Construction and Design Aspects of the Aricanduva Station of Line 2 – Green from "Companhia do Metropolitano de São Paulo – METRÔ"

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Summary

The Aricanduva Station is part of the extension of Line 2 – Green from "Companhia do Metropolitano de São Paulo – Metrô", a major urban mobility initiative currently underway. Defined by technical complexity and methodological innovation, this project introduces a unique structural design in Brazil with a caterpillar-shaped cofferdam composed of six circular cells. Arch-shaped diaphragm walls, supported by arrow-shaped Y-panels, provide high resistance against soil pressure, while reinforced concrete struts ensure excavation stability. Advanced engineering is demonstrated through both the controlled demolition of the fourth-level strut for TBM passage using sand jacks and the design of the complex arch-shaped TBM-supporting base slab. Additionally, computational modelling optimizes soil-structure interactions, while BIM integration allows for precise detailing of the TBM-supporting base slab. These engineering innovations highlight Brazil's progress in large-scale infrastructure projects, particularly the advanced engineering solutions developed by São Paulo Metrô engineers and technicians to overcome the numerous challenges encountered when designing a station.

1 INTRODUCTION

The Metro Line 2 – Green expansion represents a landmark urban mobility project in São Paulo, extending over 23 kilometres to become the city's longest subway line. Incorporating eight new stations, this extension aims to reduce travel time, improve connectivity, and relieve congestion in one of the busiest metropolitan areas in Latin America. Furthermore, it will create a critical link between the Metro's Red Line 3 and CPTM's Coral Line 11, promoting greater integration across the city's public transportation network.

Urban subway expansions in densely populated cities like São Paulo often present formidable challenges. These include interference with underground utilities, the potential impact on nearby building foundations, and strict environmental constraints. Successfully addressing these challenges requires highly optimized engineering solutions that prioritize both safety and efficiency while minimizing disruptions to local communities.

This ambitious project, illustrated in Fig. 1, is a São Paulo State government initiative under the responsibility of Companhia do Metropolitano de São Paulo, with Eduardo Maggi serving as the project manager for the Metro Line 2 expansion. The construction is being carried out by a consortium formed by the construction companies Cetenco, Acciona and Agis. It showcases advanced construction methodologies that mitigate risks but also lead to cost reductions, demonstrating the potential for innovative engineering to drive efficiency in large-scale infrastructure projects. The uniqueness of the station derives not only from its innovative construction methods but also from the complexity of the local geotechnical conditions, which required specific design solutions to ensure both project feasibility and long-term structural integrity.

2 GENERAL CHARACTERISTICS AND CONSTRUCTION METHODS

Instead of the conventional open-cut method with rectangular trenches, typically supported by anchored tiebacks or steel structs, Aricanduva Station employs an innovative approach: the multiple secant circular shafts method. This design features braced excavations with curved diaphragm walls forming circular shafts and eliminates the need for tiebacks. While this approach increases surface occupation, its geometric configuration significantly enhances structural efficiency. For the first time in São Paulo's subway system, this methodology has been applied for six secant shafts.

This design, consisting of six secant circular cells with a diameter of 33 meters each, forms a caterpillar-shaped cofferdam, 148 meters long and 32 meters deep. The diaphragm walls, consisting of the primary retaining system, are arch-shaped panels which distributes lateral soil pressure circumferentially through compression. These forces are transferred to ten arrow-shaped Y-panels, which are laterally supported by reinforced concrete struts, vertically spaced 5 to 6 meters apart. The excavation incorporates three levels of structs in shallower areas and four levels in deeper sections, all extending to the base slab. A cross-sectional representation of this system is provided in Fig. 1 (right).

Fig. 1 Aricanduva Station under construction (left). Cross-sectional view of Aricanduva Station (right).

This self-equilibrating structural system offers several advantages. By eliminating the need for costly anchored tiebacks, the method reduces construction expenses. Additionally, it avoids the necessity for groundwater lowering, which can pose risks to the stability of surrounding buildings. Furthermore, avoiding this process simplifies construction, as ground investigations revealed the presence of 30 meters height equivalent groundwater at the lowest point of excavation.

The use of reinforced concrete struts enables horizontal spans of up to 23 meters between supports, a notable improvement compared to the closer spacing required for steel struts. This wider spacing facilitates unrestricted excavation, efficient equipment movement, and seamless hoisting operations. Furthermore, since most of the loads imposed on the retaining structure are transmitted as compressive forces (Fig. 2), smaller concrete sections are used, minimizing the steel consumption, environmental impact and material waste of the project.

