Variation of the k_0 relationship in clay subsoil, during the passage of a pressurized shield

Gutiérrez, L.E. & Schmitter, J.J.
ICA, Mexico City, D.F., México

2011 Pan-Am CGS Geotechnical Conference

ABSTRACT
The paper describes the variation of the horizontal and vertical effective stress ratio (k_0) determined with the aid of a piezo-cell installed for such purpose in the soft clay subsoil of a site, after passing of a pressurized shield.

RÉSUMÉ
L´article décrit la variation des contraintes effectives horizontales et verticales (k_0), déterminées au moyen d´un piezo-cellule installé pour ce but, dans le mou sous-sol d´un endroit par lequel a traversé un écu de pression.

1 INTRODUCTION

During construction of tunnels through soft clay-type soils below the phreatic level using the EPB (Earth Pressure Balance) pressurized shield, the advance of the Tunnel Boring Machine (TBM) additional pressure is generated. These pressures are particularly high in the pore water pressure and in the total horizontal pressure of the subsoil in the immediate vicinity of the TBM. Such changes in pressure to the horizontal and vertical effective stresses in the subsoil and the ratio between them, is usually expressed as k_0.

It is also important to note that the determination of the k_0 ratio and its eventual variation due to the application of external actions, such as that induced by the passage of a TBM shield, becomes fundamental for the design of the initial support of the tunnel excavated through soft soils. In this situation, typically the primary tunnel design is resolved by the use of reinforced concrete segmented rings. Also the design of the tunnels final lining is commonly resolved by means of cast-in-place reinforced concrete.

In general, the value of the k_0 ratio is determined in terms of empirical relationships or otherwise by means of laboratory test results, with the probability of a certain degree of uncertainty. It is therefore quite convenient to determine directly in the field such k_0 relationship through the installation and monitoring of an instrument known a "*piezo-cell*" (combination of a cell with a fast-response piezometer), with which it is possible to measure not only the total horizontal pressure of the subsoil but also the pore water pressure, and their variations with time.

Mention should also be made that the total vertical pressure in the subsoil, required for determining the value of the k_0 relationship, is directly calculated as a function of the dead weight of the soil, under the hypothesis that such value does not vary significantly as a result of the external forces, such as those induced by the passage of the TBM shield.

The objective of this paper is to show how pressures - horizontal total pressure and pore-water pressure - were determined in the field both during the passage of a TBM EPB shield and also when the latter passes beyond the site.

2 DESCRIPTION OF THE PIEZO-CELL

The piezo-cell referred to (Figure 1) is manufactured by RST Instruments and the model number used in our tests was VWPC2100-1.0, serial number TP1046 and has a measurement range of up to 1 MPa (10 kg/cm^2), for both the piezometer and the pressure cell.

It is an instrument designed to be driven through soft soils with which it is possible to measure the pressure at the surrounding soil as well as the in-situ pore water pressure, and for such purpose it incorporates an earth pressure cell in the shape of a "spade" and a piezometer, both are of quick response and fitted with vibratory chord sensors.

Figure 1. Piezo-cell and measurement box

Prior to the installation of the piezo-cell it is recommended to protect the porous stone of its piezometer against eventual clogging with fine materials, by placing for example a previous geotextile fabric as shown in Figure 2.

Figure 2. Protecting the piezometer of the piezo-cell

It is common for this device to be driven vertically (Figure 3), therefore allowing measurement of the horizontal stress in the subsoil acting against the flat side of its “spade”.

Figure 3. Piezo-cell ready to be driven

Prior to their insertion in the field, the two components of the piezo-cell have already been properly calibrated in compliance with standard procedures established for such purpose.

3 INSTALLATION OF THE PIEZO-CELL

The following sequences confirm the stages necessary to complete the installation of the piezo-cell in the field; Figure 4 depicts the schematics of the instrument installed.

