Root Piles Installed Through Heterogeneous Technogenic Layer Followed by a Residual Soil

Daniel Kina Murakami
Universidade de São Paulo, São Paulo, Brazil, daniel.murakami@gmail.com

Mario Sáez
Sáez Fundações; São Paulo; Brazil; marioantoniosaez@gmail.com

Fabian Corgnier
Teknier Engenharia; São Paulo; Brazil fabian@teknier.com.br

Sergio Ludemann
Ludemann Engenharia; São Paulo; Brazil; sergio@ludemann.com.br

Alexandre Rocha
Tecnijet Engenharia; São Paulo; Brazil; alexandre@tecnijet.com.br

ABSTRACT: The project site is an expansion of ETA Guaraú. The soil profile indicated a heterogeneous technogenic layer of different materials about 30.0 m depth, followed by residual soil. Therefore, the project required root piles with constant cross-sections embedded in the residual soil (36.0 m to 42.0 m depth). The first six test piles allowed the improvement of the drilling equipment, designed to work with compressed air and water simultaneously, overcoming obstacles such as bushing, rubble, and gravel, among others, which conceded the application of air strokes after filling the shaft. The depth of the piles was monitored by torque reading on the drilling rigs in constant advance. Besides, variations in the shaft friction distribution and cross-section along the shaft (mortar over-break rate) were observed due to the soil heterogeneity. Further, the collected signals from the integrity and dynamic tests were atypical and difficult to interpret, constituting an additional challenge due to the project's complexity, and each tested pile had its own identity. Moreover, the dynamic and instrumented static load tests showed higher shaft friction in the landfill, lower in the residual soil, and reduced load at the pile toe. Furthermore, the tests provided quality assurance of the deep foundations.

KEYWORDS: Root Pile, Methodology, Heterogeneous Technogenic Layer, Pile Integrity Test, Dynamic Load Test, Instrumented Static Load Test.

1 Introduction

Sabesp (Waste and Water Management Company of the State of São Paulo) selected an adjacent area to the Guaraú Water Treatment Plant, in the northern area of São Paulo county, for the implementation of Sludge Tanks as part of the Cantareira System expansion project.

The Standard Penetration Tests (SPT) of the project site detected a heterogeneous technogenic layer consisting of a mixture of materials (bushing, rubble and gravel, among others), forming a layer with a thickness ranging from 25.0 to 30.0 m, which needed to be transposed to embed the deep foundations into the competent underlying residual soil horizon.

The project foresaw root piles with constant diameter along the pile shaft without reducing the diameter along the pile installation, which required the development of a specific cutting tool and an appropriate construction method for this project site.

2 Geotechnical Description of the Soil

For the initial soil investigation, three SPT boreholes were conducted, which encountered an impenetrable material within the landfill layer without reaching the underlying bedrock. A subsequent mixed (percussion and rotary) borehole campaign was carried out to determine the thickness of the heterogeneous technogenic layer, the thickness and type of impenetrable materials within the waste, and the condition of the soil/rock foundation to support the pile toe. These mixed boreholes revealed a landfill layer with a thickness of approximately 30.0 m. This layer consists of debris, rock blocks, woods, and other organic remains. The impenetrable layers encountered during percussion boreholes, composed of rock fragments and, in some cases, debris, had thicknesses of up to 5.0 m. Beneath the landfill layer, residual soil from the crystalline basement of the region was identified.

According to the boreholes, the basement consists of granite, gneiss, and mylonite with variable recovery levels, indicating heterogeneity in lithology, fracturing, and alteration conditions. The SPT tests showed that the resistance of residual soils started from 10 blows, increasing in depth until reaching the bedrock, which starts from 40 m below the surface. The groundwater table level was not detected in boreholes. It is worth noting that this project was located adjacent to the Taxaquara Geological Failure, as indicated by the geological map provided by DERSA - Road Development SA. Saez et al. (2020) provide more details regarding the soil conditions.