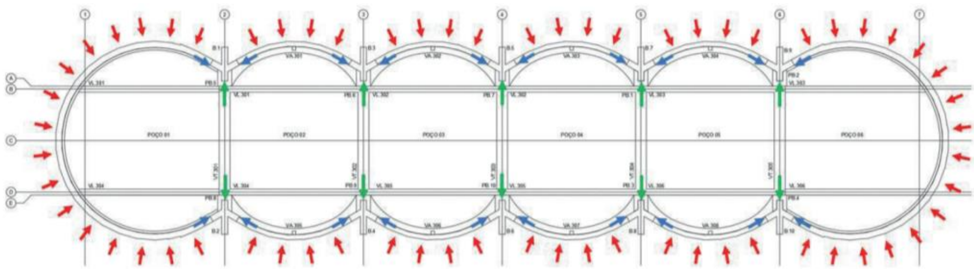

Fig. 2 Load distribution within the retaining structure.

3 CONSTRUCTION SEQUENCE

The construction sequence of Aricanduva Station begins with the execution of the Y-panels (Fig. 3) and the diaphragm wall panels at ground level, both elements of the primary retaining system. The diaphragm wall panels extend to a depth of 41 meters. In the initial excavation phases through soft soil layers, a clamshell-type machine was utilized. For deeper sections and closing panels, the process transitioned to a hydromill.

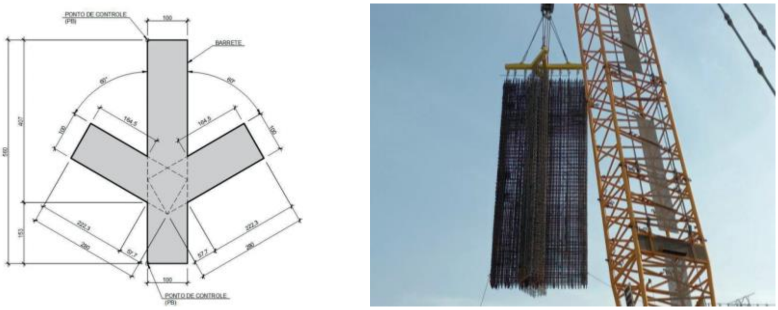

Fig. 3 Geometry of Arrow-shaped Y-panels (left). Reinforcement assembly for Y-panels (right).

The choice of the hydromill was crucial to the success of the construction. This equipment not only ensures greater verticality of the panels - an essential requirement for the retaining system’s proper function, as will be explained later - but is also capable of cutting into the already hardened concrete of adjacent panels. This capability ensures tight contact between panels (Fig. 4, left), resulting in extremely low permeability of the wall and eliminating the need for groundwater lowering in the region.

As the excavation progresses, horizontal bracing of the retaining structure is executed by constructing five levels of reinforced concrete struts per excavation level. These struts have cross-sectional dimensions ranging from 1.80 × 1.80 m to 2.32 × 1.80 m and are capable of transmitting compression forces of up to 60,000 kN. Additionally, arched beams built along the internal perimeter of the shafts channel lateral pressures received by the primary lining to the node connections between the struts and Y-panels, ensuring local equilibrium as shown in Fig. 4 (right).

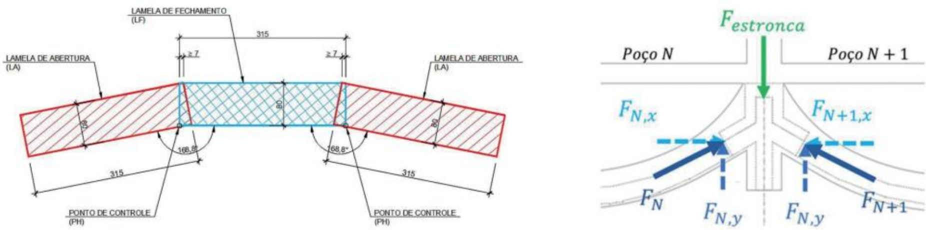

Fig. 4 Detail of closing lamellas executed with a hydromill (left). Nodal equilibrium of forces at the Y-panels (right).

At the completion of the excavation, the station’s base slab is constructed. In addition to supporting the permanent track, platforms, and providing the final horizontal bracing line for the retaining structure, the slab also counteracts the uplift forces caused by hydrostatic pressure. Its complex geometry, with varying sections and multiple openings to accommodate structural components, allows for the assembly and support of the Tunnel Boring Machine (TBM). The slab also withstands significant reaction forces during the TBM’s launch. In this context, the use of BIM modelling, as illustrated in Fig. 5 (left), was indispensable for accurate evaluation and efficient structural detailing.

