Performance of a pioneer foundation of the skirt type for the Metro-Line 12 overpass on the Mexico City soft clay

Comportement d'un nouveau type de fondations de type radier à jupe, utilisé pour les tronçons en viaduc de la ligne 12 du Métro fondés sur les argiles molles de Mexico

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ABSTRACT: Given the extension and importance of Mexico City's Metro-Line 12, it was considered relevant to monitor the behavior of the foundation of one of the supports for the overpass solution, which is laid on very soft clayey soils. This pioneer foundation, a footing or foundation slab with long skirts, locally known as structural cell or "inverted glass" type, was used for the first time in the city. Geotechnical sensors and accelerometers were included in the foundation to follow its behavior, not only during its construction and long term operation, but to record significant variables during strong earthquakes. From measurements made to date (two years after the beginning of construction) it stands out the effective coefficient K of earth pressure, reaching values close to the unit, at the soil-concrete walls (cast in place) contact.

RÉSUMÉ : Au vu des dimensions et de l'importance de la Ligne 12 du Métro de la ville de Mexico, il a été jugé nécessaire de procéder à l'auscultation des fondations de l'un des appuis du tronçon de la ligne en viaduc, implantées dans des sols lacustres très mous. Les fondations, d'un type nouveau à Mexico, sont constituées par un radier avec une jupe de parois moulées et sont connues localement comme cellule structurée ou « verre renversé ». Des jauges géotechniques et accéléromètriques ont été insérées dans les fondations afin non seulement de suivre leur comportement durant la construction et à long terme mais aussi d'enregistrer certaines variables importantes durant les séismes intenses. Les mesures réalisées à ce jour mettent en évidence un coefficient de poussée des terres K effectif de l'ordre de l'unité au contact entre le sol et les parois de béton.

KEYWORDS: Foundations, Static and seismic performance, geotechnical instrumentation, soft clayey soils.

1 INTRODUCTION.

Construction of Mexico City's Metro-Line 12 has involved tunnel, semi-deep box, surface and overpass solutions along 25 km of development, connecting the southeast and southwest zones of the country's capital. Stratigraphic conditions along the layout have demanded novel solutions, mainly at the portion that runs into Lake zone subsoil consisting of very compressible and low strenght clayey lacustrine deposits. Such is the case of a pioneering type of foundation in Mexico City, known locally as structural cell or "inverted glass" which was used at the supports of an overpass almost 1.7 km long located near the Tláhuac terminal station. This reinforced concrete foundation consists of four perimeter walls, each 60 cm thick and 10.5 m long, cast in place, that constitute the skirting, Figure 1. The precast footing-column unit is integrated to the four perimeter walls by casting in place the rest of the footing's four sides, thus forming what is known locally as an "inverted glass".

The instrumented support is named ZP16, and is located between the Zapotitlán and Nopalera stations. The foundation's behavior is exposed based on vertical pressures measured under the footing, lateral pressures on the walls, and pore water pressures at the contact between clayey soil and walls, for which total pressure cells, push-in pressure cells, and piezometers were used, respectively. With the objective to improve our knowledge on the behavior since the construction process, in the long term and during an earthquake, the adopted instrumentation required long life trustworthy ad hoc equipment with sufficient precision and immediate dynamic response during seismic events. The latter required the adoption of an automatic recording system for these geotechnical data and the accelerations measured at the footing.

This paper describes the type of foundation, its construction process, the geotechnical and accelerographic instrumentation that was integrated into the foundation, and the monitoring carried out to learn about its geotechnical behavior, not only during construction and long term operation, but to record significant variables in the foundation precisely during a strong earthquake. The monitoring time period covers the constructive process and its evolution over almost two years. It also includes static measurements before and after two earthquakes of moderate intensity.

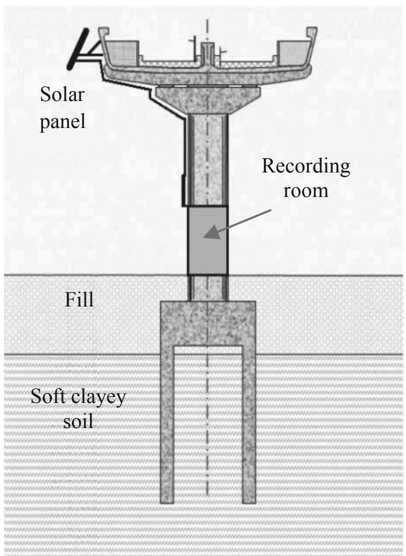

Figure 1. Overpass for Metro-Line 12. Support ZP-16.

