Sao Paulo Metro System – Sacoma Station: A Case History

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ABSTRACT: Megacities demand more and more mass transportation services in order to keep the balance between both growing in size and efficiency. The need of transport infrastructure within increasingly restrained spaces and difficult geotechnical conditions pose a challenge to engineers. This paper presents a typical case of a metro station built under difficult geological conditions in a tight space of a megacity: the design and construction of Sacoma Station in Sao Paulo, Brazil. Local conditions, design requirements, engineering decisions and field performance are discussed next.

KEYWORDS: Megacities, mass transportation, underground stations, numerical modeling, ground anchors, water level control, damage prediction, performance prediction, field performance.

1. INTRODUCTION

An attempt is made to present here a case history of design and construction of an underground metro station with difficult geology in a very restrained space, which are typical conditions found in megacities. Firstly, some information about the city of Sao Paulo is presented.

The capital of Sao Paulo State is the largest and economically most important city of South America, with roughly 10 million residents within city limits and 20 million residents within its metropolitan region. The city's GPD in the year of 2005 was US$ 156 billion, larger than 22 U.S. states and nearly the same as of nations like Israel and Chile.

Figure 1 show the location of Sao Paulo City inside Brazil, while Figure 2 shows an aerial view of the city.

Figure 1. Location of Sao Paulo City.

Figure 2. Aerial view of downtown Sao Paulo.

Founded in 1554 by European Jesuit missionaries, after the end of the XIX century the city sprawled over a large area of the southeastern Brazilian continental plateau, and experienced a development model that favored cars rather than public transportation. As a result, Sao Paulo suffers with congested traffic and insufficient public transportation services.

Sao Paulo Metro system construction began in the 70's, as an attempt to shift this model to a more contemporary and efficient concept. Sao Paulo Metro net is still small (61 km) compared to the size and needs of the city, and is under constant expansion. Figure 3 shows the present configuration of Sao Paulo Metro net.

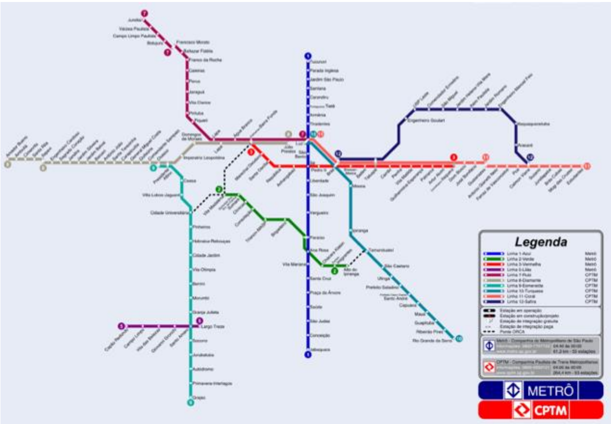

Figure 3. Sao Paulo Metro net.

Recent expansion works include Sacoma cut and cover underground Station, which is part of Line 2 (Green Line). It is expected to be fully operational in 2010 and has an expected demand of 96,000 passengers per day. The station is connected with Tiradentes Express Bus, a light rapid transit system, and is one of the largest metro stations in town.

2. GEOLOGICAL/GEOTHECNICAL CONDITIONS

Sao Paulo rests over a Tertiary sedimentary soil basin know as Taubate Group. At station's site Taubate Group is represented by Resende Formation, composed mainly by a very hard overconsolidated grey clay (overconsolidation pressures in excess of 1 MPa), know locally as "taguá". As usual with this kind of soil formation, "taguá" is sometimes heavily fissured, although this was not a present feature at Station's site. Also part of Resende Formation are isolated lenses of compact sand.

On top of the Tertiary formation there is a 10 m thick Alluvial deposit laid by the nearby Tamanduateí river. The Alluvial deposit comprises very soft and nearly normally consolidated organic silty clays as well as very loose clayey sands, arranged randomly in the form of layers and lenses in which the organic clays are the majority. As a result, water level is located near surface, in the range of 1 to 2 m deep, these few meters composed of a soft clayey fill laid without engineering control. Figure 4 shows the typical subsoil profile of the station's site.