3 Deep Foundations in Root Piles

Based on the soil conditions, only a few foundation solutions were feasible. For this project, the solution adopted was root piles with a diameter of 0.31 m for loads up to 800 kN and a diameter of 0.41 m for loads up to 1,300 kN. These piles can penetrate rocky materials and debris within the landfill mass. However, the heterogeneous mass with centimeter to metric-sized rock fragments, debris or both would pose a risk of damage and equipment loss when using conventional drilling equipment such as Down the Hole hammers (DTH). Additionally, telescoping of the pile shaft (reducing the diameter) would be necessary for each passage through rock blocks, making it technically unsuitable. Therefore, special eccentric hammers of the ODEX type were recommended at that time.

The Davi Cabral method (1986) was adopted to estimate the bearing capacity of these piles. The project included the necessary pile lengths for each reference borehole, avoiding reaching the bedrock to ensure uniform load-settlement behavior of the foundation elements.

4. Executive Methodology

4.1 Development of the Cutting Tool

Conventional tricones and carbide shoes were used for the soil sections at each pile's beginning and end.

Due to the heterogeneity of the landfill (spoil area), and to avoid telescoping, the tool to be used should operate as a cutting and drilling tool with simultaneous water and compressed air. Thus, this tool was initially designed as a set consisting of an internal-mounted DTH hammer coupled with a cutting shoe (see Figures 1 and 2). This set was designed to maintain a maximum vertical impact stroke of 40 mm, similar to the standard bottom hammer (DTH - Down the Hole). The set had peripheral air outlets (similar to the DTH hammer) to prevent the mortar's choking during the piles' injection.

Figure 1. DTH hammer coupled with a cutting shoe (Saez et al., 2020)

Figure 2. Last cutting tool used to install the root piles (Saez et al., 2020)

4.2. Construction Method of the Piles

The following construction method was adopted, allowing the installation of the piles without telescoping, as established in the project conception:

- Start drilling using a carbide shoe until reaching the impenetrable layer.
- Replace the carbide shoe for the hammer + bit assembly (DTH hammer) and restart the drilling to the desired depth. Use torque reading as a criterion to stop drilling.
- Flush the borehole with clean water and compressed air to ensure the removal of rock fragments at the bottom of the hole. Repeat the procedure until translucent water is observed at the top of the borehole.
- Perform another flushing of the borehole using a 2 ½" PVC composition to ensure the removal of fines.
- Remove 01 tube (L=1.50 m) from the composition.
- Start mortar injection (30 bags of cement).
- Apply a compressed air blow (3.0 kgf/cm²).
- Begin tube extraction, simultaneously completing the mortar column up to the top of the borehole.
- Apply a new compressed air blow at the middle depth of the pile.
- Completely remove the tubes, completing the mortar column up to the top of the borehole, concluding the pile.

4.3 Quality Control

The initial phase of the test piles clearly showed the difficulties in removing the pipe composition + shoe after the first blow of compressed air during the mortar injection ("soil plug"), as well as the lack of fluidity of the mortar visually detected in the final phase of injection after the prolonged time of pipe removal, due to the special length of the piles, ranging from 30.0 m to 40.0 m.

A revision of the mortar mix was requested as the lack of fluidity could lead to an early setting. The design of the tool (shoe) was reviewed, introducing air outlets and lateral bits to minimize the possibility of soil plugs.

The construction method was optimized with the new cutting tool and the new mortar mix, with improved fluidity, and the first blow of compressed air was applied after removing at least 01 casing pipe segment. Pipes 1.50 m long were used instead of the conventional 1.00 m length to reduce the number of joints and maneuvers when removing casing pipes. The second blow of compressed air was applied at the mid-length of the pile, still within the landfill layer.

The compressed air blows were applied with a pressure of 3.0 kgf/cm². Manometers were used in visible locations on the drilling rigs to allow the photographic recording and executive control of the applied pressures. Most of these blows exceeded the specified value due to the difficulty of accurately controlling the output register in the compressors.

In an initial testing phase, a methodology was developed to halt the drilling after reaching the stratum that achieved the specified load-bearing capacity in the design of the deep foundations. It was observed that with the constant drilling progress, after penetrating the landfill layer and reaching the layer of residual soil or altered rock, a torque was reached that resulted in a pressure above 160 bars in the hydraulic pump of the drilling rigs in Reservoir 1 and 120 bars in Reservoir 2, significantly different from the pressures encountered in the heterogeneous technogenic layer, which ranged between 40 and 80 bars. The capacity of these test piles was determined through dynamic load tests (PDA).