2 SCOPE AND OBJECTIVES

The instrumentation's primary objective is to compare theoretical and semi empirical forecasts that have been assumed during the design stages, refering to load capacity and its movements, with the experimental results derived from instrument monitoring. Specific objectives contemplate 1) knowing the magnitude of total and effective lateral pressures in static and long term conditions; 2) the same, but during moderate and high intensity earthquakes; and 3) quantifying the footing base contribution to the bearing capacity of the foundation system against axial static loads. In this paper, field measurements and design forecasts will not be compared.

3 GENERAL DESCRIPTION OF THE STRUCTURAL CELL

For about 40 supports of the Metro-Line 12 overpass, an innovative foundation solution was used like the studied one, according to prevailing conditions at Tláhuac Avenue consisting of very thick soft clayey soils. The foundation's construction began with the excavation and casting of reinforced concrete walls with the diaphragm wall technique, forming a square plan section of 6.5 m exterior sides starting at 2.5 m depth. Once the central core soil was excavated to a depth of 3 m, a reinforced slab was built at the bottom, which temporarily received the precast footing-column unit, whose dimensions are smaller than the cell's inner dimensions, in order to allow its transport from the manufacturing plant. Once the monolithic footing-column unit was installed and leveled, its periphery was cast in place with high resistance concrete, ensuring a structural continuity along the footing's entire height (1.7 m) with its four perimeter walls, prior overlapping of their reinforcement bars.

4 STRATIGRAPHIC CONDITIONS OF THE SITE

There is a stratified formation of very soft clayey soils at the site, interbedded with sandy or volcanic ash soils strata of variable thicknesses (decimeters) at the more shallow portion. This lacustrine formation reaches a thickness of 79 m, with deep deposits below it consisting of sandy soils. A silty layer 3 m thick was detected at 56 m depth. Based on a nearby cone penetration test (CPT), the cone point's resistance q_c from surface to 3.1 m depth was defined at 1 MPa. A sandy stratum of 3.1 to 4 m reached a maximum q_c value of 6 MPa. But, below the 8 m depth, and down to the 25 m depth explored by CPT, there were very soft clay conditions, with very low q_c values. Undrained shear strength at these depths reached values of 28 to 50 kPa. In summary, it is a site of lacustrine deposit with very low shear resistance and high compressibility. Therefore, the foundation for a work of infrastructure like the one described here, with high applied loads per column, represents an engineering challenge.

5 GENERAL DESCRIPTION AND FOCUS OF THE GEOTECHNICAL AND SEISMIC INSTRUMENTATION

Following relevant guidelines of Terzaghi and Peck (1967), Peck (1960), and Dunnicliff (1988), among others, the foundation's design was outlined responding to specific questions of possible behavior and distinguishing the internal variables that determine and explain it. This also determined the type of sensors that would measure these variables and their location. Also, from an analysis of the expected level of stresses and deformations, transducer measurement intervals were defined.

It was not possible to place instruments in the body of the walls as was initially intended, because they had already been cast when it was decided to study this support. The initial plan was to measure pressures on the walls using jack-out pressure cells, in order to ensure their contact with the soil walls at the excavated ditch.

5.1 *Pressure cells at the soil-footing contact*

The instrumentation included the installation of seven pressure cells, Figure 2, under the thin bottom slab with which it is possible to measure total vertical stresses immediately below the slab on which the footing-column unit gravitates temporally. Six cells were of resistive type (SG), and one was of vibrating wire type (VW).

Figure 2. Installation of pressure cells below the footing-column unit.

5.2 *Push-in pressure cells*

Penetrating pressure cells, known as push-in pressure cells, Figure 3, were pushed in outside the walls in vertical position and just at the contact with the clayey subsoil. This instrument has a pressure cell to measure total horizontal stresses, perpendicular to the wall, precisely at the exterior sides of the structural cell. Three push-in-cells of SG type were installed; each one has an integrated electric piezometer that records pore water pressure at the foundation's wall-soil contact. Two of these sensors were placed in the South longitudinal wall, at one and two thirds of the wall's depth, and only one was placed in the North wall at two thirds of its depth, Figure 4. Thus, with the difference between total pressure and pore water pressure measured at each push-in-cell, horizontal stresses were recorded in terms of effective stresses.