Once the retaining structure is completed (the excavation or downward phase) and the TBM has pass, the construction enters the upward phase. This phase involves the execution of the secondary retaining system and all other components of the internal floors, walls and stairs, which are supported by the already constructed struts.

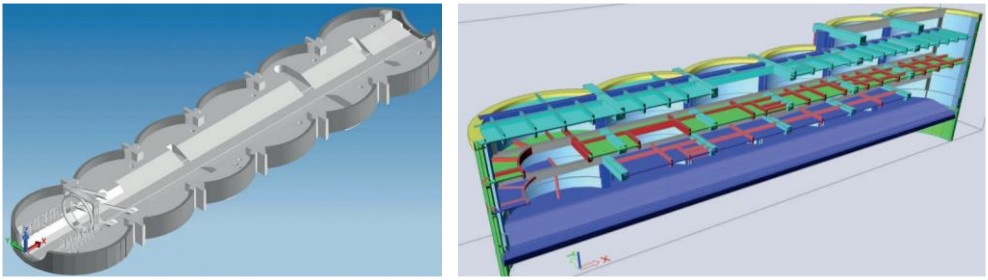

Fig. 5 BIM model of the base slab (left). Global finite element model of the station (right).

4 COMPUTATIONAL MODELLING

A project of this scale and importance demanded the use of the most advanced computational modelling and analysis techniques, developed at Casagrande Eng. offices in Brazil and Portugal. Noteworthy is the high complexity of the soil-structure interaction analyses and the significant influence of the construction sequence on the distribution of forces among the various structural elements.

Soil modelling was conducted using specialized finite element software [1] that accounted for soil-structure interaction, the geological profile of each shaft, and the excavation stages. These analyses evaluated soil pressure, hydrostatic pressure, and the equivalent stiffness of soil springs.

Three-dimensional structural analyses of the interconnected shafts were performed using another finite element software [2]. Structural components were modelled using a combination of bar elements (struts, beams, columns etc.) and shell elements (diaphragm walls, Y-panels, slabs etc.), as illustrated in Fig. 5 (right). The surrounding soil was represented by compression-only springs linked to the corresponding shell elements of the diaphragm walls. Nonlinear analyses were conducted throughout the project, considering the excavation sequence and incorporating the effects of deformation to capture second-order forces. All structural components were designed to withstand both final conditions and intermediate stages of construction.

An example of the project's complexity is the arch-shaped base slab, which, due to it intricate geometry, was analysed not only using global models but also through local models to study its critical sections with greater precision. These local models were developed using finite element software [3] capable of performing nonlinear physical and geometric analyses. The aim was to refine the stress distribution evaluation and ensure the adequacy of the reinforcement design. Some of the results can be found in Section 5.5 of this article.

5 DESIGN ASPECTS

After presenting the overall project and analytical approach, the following subsections highlight specific considerations and challenges related to the design and construction of Aricanduva Station.

5.1 Primary and Secondary Retaining Systems

The primary lining of Aricanduva Station consists of diaphragm walls with a thickness of 100 cm for the outer shafts and 80 cm for the inner shafts. The design premise assumes that these elements must resist the total load resulting from the combination of soil pressure and hydrostatic pressure. Due to the construction method, where each panel is independently executed but overlaps with adjacent ones, there is contact between the reinforced concrete panels, but no continuity of reinforcement in the vertical joints formed between them.

As a result, when subjected to the combined effects of circumferential horizontal compression and bending moments, the vertical joints can only resist compression and cannot withstand tensile forces. To simulate this real physical behaviour in the structural analysis program, the tensile resistance of the shell elements representing the panels was removed in the direction perpendicular to the vertical joints (the direction of circumferential compression). This behaviour is illustrated in the horizontal bending moment diagrams shown in Fig. 6.