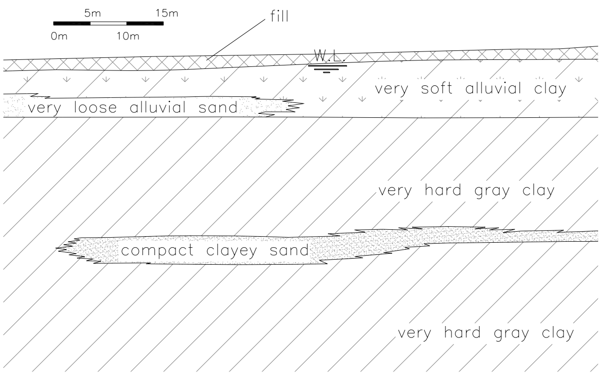

Figure 4. Typical subsoil profile at Sacoma Station.

Geotechnical investigations had to be planned and carried out under budget and availability limitations, so investigations had to be optimized in the best possible way.

Field investigations included around 650 m of standard penetration tests, 33 in situ permeability test soundings, 14 vane tests, 40 m of piezocone penetration tests and 22 m of flat dilatometer tests. Results from several CamKometer tests carried in the same soil formations at a nearby location were also made available.

Disturbed samples were taken from the Station's site in order to determinate water content profile, particle size distribution and Aterrberg limits. Results from triaxial tests in block samples from a nearby location with the same soil formations were also made available.

For each soil type, important design parameters such as in situ stress state, shear strength and soil stiffness were correlated with SPT blow count values so that spatial distribution of these features could be well established. This procedure compensated the fairly few number of special investigations available and later proved to yield good results, when measurements and predictions were compared. This, combined with the amount of available SPT tests, allowed for the compartmentalization of the station excavation support walls in segments of uniform subsoil profiles and engineering properties.

3. LOCAL CONDITIONS

Sacoma's neighbourhood is densely occupied with buildings with commercial, residential, religious and educational uses. Most buildings in the area are low height concrete frame structures with driven wood or concrete pile foundations, with up to five floors. There are also ordinary small houses and warehouses built upon footings, resting on the Alluvial organic clay. Local streets carry a heavy traffic flow between downtown and other cities of the metropolitan region. Under these streets there is an array of underground utilities that include water mains, sewer system, communications and electric power ducts.

The shallow train tracks position favored the choice for an open cut to build the station, rather than a bored tunnel station option. Dense urban occupation meant that only a tight space was available between neighbouring buildings, which included a five stories Postal Service concrete frame building and even an architectural heritage building close to the station.

Figures 5 and 6 show pictures of the neighbourhood prior to the beginning of works.

Figure 5. Station's vicinity before excavation.


Figure 6. A different angle of station's vicinity before excavation.

4. STATION DESIGN

The station layout comprises a main pit with a 140 m x 20 m footprint and depths in the range of 19 m to 24 m, and two auxiliary pits for access (North and South) with 10 m depth each.

Tight space, saturated organic clays, sensitive buildings and utilities meant that a very stringent control of ground water level, settlements and horizontal displacements was required.

The station runs loosely aligned with Greenfeld Street (Figure 7). As mentioned before, some surrounding streets carry heavy traffic flow, as in the case of Bom Pastor Street, also shown in Figure 7. Therefore one of the first design requirements was to reestablish traffic as soon as possible at Bom Pastor Street. In order to achieve this requirement, a 20 m x 20 m area of the main pit below Bom Pastor Street was excavated using top-down method, as opposed with bottom-up method used for the rest of the station.

Figure 7. Aerial view of Sacoma Station's vicinity before beginning of works. Station lies along Greenfeld Street between Bom Pastor and Agostinho Gomes Streets.

Other requirement imposed by Sao Paulo Metro Company was a very tight schedule of 30 months for station completion. Also, the Metro Company demanded the station to be waterproof, which implied that a temporary excavation support would be desirable, allowing a later convenient installation of a waterproofing system before construction of permanent structures. A full description of the station's waterproofing system is presented by Negro et al (2009).

Finally, any ground anchors used were to be temporary and should be deactivated after work completion, to avoid future interferences with neighbours basements and possible risk of accidents.

The Station's design consisted of different disciplines, including but not limited to:

- Temporary Excavation Support.
- Relocation of Interferences.
- Geotechnical Monitoring.
- Waterproofing.
- Final Structure.
- Architecture.
- Systems (water, sewer, ventilation, security, communication, electric power, etc.)