After the test piles were installed with good results of the PDA testing, the work began with the execution of the permanent piles on the north and south faces of the project as a strategy to observe the response of the ground to the injected volumes. It was initially observed that in the NE face, the absorption of mortar was at least 100% higher compared to the south face. The grout absorption graph can be found in Saez et al. (2020).

During the pile installation, adverse situations occurred, such as:

- Loss of casing pipes + cutting shoes due to the soil plug.
- Loss of drill holes in the final phase after detecting misalignment above 1%.
- Loss of casing pipes due to wear on the joint threads.

The cutting tool was further optimized by modifying the position of the tungsten bits (cutting) and the compressed air outlets, thus reducing soil plug incidents.
An impact damping system was introduced, with a stroke of 40.0 mm, similar to the stroke of the DTH hammers used in conventional piles. When the stroke of the shoe exceeded these 40.0 mm, the tool was sent for regrinding.

In the final phase of pile execution, with 95% of the piles completed, the significant volume of mortar over-break in the NE face was confirmed. The graph of the mortar over-break can be found in Saez et al. (2020). At this stage of the work, significant fatigue was observed in the cutting tools and equipment in general, including the drilling rigs.

Artesian well during the drilling phase (Figure 3) and total water loss during the flushing phase were observed at this location. This problem was solved injecting a less dry mortar into the borehole and restart the pile injection at least 6,0 hours later.

Figure 3. Artesian well during the drilling phase

5 Integrity tests, Dynamic and Static Loading Tests on Piles

The data collected from integrity and dynamic tests proved to be atypical and difficult to interpret, which was an additional challenge due to the project's complexity. No typical signal representative of the project piles was observed, indicating that each tested pile had its own "identity," meaning its unique variation in cross-section along the depth and its individual distribution of shaft friction. The dynamic and instrumented static load tests showed agreement: higher shaft friction in the landfill region, lower friction mobilized in the residual soil, and lower load mobilized at the pile toe.

Figure 4a shows the graph of all SLTs and the result of the CAPWAP analysis for pile ET-07 TQ2. Figure 4b indicates the results obtained from the strain gauges installed in the pile ET-07 TQ2 for each load increment of the SLT, ranging from 153 kN to 1280 kN. A total of 6 strain gauges (S1 to S6) were installed at different depths. The following depths indicate where they were installed: S1: 1.0 m; S2: 6.7 m; S3: 12.4 m; S4: 18.2 m; S5: 23.9 m; S6: 29.5 m.

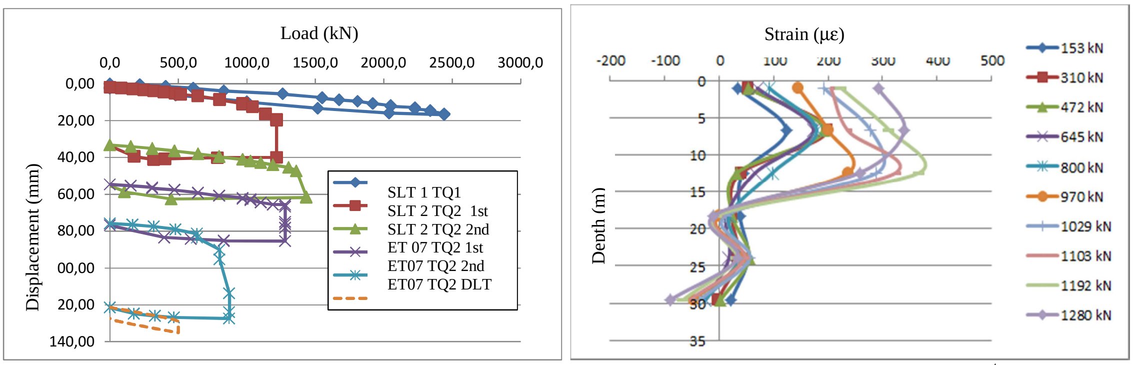

Figure 4. a) SLTs and DLT result of the pile ET07 TQ2; b) strain vs. depth of the 1st SLT in the pile ET07 TQ2