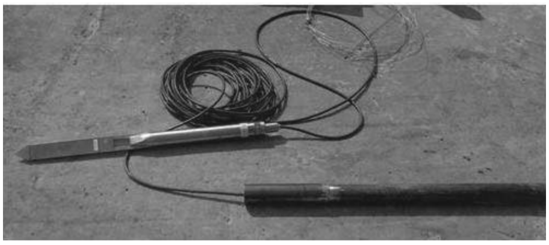

Figure 3. Push-in pressure cell.

5.3 *Resistive and vibrating wire piezometers*

These were the first instruments to be installed, all embedded at the soil-exterior wall contact, except one that was placed at the inside wall-soil contact. The VW piezometers do not have a rapid answer to pore pressure changes during seismic events, so they will not be connected to the seismic data receiver. Nonetheless, they do have the advantage of recording long term pore pressure changes, with a consistent and very stable manner. The SG piezometers will be connected to the digital data recorder, because they have better dynamic response. This has been verified in prior instrumentation projects, even embedding the piezometers directly in clayey soil (Mendoza, 2004; Mendoza et al., 2000). The location of the six SG piezometers and two VW piezometers is shown in the foundation plan, Figure 4. Installation depth was derived from the site stratigraphic conditions, seeking one and two thirds of the wall-height, but embedding the sensors in clay.

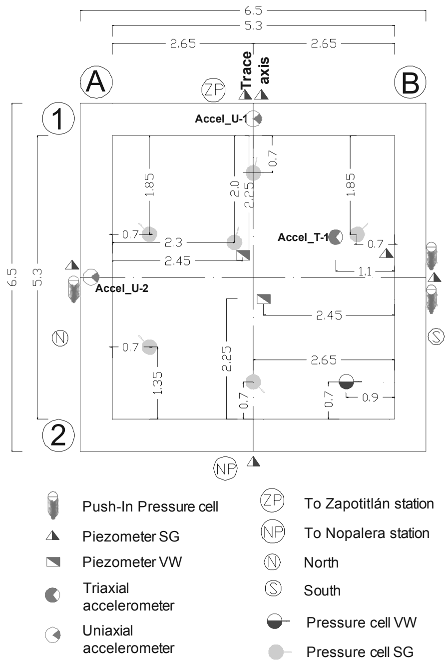

Figure 4. Sensors layout at the instrumented foundation.

5.4 *Accelerometers*

Accelerometers were integrated to the structural cell, which allows knowing information about its movements in case of seismic events, as well as the forces that those actions exert on the foundation system. A triaxial accelerometers set (boring type) was placed in such a way as to record accelerations near the system's center in horizontal directions, parallel and transversal to the tracing axis, and in the vertical direction. These three sensors were embedded in the precast footing's concrete, becoming a trustworthy recorder of its movements. In addition, two single axis accelerometers were placed in vertical position, and embedded in the concrete cast in site joining the footing and the walls. Its location toward the footing's periphery intends to distinguish, if there are any, rocking movements of the system.

5.5 *Digital recorder and recording room*

The geotechnical sensors and accelerometers described above will be connected to an automatic digital recording system that will be activated when a prescribed acceleration threshold is exceeded due to a seismic event, recording the dynamic actions on the foundation, with a pre and post event. The digital recording system has the capacity to capture up to 24 channels simultaneously, with great precision and at very high speeds; indeed, it will be usual to record a seismic event with rates of 250 samples per second.

The automatic recording system will also allow maintaining permanent systematic monitoring in order to know the long term behavior of the support, thus verifying its structural health. There is a recording room to which all the cable terminals of the geotechnical instruments and accelerometers arrive. Over there, the resistive type and full bridge instruments and accelerometers will be connected permanently to the automatic digital recorder, to record their signals in the long-term and during seismic events. The VW sensors will be manually recorded with portable units. The digital recorder is properly safeguarded inside this room, given the valuable information it will be receiving, and because its own cost. Therefore, the room was built totally of reinforced concrete and has a metal door with security locks. It will have a voice and data system to have remote access to the information via Internet. Solar energy is used for electric supply to the recording system.