This paper focus the geotechnical aspects of Sacoma Station's design. Hereafter the main features of Sacoma Station design, namely the Excavation Support Design is addressed.

The calculation was carried using numerical analysis (2D Finite Element Method). Soils were modeled by means of linear elastic-plastic model with non associated Mohr-Coulomb criterium. The effect of excavation on pore pressures was taken into account using only steady state flow analyses after each excavation phase (the undrained pore water pressure was always neglected). Numerical analysis was implemented using software Plaxis V8. Although using a simplified constitutive model, care was taken when treating and selecting parameters from data gathered from geotechnical investigations. The comparison between predicted and measured field performance proved that even simplified models can yield sensible results, when the input data is previously selected with engineering judgment and adequate reasoning.

For example, in situ stress ratios of the Tertiary clay provided by flat dilatometer tests were in the range of 1.0 to 4.0. K_0 values had a significant impact on the bending moment acting on the retaining wall. From previous experience with the same soil formation, design team adopted a value of 2.0 as the expected average value for K_0. The effect of discrepancies between the expected/adopted value and the real in situ stress ratio was studied carrying out parametric analyses with K_0 values ranging from 1.0 to 4.0. It was seen that for K_0 values higher than those adopted by design, the bore piles would suffer a plastic hinge at a specific position, but system would remain stable, besides some increased horizontal displacement and increased settlement. Moreover, horizontal displacements of the wall were correlated with K_0 value of the Tertiary clay, making feasible the use observational method in an open cut. Horizontal displacements of the wall measured using total station readings later proved the adopted K_0 value of 2.0 to be correct.

The support system had to deal with materials of highly contrasting stiffness, namely the very soft organic Aluviall clay and the very hard Tertiary clay. As a result, engineer solutions and equipments were to be equally feasible and applicable in both types of soil, while avoiding water and soil loss from the retaining wall. The solution selected was to build the main excavation support using 1.2 m diameter bored piles spaced at 1.5 m between axis. The pile borings were cased throughout the Alluvial layer and additional stabilization was provided by means of bentonite slurry. CCP (jet grouting) columns were used between concrete piles to reduce soil drainage during excavation. As a result of the Tertiary clay composition, structure and due to its high overconsolidation ratio, its average permeability is as low as 10^{-7} cm/s, and thus the CCP columns had to penetrate only 1 to 2 meters in the Tertiary clay layer. A cross section of the combined CCP-bored piles support system is show in Figure 8.

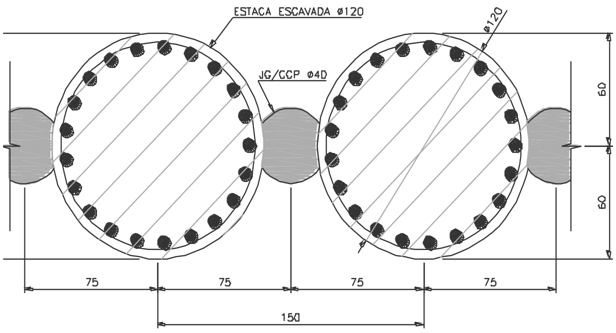

Figure 8. Main excavation support cross section.

The support system included temporary ground anchors with working loads ranging from 300 kN to 1,000 kN. It also included a secondary smoothening wall of cast in place concrete applied against the bored piles just after each excavation phase.

After excavation completion, ground anchors were to be successively deactivated, lower rows first, while final structure construction was made in stages from bottom to top. Also at this stage, waterproofing was applied between temporary support and final structure. During design development it was found that keeping the last lower row of ground anchors activated would benefit control of horizontal displacements and limit bending moments on the bored piles, and a special allowance was granted from Metro Company in order to left those anchors activated.

In order to control water and soil loss, design specifications asked for a drainage preventing valve during drilling of ground anchors. Preventing valves have been widely used in the control of grouting loss during CCP execution in horizontal position.

The ancillary pits were designed in a similar fashion. Support was provided by means of 40 cm diameter secant bored piles, spaced at 38 cm between axis. Working loads for ground anchors ranged from 300 kN to 600 kN. Figure 9 shows the support cross section for the North and South Access Pits.