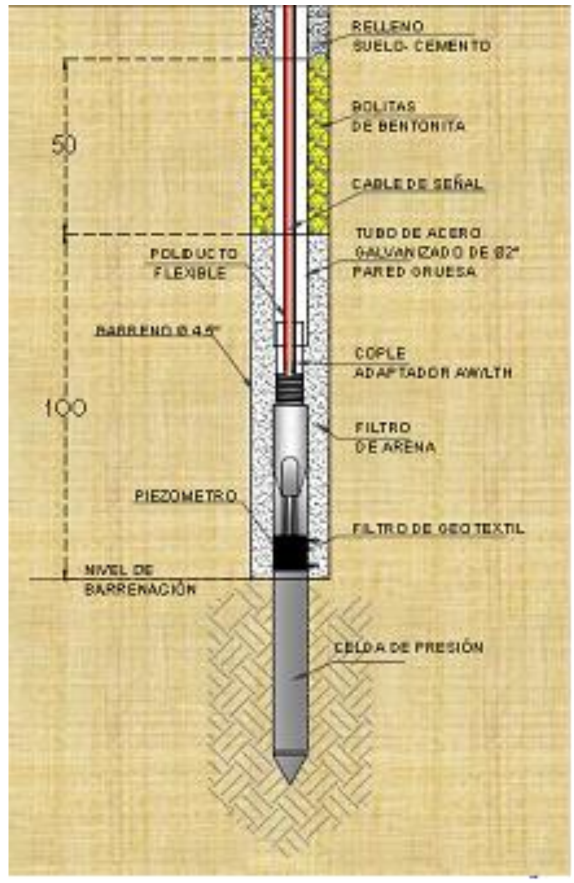

Figure 4. Piezo-cell installed

a) Initially, with the help of a rotary drilling rig Longyear 34 or similar, a bore hole is advanced having a diameter of 12 cm (4½”) down to a depth of 50 cm above the elevation of the corresponding installation. The reason for this is to have the least disturbance of the state of stresses of the stratum where the piezo-cell will be installed. During the drilling process clean water is used so as not to alter significantly the permeability of the strata crossed through.
b) Upon completion of the bore hole the depth of the boring is verified as well as its cleanliness by means of a tamper attached to a probe. It is therefore checked that no obstacles exist that

could prevent the free passage of the piezo-cell and its accessories. If necessary, the boring should be flushed with clean water.

c) Prior to its installation, the cable of the piezo-cell is protected by means of flexible plastic hose with a diameter of 2 cm (¾") along its full length. The plastic hose will be inserted inside the adapter fastened to the piezo-cell as well as through the first section of the 5 cm (2") diameter galvanized pipe that is placed against the adapter. Next, the subsequent sections of the galvanized pipe will be attached until reaching the required depth for the installation.
d) After completion of the protecting pipe of the piezo-cell, the cell will be inserted inside the bore hole drilled for such purpose, until the bottom level is reached, and then the piezo-cell itself is driven through the natural ground until it penetrates 50 cm. Driving should be performed carefully so that the lower part of the instrument, where the pressure cell is attached, directly interact with the surrounding soil, whereas its upper part, where the piezometer is found, remains above the driven section. Then a filter of fine sand, with a height of 100 cm, is placed.
e) Fifty centimetres above the sand filter an impervious seal is placed by dropping dry bentonite pellets.
f) Subsequently, the annular space left between the boring walls and the galvanized pipe are filled with self-setting drilling mud which is injected above the bentonite seal with soil-cement.
g) Finally, and as a protective measure, a manhole cover is built at ground surface.

4 SITE OF THE INSTALLATION

The piezo-cell whose results are presented in this paper was installed at a distance of about 60 m north of shaft L-0 of the Eastern Outfall Tunnel that is being built under the supervision of CONAGUA (Figure 5). Such shaft L-0 is located at the southeastern corner of the crossing between boulevards Gran Canal and Periférico Norte, in Mexico City.

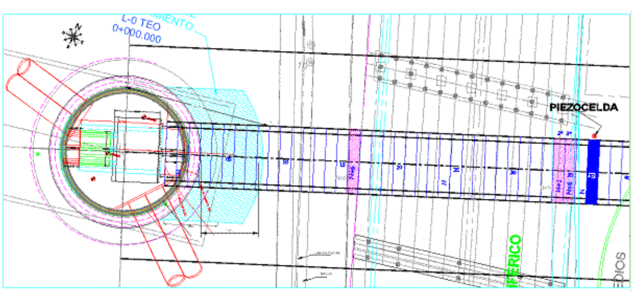

Figure 5. Location in plan of the piezo-cell installed

The vertical plane containing the "spade" was located perpendicular to the tunnel axis and its final installation depth of 18.4 m placed it practically at the same elevation that the project axis of the former. It is reiterated that the piezo-cell was installed at a distance of 50 cm from the spandrel of the segmented concrete lining prior to passage of the EPB TBM shield by the site.

With data retrieved from the geotechnical model of the site, as shown in Tables 1 and 2, it is possible to determine that the average unit weight of the subsoil at the site becomes equal to 12.2 kN/m^3 (1.24 t/m^3) and, therefore, the total vertical pressure at a depth of 18.4 m was calculated to be 224 kPa (22.8 t/m^2).