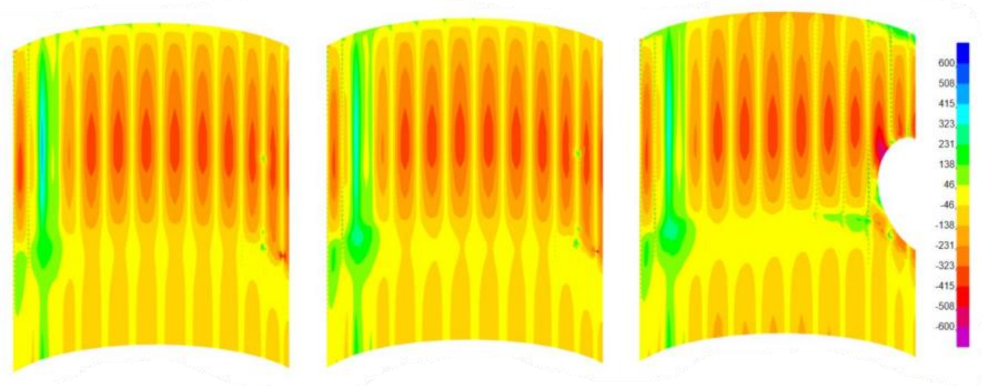

Fig. 6 Distribution of horizontal bending moments in diaphragm walls

The structural capacity of the diaphragm walls was verified using moment-axial force (M-N) interaction diagrams, with the primary parameters being concrete strength and the contact thickness between panels. Since this thickness is directly influenced by the panels' verticality, reduced contact thicknesses were considered in calculations to account for potential construction deviations within verticality tolerances. To ensure compliance with design values, strict verticality control during panel construction is required, limiting deviations to values on the order of 1:100.

To ensure waterproofing, a PVC geomembrane is applied over the primary retaining lining (Fig. 7). This geomembrane prevents water seepage through the panels over the station's service life. A secondary retaining lining, consisting of a 40 cm thick cast-in-place reinforced concrete wall, is then installed over the waterproofing layer.

Fig. 7 Application of yellow PVC geomembrane over the primary retaining lining

The design premise for Aricanduva Station assumes that the secondary retaining wall only needs to resist hydrostatic pressure. This significantly reduced the thickness of the secondary lining, leading to substantial material savings.

5.2 Soft Soil Treatment

Geotechnical investigations during both the basic and executive design phases revealed the presence of alluvial soil layers with variable thicknesses, predominantly between 6 and 9 meters deep. This geological condition posed significant challenges for proper panel excavation, particularly due to the presence of a saturated, very soft clay layer beneath the backfill (Fig. 8, left).

The solution to this challenge involved in-situ soil treatment using a practical, fast, and cost-effective method. For Aricanduva Station, the objective of the soil reinforcement was to stabilize the primary lining excavations, which are kept open and stable with bentonite slurry during reinforcement cage lowering and concrete pouring.

The chosen solution was a modified Jet Grouting technique with a low cement content (200 kg/m³) and rapid intervention parameters, referred to as "Jet Light" (Fig. 8, right). The low cement content was verified through an empirical field procedure known as the "Bucket Test." This field test, commonly used for saturated organic soft soils, evaluates treatment technologies involving soil mixing or cement grout injections.

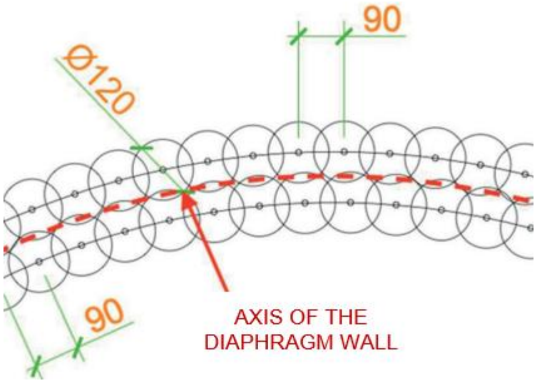

Fig. 8 Excavation of soft soil at Aricanduva Station (left). Soft soil treatment scheme using "Jet Light" (right).

5.3 Connection Between Struts and Y-Pannels

As previously mentioned, the horizontal struts support the Y-panels laterally. In addition to their bracing function, these struts also serve as supports for all internal station floors, resulting in significant shear forces that must be transmitted from the struts to the Y-panels.

Given that the struts and barrettes are constructed in separate stages, a special detailing was required for the connection to ensure that the shear forces could be fully transmitted across the interface. This detailing mobilizes the barrettes' role as the station's primary vertical supports.

Due to the high magnitude of loads to be transferred through these connections, the use of conventional reinforcement was impractical because of the excessive density of passive bars needed in the limited available space. The alternative solution, shown in Fig. 9, was to use a set of post-tensioning bars. These bars apply transverse compression to the connection planes, significantly increasing resistance through interface friction while avoiding reinforcement congestion.