6 SOME ASPECTS OF THE FOUNDATION'S BEHAVIOR

6.1 *Evolution of the lateral pressures on the foundation walls*

The push-in-cells have provided valuable information to understand the behavior of this novel foundation, giving relevant data for future designs. Figure 5 displays the evolution of horizontal pressure at 9.1 m depth on the exterior side of the North wall. It can be appreciated that few after the walls were built, total horizontal pressures are noticeably larger than total vertical pressures. Also shown is the horizontal pressure decrease over time, asymptotically tending to a certain value. With the foundation's small settlements, and two years after construction began, the total horizontal pressure's tendency is to reach the same value of the vertical pressure. Pore pressure exhibits small variations, apparently related to seasonal changes of the water table level.

During the period of almost two years shown in the abscissas of Figure 5, there were two earthquakes that were not recorded because the digital recording system was not connected, due to the recording room had not been finished yet. There was a Mw 6.5 earthquake with epicenter in Zumpango del Rio, Guerrero, on Saturday night December 10 2011. Next Monday morning, readings of all the sensors were made, with the lower one for the day shown; readings recorded a few weeks later show a clear tendency to continue the one just before the earthquake. Thus, it has been assumed that there was a sudden and transitory decrease, as shown in Figure 5, caused by the earthquake. Nonetheless, it is striking that the more intense earthquake on March 20 2012, with inland epicenter between the states of Oaxaca and Guerrero, with Mw 7.4 magnitude, caused no pressure variation, as shown in Figure 5.

Figure 6 shows the variation of the true coefficient of earth pressure K, indicating that in the term of two years after the walls construction, it reaches asymptotic values close to the unit. Measurements show a total coincidence, which should be underlined, because the coefficient K is systematically equals to one in push-in-cells placed at the soil-wall contact, at different depths. This is equivalent to consider that the effective friction angle is null at the soil-wall contact in the long term, if we consider the expressions of the active and passive coefficients, taking into account the Rankine criteria, or else, that of the coefficient at rest, as per Jaky's expression.

Also systematically, the measurements showed the effect of the December 10 2011 earthquake, its gradual recovery, and then the null effect on lateral pressures of an earthquake of larger magnitude. Relatively high values for coefficient K seem likely, although measurements also exist with spade-shaped pressure cells such as those described here; values as high as 4.4 (Tedd and Charles, 1982) have been measured in London clay.

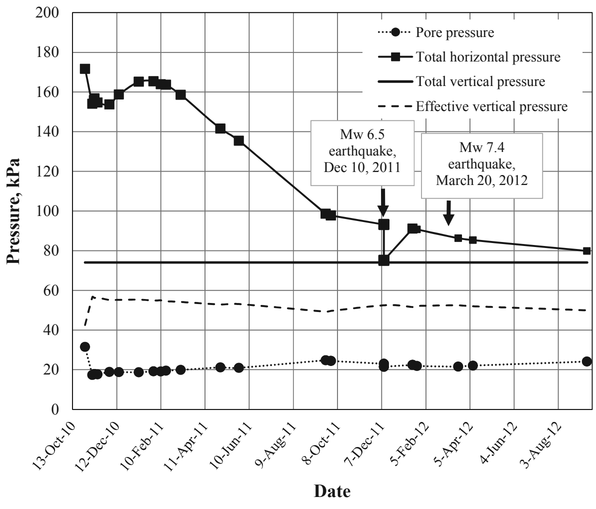

Figure 5. Evolution of total horizontal and pore water pressures. PCSG3, push-in pressure cell (N wall, 9.1 m depth below ground level).

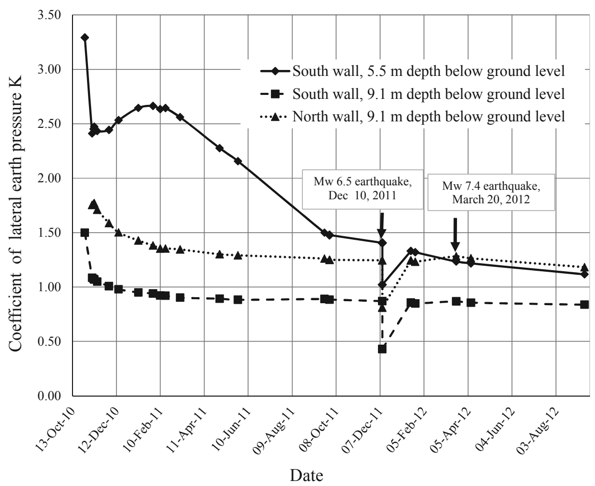

Figure 6. Time history of the effective coefficient of earth pressure.