Table 1. Geotechnical model of the site, part 1 of 2

St.	SUCS	Depth (m)	S_s (-)	c (kPa)	ϕ (°)
A	SM	0.0 to 2.7	-	24	28
B1	CH	2.7 to 4.5	-	11	0
B2	CH/MH	4.5 to 9.9	2.08	32	0
B3	CH	9.9 to 12.5	2.07	24	0
C	MH	12.5 to 13.9	2.07	24	0
D1	CH/MH	13.9 to 21.7	2.22	37	0
D2	CH/MH	21.7 to 26.8	2.12	41	0

Table 2. Geotechnical model of the site, part 2 of 2

St.	γ (kN/m^3)	E (kPa)	ν (-)	w (%)	k_0 (-)
A	16.0	12000	0.35	21	0.54
B1	12.0	4903	0.45	250	0.81
B2	11.9	7165	0.45	321	0.81
B3	11.5	7742	0.45	335	0.81
C	16.0	8171	0.35	335	0.54
D1	11.5	5985	0.40	273	0.66
D2	11.6	8243	0.35	326	0.54

5 RESULTS OF THE MEASUREMENTS

The first reading of the piezo-cell was made on 28th October 2009. Fifty days afterwards, i.e. on December 17 of that same year, the nose of the EPB shield that had departed shaft L-0, passed to the right of the installed piezo-cell and, when the rest of the TBM shield had passed through the tunnel, the initial support No. 37 was installed immediately with its spandrel located at no more than 50 cm from the piezo-cell.

As a result of an accidental flooding, operation of the TBM shield came to a stop on the 3rd February 2010 when its nose had covered a distance of 248 m with respect to the axis of shaft L-0 and lining ring No. 157 had already been placed.

In Figures 6 and 7 shown below there is a graphic representation of the results from the measurements (Pressures) carried out with the piezo-cell as a function of time (Dates) and in terms of distance, respectively.

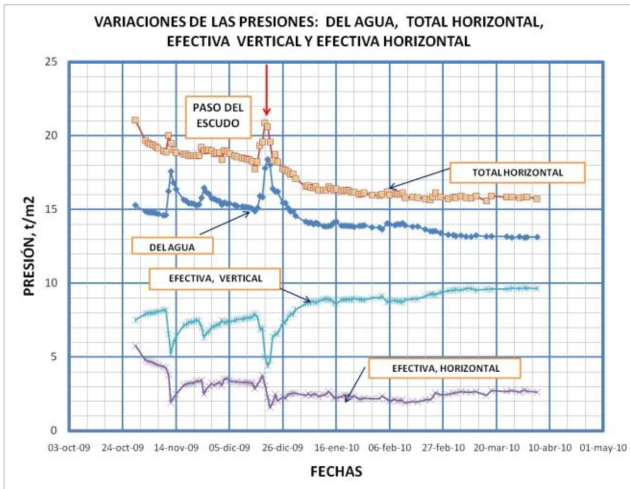

Figure 6. Variations with time of water, total horizontal, effective horizontal and effective vertical pressures

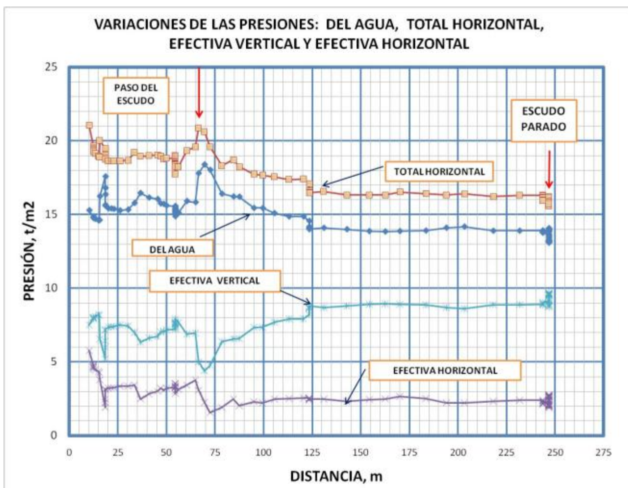

Figure 7. Variations in terms of distance of water, total horizontal, effective horizontal and effective vertical pressures

It is important to mention that water and total pressures are directly recorded by the instrument whereas the horizontal and effective pressures are calculated. It is also important to clarify that the initial measurements with the piezo-cell provide values that are unusually high since their stabilization takes almost two weeks to be achieved.