It can be observed in Figure 4b that the strain gauges indicated greater deformation in the landfill region (depth up to 30.0 m), with higher shaft friction between 12.4 m and 18.2 m, due to the greater difference in deformations between strain gauges S3 and S4. The result of this instrumented load test was essential for understanding the behavior of the piles subjected to axial loads and served as a basis for applying the Signal-Matching Method in the Dynamic Load Test (CAPWAP analysis).

In the CAPWAP analyses, the Signal-Matching technique proposed by Murakami (2015, 2018) was employed, aiming to model the soil-pile system in a way that presents higher shaft friction in the landfill region. A plug-on shaft (soil mass adhered to the pile shaft) with greater intensity was required at specific depths to apply the technique. Otherwise, the analyses would indicate a higher value of shaft friction in the first meters, diverging from the result of the instrumented static load test.

In SLT2-TQ2, there was an increase in the maximum load reached from 1,217 kN (1st test) to 1,435 kN (2nd test). In ET-07 TQ2, there was a decrease in the maximum load from 1,280 kN (1st test) to 872 kN (2nd test), with greater displacements from 30.72 mm to 52.67 mm. Subsequently, an Integrity and Dynamic Test was performed on this pile. The Dynamic Test showed a mobilized load of 500 kN and impedance reductions along the shaft, indicating structural damage. In pile ET-07, the pile set increased considerably (6 mm) for a drop height of 40 cm, while in the other tests, the pile sets ranged from zero to 2 mm, with drop heights between 40 cm and 160 cm. The structural damage identified in CAPWAP would explain the reduction in the load-bearing capacity of pile ET-07 TQ2. Furthermore, the second result of the SLT in the pile ET-07 TQ2 (reduced load capacity and structural damage) was an isolated case and not representative of the entire project since the other results from Dynamic, Static, and Integrity Tests did not indicate a similar outcome.

The tables with the Dynamic Loading Tests (DLT) results obtained for Tank 1 and 2 can be found in Murakami et al. (2020). Higher values of shaft friction and reduced load at the pile toe are noticeable. Despite the atypical and difficult-to-interpret collected signals, the Match Quality values were good, ranging from 0.49 to 3.28, with an average of 1.69. Except for pile ET-07 in Tank 2, which had a Match Quality of 5.33.

Figure 5 demonstrates agreement regarding the integrity of pile E09 in Tank 2. The Integrity Test indicates a pulse in the same direction as the initial pulse near 4.0 m, indicating an impedance reduction in this region. In contrast, this reduction extends to approximately 18.0 m in the Dynamic Test.

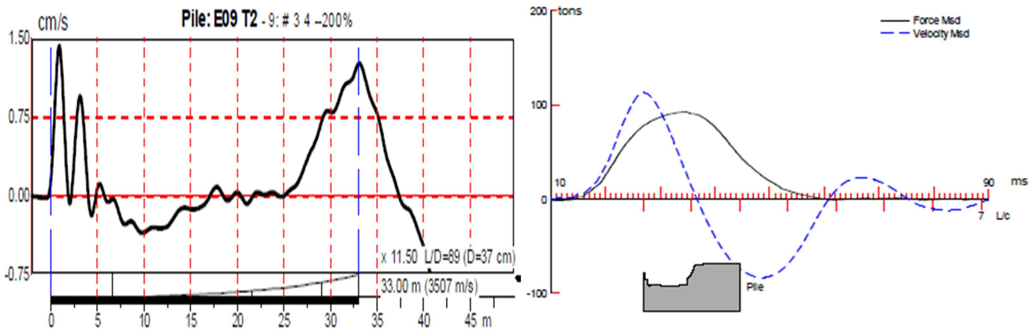

Figure 5. Impedance reduction on Pile E09 TQ2 a) PIT testing; b) CAPWAP

Figure 6 illustrates the signals from pile ET-07 in Tank 2 after the second Load Test. It should be noted that the Integrity Test and the Dynamic Test were conducted on the pile cap where the Static Load Test (SLT) was performed, which had a larger cross-sectional area than the pile. There was insufficient time to remove the pile cap and install a follower on the pile with the same cross-sectional area. Nonetheless, the tests showed agreement with the previously conducted SLT.

