successive sections have been analyzed following this approach to modify the face-pressures applied during construction.

7 CONCLUSIONS

Analysis and measurements of this Metro project have shown that soft soil tunnelling in urban environments is a very complex process that needs to be studied, especially to guarantee safe and economic construction processes.

There are several methods to determine face pressures, settlements and loads on linings for TBM tunnels, from empirical approaches to very complex 3D models. However every project involves very particular soil conditions as the ones presented in this paper, hence it becomes necessary to use appropriate methods to define the TBM tunnel performance and its effect on the surrounding structures.

During this project several numerical methods were used to estimate the effects on neighbor structures and loads on linings. Topography was used to control and monitor settlements throughout the whole tunnel.

Using an innovative instrumentation system, many important factors were measured and used to feedback the numerical models and prevent any possible damage during construction.

In the particular section presented herein, the instrumentation system was used to have an integral vision of the project that impacted on the decision making process, leading to important savings. Use of this technology, became a very useful tool to assess the TBM advance impact on the soil and structures. Besides, it was necessary to develop specific systems to measure particular conditions, as the convergence and divergence system.

This experience has proved that instrumentation is an engineering area that should be integrated to all the construction stages, from planning to operations. It allows for geotechnical exploration simplifications, measurement of design parameters, identification of possible risks and assessment of surrounding structures performance.

This project will impact the procedures carried out to design soft-soil tunnels in Mexico and relevant information gathered from it, should be used to generate a database for future projects.

8 REFERENCES

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