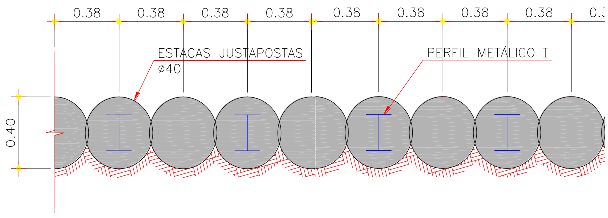

Figure 9. Ancillary pits excavation support cross section.

Building damage due to displacements induce by excavation was predicted using the criterion proposed by Boscardin e Cording (1989). Major damage was predicted only for a neighbouring warehouse, a prediction proved correct later, during the course of works. Figure 10 shows an aerial view of Sacoma Station work site just after reestablishing of traffic at Bom Pastor Street. Figure 11 shows excavation in progress in the Main and South Access.

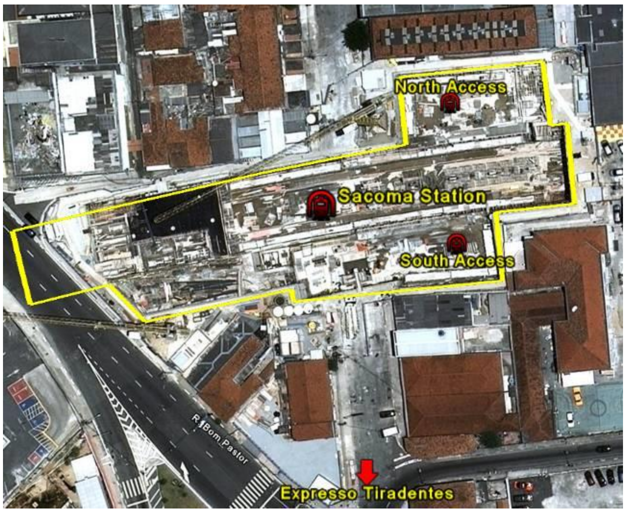

Figure 10. Aerial view of station's work site.

Figure 11. South access pit on the left and main excavation of station.

Finally, Figure 12 shows details of the top-down excavation in progress below Bom Pastor Street, after reestablishing of traffic. One can notice the roof covering supported by temporary columns (1.2 m diameter bored piles), the excavation support with partially completed smoothening wall and the western tunnel portal.

Figure 12. Top-down excavation below Bom Pastor Street.

4. FIELD PERFORMANCE

Geotechnical monitoring was provided by means of settlement points, deep settlement points, convergence points, inclinometers, water level indicators, load cells, piezometers, strain gauges, total stations and tiltmeters.

Monitoring proved essential to assess support performance. Field performance assessment and comparison between measured and predicted displacements pictured a good overall field performance. Figure 13 shows predicted and measured horizontal displacements of the main supporting wall. Measures of horizontal displacements were taken from convergence points, while predicted ones result from numerical analysis. Note that all predicted values shown refer to type A predictions according to Lambe (1973), performed before construction.

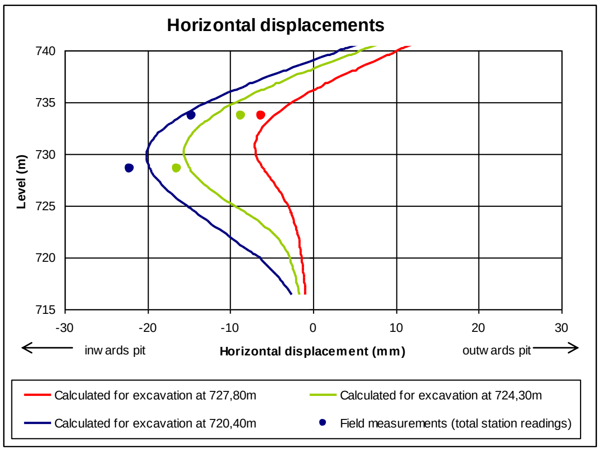

Figure 13. Measured and predicted horizontal displacements of Main Pit support wall.