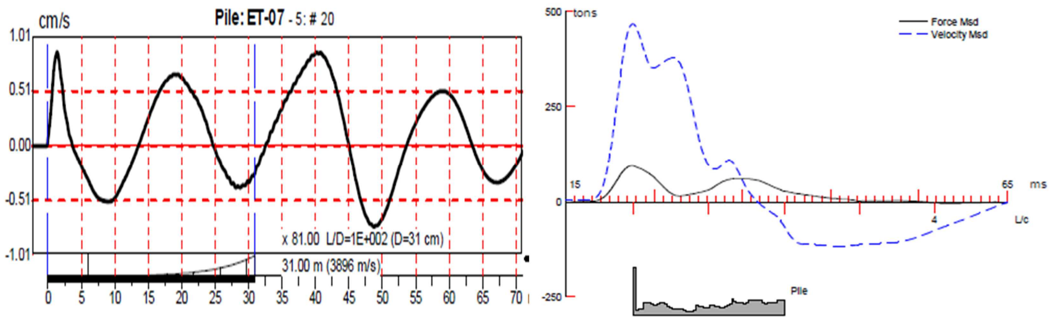

Figure 6. Pile ET07 a) PIT Testing; b) CAPWAP

It is worth noting that in the piles tested using the Integrity Test, the L/D ratio (pile length over its diameter) was approximately 90. This value exceeds the recommended range for optimal PIT performance (L/D between 30 and 50). Under these conditions, the piles' length exceeds the integrity test's sensitivity limit. However, the comparison between the Integrity, Dynamic, and Static Tests helped us understand the behavior of the piles. It provided a better understanding of the signals collected from the PIT, despite the L/D ratio being approximately 90. More details of the Integrity Tests, Static and Dynamic Load Tests can be found in Murakami et al. (2020).

6 ETA Guaraú nowadays

Figure 7 shows the project site at the beginning of the installation of the root piles. Figure 8 shows that the piles were successfully installed through the technogenic layer, reaching the residual soil where the toe of the piles was embedded, being able to support the design load of the Sludge Tanks.


Figure 7. Project site at the beginning of the installation of the root piles


Figure 8. ETA Guaraú nowadays

6 Conclusions

This project proved to be challenging both during the pile installation and interpretation of the conducted tests. The pile installation's quality control allowed ensuring the foundations' performance and improving the understanding of their behavior.

The drilling technique developed, using a mixed tool of compressed air and water, followed by a tungsten carbide crown until the end of drilling in the residual soil, proved to be suitable, allowing the maintenance of a constant diameter of the pile shaft as specified in the design. It was possible to drill through the heterogeneous technogenic layer with a thickness of up to 30 meters.

The signals collected from the integrity and dynamic tests were atypical and difficult to interpret, indicating an additional challenge due to the complexity of the foundation work. No typical signal representative of the piles in the project was observed, indicating that each tested pile had its own "identity," meaning its own variation in cross-section along the depth and its own distribution of shaft friction. Despite these difficulties, integrity tests and dynamic tests were maintained as part of the quality control for this project site, considering the numerous incidents reported below, as these tests allowed, at least, identifying cases with severe damage, resulting in the abandonment of such piles and the execution of additional reinforcement piles.

The instrumented static load test was essential for a better understanding of the pile behavior in this project site. Increased shaft friction was observed in the landfill region, with minimal load mobilization at the pile toe. In the dynamic tests, the technique presented by Murakami (2015, 2018) was used to perform CAPWAP analyses and present results similar to those of the instrumented static load test. The "plug on shaft" technique was applied with higher intensity at specific depths to avoid overestimating the shaft friction in the first meters.