In this comparison we are aware that our clay is normally consolidated, whereas London clay is pre-consolidated. Undoubtedly, these results are of great relevance to review assumed hypotheses at the geotechnical design stage of foundations (Martínez, 2012) consisting of structural cells.

6.2 *Regarding what was recorded with the first runs of the Metro trains*

During the first trial runs of the Metro-Line 12 trains, we had the opportunity to record dynamically the different variables that could potentially be monitored automatically. The result of these measurements is exemplified in Figure 7, with the recording of the vertical pressure increase under the footing, measured with pressure cell 1.

The great sensitivity of the measuring equipment and digital recording stands out, which allows recording vertical pressure changes with a resolution of at least 0.05 kPa. The largest recorded change reached a value of 0.6 kPa, and the average value was of the order of only 0.32 kPa. If graphically such vertical pressure increases under the footing seem significant, their real magnitude must be considered negligible when compared to acting vertical pressures under sustained load. It is thus clear that although the measuring systems record them very clearly, vertical pressure increases under the footing due to Line 12 trains runs are minimal, showing the efficiency of the foundation system, since the support work is evidently provided by the adherence-friction on the periphery of the structural cell. One arrives to those same conclusions observing the variations, upon the passing of the Metro trains, of the total lateral pressure on the walls, or the pore pressure in that same contact, results that are not included in this paper.

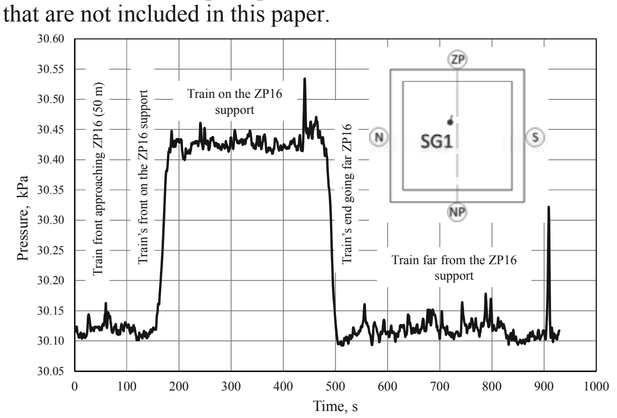

Figure 7. Changes of the total vertical pressure under the footing due to Metro train transit. Pressure Cell SG1.

7 CONCLUSIONS

The geotechnical sensors installed in this foundation have had an excellent response to date. They provide consistent readings, with well-defined tendencies over time, and will be the reason for detailed analyses for a more extensive interpretation. The geotechnical instrumentation attached or installed during construction of the foundation consists of 18 electronic sensors of SG type, connected to a digital recorder; and 3 of the VW type, for monitoring with portable read-out box. The accelerometers embedded in the footing will provide the time series of the accelerations suffered by the foundation during seismic events, and will activate the recording system of the geotechnical sensors, following a master-slave arrangement.

At this first monitoring stage of the foundation we can point out that vertical pressures under the footing clearly suffered the increase due to the placement and weight of the footing-column unit, gravitating on the temporary slab at the bottom of the excavation. Then, a pressure decrease is appreciated later, which is interpreted as a transference process of that load toward the perimeter walls that begin to work as a set by adherence-friction with the surrounding soil. It seems that in the structural cell's behavior, an integral mechanism with the soil central core predominates, the core moving as a whole together with the structural cell; an example of this is that pore water pressure measured at the same depth inside and outside the walls is practically the same.

On the other hand, the push-in-cells installed at the contact of the outside walls indicate surprisingly high lateral pressures, at least soon after being installed. Total horizontal pressures reach values higher than total vertical pressures, although after two years, they diminish and reach finally an almost constant value. These high lateral pressures are clearly beneficial for the foundation's overall behavior against lateral actions and a rotating tendency imposed by seismic rocking moments.

We point out the high values obtained for the coefficient K, in terms of effective stresses, which was established based on direct measurements of both total lateral stresses and pore water pressures. Initial K values of up to 3.4 are reached. Nonetheless, in a time period of almost two years after the walls were built, the K value at three points of measurement coincides asymptotically with an almost unitary constant value.

A first earthquake of low intensity on the foundation caused a sudden, reduced and transitory horizontal pressure decrease on the walls, but a rapid recovery of the tendency shown with sustained loads was observed.

The Metro Line 12 trains runs impose no significant changes in vertical pressure under the footing, nor on lateral pressures or pore water pressures on the sides of the perimeter walls.

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