Figure 14 shows where the measured horizontal displacements lay among available data gathered by Long (2001). Long reviewed past work and established an updated database for ground movements associated with deep excavations involving 269 case records with strutted, tie-back anchored, or top-down supported walls, and 27 cases of cantilever walls. It can be seen that the displacements measured at Sacoma Station agrees with other similar observations made around the world. Figure 14 also shows the line proposed by Clough & O'Rourke (1990), which relates system stiffness and ground movement for walls with bottom heave safety factor greater than 3.0.

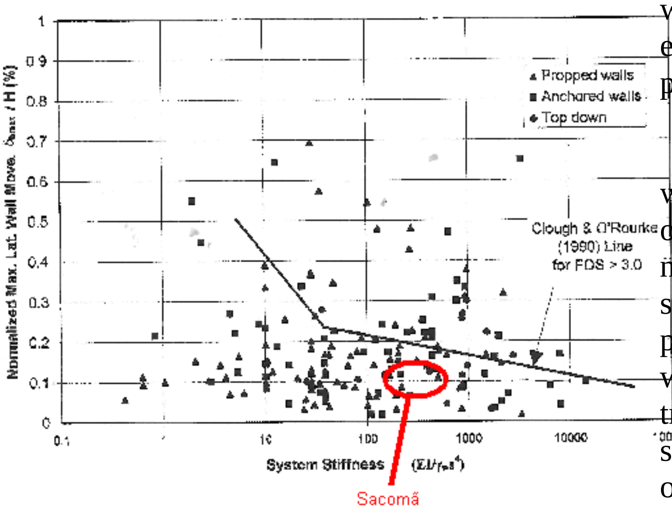

Figure 14. Measured horizontal displacements at Sacoma Station and Long (2001) database.

Figure 15 shows the typical results of settlement measured at settlement points installed at neighbouring buildings columns. It can be seen that settlements are low, in the same range of the predicted ones.

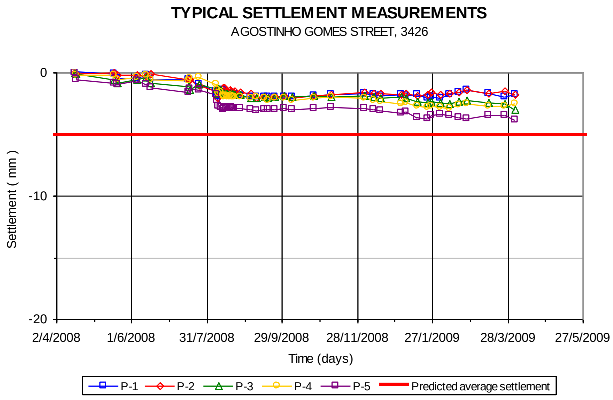

Figure 15. Typical settlement measurement results.

One of the main difficulties found was to balance conflicting objectives of the parts involved in the project: the Metro Company had a tight schedule, so contractor made its best efforts to increase its rate of production, which in turn may conflict sometimes with everyone's objective of achieving adequate performance of the support system.

One typical case of conflicting objectives was seen during ground anchor's drilling. On one hand the drainage preventing valve was not available by the ground anchors subcontractor, and on the other hand very high production rates were achieved when drilling with water injection at pressures far too high trough very soft clays. As a consequence, some parts of the wall experienced heavy loss of soil and water during drilling of ground anchors, especially around North Access Pit. Major damage and interdiction was reported on a neighbouring warehouse, although major damage was already predicted for this structure during damage analysis. This was the only interdiction made during excavation works. Minor damages were reported on other surrounding buildings, and in most cases they were also related to ground anchors' drilling. Figure 16 shows measured settlements of the interdicted warehouse, clearly showing the deleterious effect of drilling with such high pressures throughout very soft clays. Compare it with settlements shown in Figure 15.

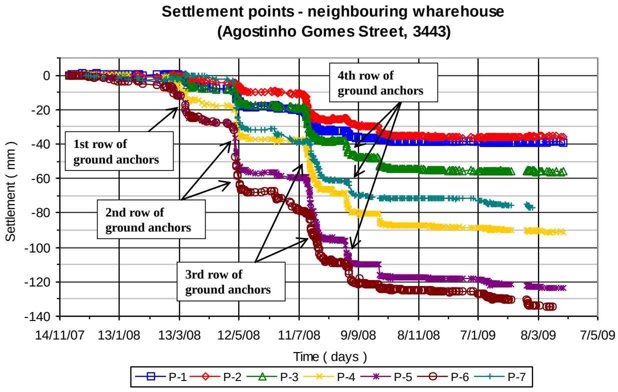

Figure 16. Effect of drilling with high pressure injection water throughout soft clay on a neighbour warehouse.