The second load test conducted on pile ET-07 revealed different behavior compared to the other piles in the project, indicating a lower load in the second test (872 kN). The subsequent DLT conducted after the second static load test on this pile indicated structural damage and reduced mobilized load (500 kN), which would explain the reduced load-bearing capacity in the second static test. These structural damages in the shaft of this pile prevented considering the results of these load tests for the purpose of foundation quality control.

The results of the pile tests (PDA, static load test, and integrity test) highlighted the need to increase the minimum number of tested piles to at least 10% of the total number of installed piles due to the geological and geotechnical anomalies encountered. These anomalies included complete loss of water during the flushing phase in some piles and artesian conditions encountered during the drilling of other piles. The empirical correlation between the torque of the drilling rigs with constant advance and the load-bearing capacity obtained from the PDA tests proved to be a useful tool for verifying the pile lengths during construction.

Regarding the obtained values of FS (Factor of Safety) lower than 2.0 and sometimes even lower than 1.6, a statistical distribution of the FS results was developed, obtaining the probabilities of FS being less than or equal to 1.0. The results showed probabilities of 0.7% for Tank 1 and 1.1% for Tank 2. As this concerns the base of a water reservoir rather than isolated supports of a structure, if there is a pile with lower load-bearing capacity and, therefore, higher deformability, there is a possibility of load redistribution to neighboring piles, maintaining the equilibrium of the structure. It should also be noted that the working loads were defined for the maximum possible water level in the reservoir, which implies that larger loads than those predicted are not possible. Therefore, the results were deemed acceptable, and the project proceeded, with the reservoir now in operation.

Due to the dispersion in the results of excessive mortar over-break during pile injection up to 100%, a numerical injection control tool was developed. A tendency for higher volumes in a specific region of the project was observed, likely due to a geological failure at that location. Thus, the volumes were analyzed not based on their specific values but on the trend observed in each region.

BIBLIOGRAPHIC REFERENCES

Associação Brasileira de Normas Técnicas (2007) NBR 13208. Estacas Ensaio de carregamento dinâmico. Rio de Janeiro.

Associação Brasileira de Normas Técnicas (2006) NBR 12131. Estacas – Prova de carga estática – Método de ensaio. Rio de Janeiro.

Associação Brasileira de Normas Técnicas (2019) NBR 6122. Projeto e execução de fundações. Rio de Janeiro.

ASTM D5882 (2016) Standard Test Method for Low Strain Impact Integrity Testing of Deep Foundations, West Conshohocken, PA, USA.

Cabral, D. A. (1986). O uso da estaca raiz como fundação de obras normais. VIII. Congresso Brasileiro de Mecânica dos Solos e Engenharia de Fundações. Porto Alegre-RS, Outubro, vol. 6, MS4. pp. 71-82.

FUSP (2009). Plano da Bacia do Alto Tietê. Relatório Final/ Sub- região Juquerí Cantareira.

Likins, G. E, (2015). Pile Testing – State of Art, (Keynote Lecture) Proceedings – Seminário de Engenharia de Fundações Especiais e Geotecnia: São Paulo, Brasil.

Murakami, D. K. (2015) “Novo procedimento para realização da análise CAPWAP no ensaio de carregamento dinâmico com energia crescente em estacas pré-moldadas de concreto”, dissertação de Mestrado emEngenharia Geotécnica. Escola Politécnica da Universidade de São Paulo, São Paulo.

Murakami, D. K. (2018) “A New Concept of Match Quality of Settlements for Signal Matching Analysis on the Dynamic Pile Test”, 10th International Conference on Stress Wave Theory and Testing Methods for Deep Foundations, San Diego, California, USA.

Murakami, D. K.; Corgnier, F.; Sáez, M.; Ludemann, S. M.; Rocha, A. (2020). Análise de resultados de ensaios em estacas raiz em uma região de bota fora da ETA Guaraú - Obra da Sabesp, Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica. Campinas, SP.

Pile Dynamics, Inc. (2006) CAPWAP Manual, Cleaveland, OH, USA.

Sáez, M., Murakami, D. K., Ludemann, S. M., Anraku, C. T., Rocha, A. (2020). Fundações em Estaca Raiz num Bota-Fora. Congresso Brasileiro de Mecânica dos Solos e Engenharia Geotécnica. Campinas, SP.