From Figures 8 and 9 the following comments can be derived:

a) Water and total horizontal pressures start experiencing an important increase when the nose of the EPB shield lies at a distance of close to 5 m from the piezo-cell and they start returning to their initial values when such a nose is found 20 m away and they reach a reasonable stabilization when the nose has moved 65 m forward.
b) Water and total horizontal pressures evidence a major increase when the EPB shield is getting closer. It was found that pore water pressure goes up 3.5 t/m^2 when increasing from 14.9 to 18.4 t/m^2. On the other hand, the total horizontal pressure rises by 2.6 t/m^2 when increasing from 18.3 to 20.9 t/m^2.
c) The time period when a sudden increase of the water and total horizontal pressures is recorded, followed by their subsequent stabilization lasts between two to three weeks.
d) In general, after the shield has passed a continuous decrease of water and total horizontal pressures occurs as times goes by. In the first case, water pressure decreases from 15 to 13 t/m^2, whereas in the second, the total horizontal pressure decreases from 19 to 16 t/m^2. In both situations it can be observed that the magnitudes of the pressures tend to stabilize.
e) The distance in which a sudden increase of the water and total horizontal pressures takes place, followed by their almost total stabilization, is of about 70 m.

Figures 8 and 9 show graphically the variation of the k_0 ratio as a function of time and distance, respectively.

Figure 8. Variation of the k_0 ratio in terms of time

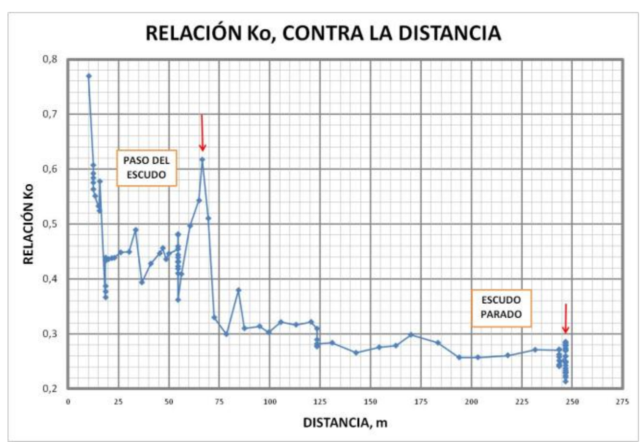

Figure 9. Variation of the k_0 ratio in terms of distance

From Figures 8 and 9 one more comment can be derived:

f) The value of the k_0 amounts to 0.45 prior to the arrival of the shield; it increases to 0.62 when the equipment passes right by the piezo-cell and subsequently decreases to a value of 0.32 to finally stabilize at 0.28.

6 CONCLUSIONS

From the measurements recorded by the piezo-cell it could be confirmed that major increments are generated upon passing of the EPB TBM shield in the pore water pressure as well as in the total horizontal pressure and they last about two to three weeks.

Considering that the "spade" of the piezo-cell was placed at an approximate distance of 60 m from the axis of shaft L-0, with an orientation perpendicular to the tunnel axis, and taking into account the results shown in the graphs presented above, it is possible to come to the following conclusions:

- Pore water pressures started increasing after 15th December 2009 when the nose of the shield was found at a distance of 5 m from the piezo-cell.
- On 17th December of that same year the nose of the shield reaches the station where the piezo-cell was installed and on that date the pore water and total horizontal pressures already showed an increase.
- On 20th December the maximum pore water pressure is recorded by the piezo-cell when the nose of the shield was at a distance of almost 8.7 m forward from the instrument.
- On 4th January 2010 the pore water pressure tends to stabilize when the nose of the shield had already moved close to 65 m away from the piezo-cell.

From these conclusions it can be inferred that the lateral skin friction generated by the jacket of the shield and not the front pressuring of the tunneling machine is the main cause for the increase in the pore-water and total horizontal pressures measured by the piezo-cell.

7 RECOMMENDATIONS

The principal and most relevant recommendation is to continue installing piezo-cells in front of the trajectory of the various EPB pressurized shields that are currently operating in Mexico City and its surroundings for the purpose of confirming the performance trends that have been observed under this study.

In future instrumentation projects include pairs of piezo-cells so as to be able to measure the total horizontal pressure in both perpendicular and parallel directions with respect to the tunnel axis.

8 REFERENCES

Gutiérrez, L. and Schmitter, J.J. 2010. Variación de la relación k_0 entre las presiones efectivas horizontal y vertical del subsuelo, inducidas durante el paso de un escudo EPB, a 56 m de la Lumbrera L-00 del TEO, *Ficha técnica,* ICA, México, Distrito Federal, México.

Jacky, J. 1994. The coefficient of earth pressure at rest, *Journal of the Society of Hungarian Architects and Engineers 7*, (22): 355-358.

Mesri, G. and Hayat, T. 1993. The coefficient of earth pressure at rest, *Canadian Geotechnical Journal*, 30: 647-666.

Terzaghi, K. 1943. *Theoretical Soil Mechanics*, John Wiley & Sons, Inc., New York.

Terzaghi, K. 1943. *Soil Mechanics in Engineering Practice*, 2nd ed., John Wiley & Sons, Inc., New York.