An attempt to control water losses through anchor's heads was made by means of sealing it with polyurethane expansive foam. The solution gave fair results, not eliminating but reducing water losses to a great extent. Figure 17 shows a ground anchor head just after application of the expansive foam.

Figure 17. Ground anchor head treated with polyurethane expansive foam.

Total elimination of water loss was not possible because water was able to found different flow paths not previously predicted by design team. Some water loss was reported coming from behind the retaining wall, as shown schematically in Figure 18. Figure 19 show a major water loss (later treated with expansive foam), probably due a flow path as the ones shown in Figure 18, and Figure 20 show some small seepage that continued through ground anchor's heads even after treatment with the expansive foam.

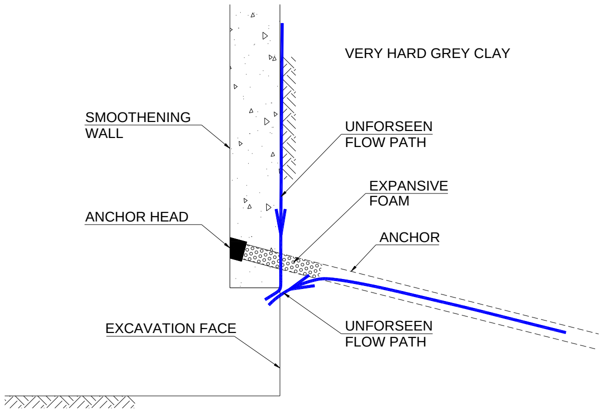

Figure 18. Unpredicted flow paths behind the retaining wall.


Figure 19. Major water loss due to an unpredicted flow path.


Figure 20. Seepage through ground anchor's heads.

Ground water lowering was also worsened by gross defects on the secant bored piles: concrete faults and verticality problems contributed to poor sealing performance of the support system at the ancillary pits. Figure 21 shows a void in the concrete of the bored secant piles.

Figure 21. Example of concrete fault in the bored secant piles.

Ground water lowering was confirmed by water level indicators readings, as shown in Figure 22. Besides ground water lowering that did occur, no major damages were recorded on the station's vicinity, in part because most of the buildings have pile foundations, in part because the soft soil was found to be slightly preconsolidated.

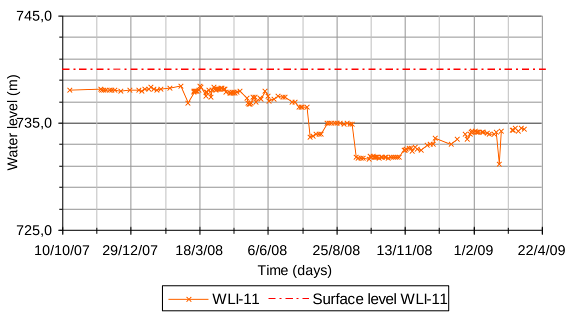

Figure 22. Water level lowering registered.

Another issue that had to be dealt with was the unknown location of neighbouring buildings' piles foundations, which were not made available by buildings' owners. As a consequence, piles' location was gathered as the drilling services proceeded, and a 3D drawing model was used in order to correct the position of the lower rows of anchors.

Losses of working load by friction along the "free anchor length" were above allowable limits given by Brazilian standards. Different attempts to correct this problem were made by the ground anchor subcontractor, without much success. Besides the losses recorded, no measurable negative effect on the support system was detected. Moreover, in the few months scale while the ground anchors were active, no significant load loss was recorded by the load cells.

5. CONCLUSIONS

Sacoma open cut station presents a typical case of the challenges found by geotechnical engineers in megacities. The value of basic design practices like careful selection of parameters, adequate understanding of important features of the support wall system and … ARSENIO, ESTÃO ME EXPULSANDO. PEÇO A GENTILEZA DE COMPLETAR QUE AMANHÃ EU TERMINO E MANDO. PLEASE MAKE IT QUICK...