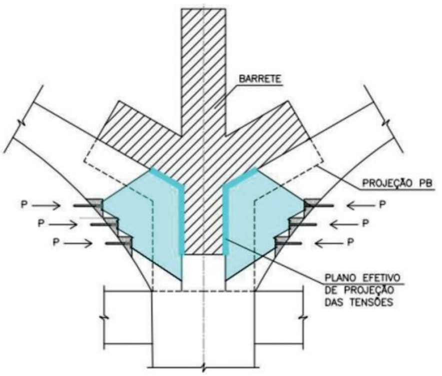

Fig. 9 Scheme for strut-to-Y-panels connection using post-tensioning bars (left). Execution of strut-to-Y-panels connection (right)

5.4 Temporary Beams Demolition (Sand Jack System)

The containment structure of Aricanduva Station consists of five levels: levels 1 to 4 are composed of horizontal struts and arch beams, while the fifth level corresponds to the base slab. The strutting of the barrettes at all levels is essential to ensure stability during the excavation phases (the "descent phase"). The magnitude of forces acting on the containment walls prevents excavation from progressing to the next level until the previous level's strutting is fully installed.

As shown in Fig. 13, the 4th-level strut presented a unique challenge. While it was necessary to ensure excavation stability during the descent phase, it interfered with the passage of the TBM. To address this, the basic design specified that, after constructing and securing the base slab, the 4th-level strut would be demolished to allow the TBM to pass and be assembled and later reconstructed.

This situation imposed two key design considerations:

- Force Redistribution: After the TBM passes, the compression force initially carried by the 4th-level strut is redistributed between the 3rd-level struts and the base slab. As a result, both the 3rd-level struts and the base slab were designed to accommodate this additional load.
- Safe Demolition: The demolition of the 4th-level strut involved elements subjected to compression forces of 35,000 to 40,000 kN. To prevent sudden brittle failure during demolition, a safer method was devised using a metallic device called a sand jack (Fig. 10).

The sand jack system consists of a metal casing filled with dry sand, sealed during construction. As excavation progresses and compression forces build up in the strut, the sand compacts, ensuring load transfer to the barrette while functioning as a strut. This process is called "jacking."

Once the base slab is consolidated, openings in the sand jack are uncovered, allowing the sand to be gradually removed. As the sand is released, the metallic plates of the jack slide over each other, incrementally reducing the compression force. This controlled load release, referred to as "un-jacking", enables safe and controlled demolition of the strut, as it is no longer subjected to high compression forces.

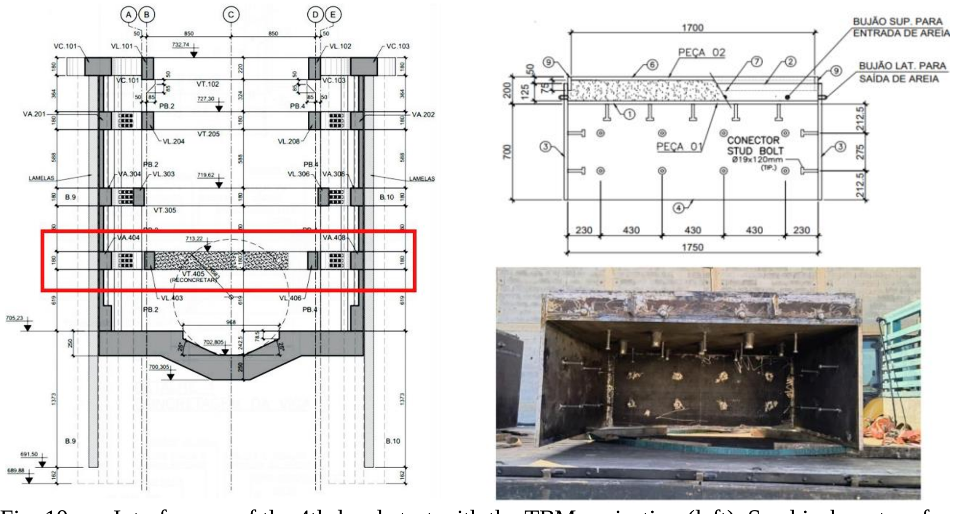

Fig. 10 Interference of the 4th-level strut with the TBM projection (left). Sand jack system for incremental load release during strut demolition (right).

5.5 Arch-shaped Base Slab

As discussed in Section 4, due to its intricate geometry, the arch-shaped base slab was analysed not only through global models but also with local models to study its critical sections with greater precision. Special attention was given to the regions near the corbels, where interactions with the primary retaining structure influence the load transfer mechanism.

By incorporating detailed reinforcement layouts and boundary conditions that reflect the actual construction scenario, these local models provided a more accurate representation of the base slab's structural behaviour under various loading conditions, as shown in Figs. 11.

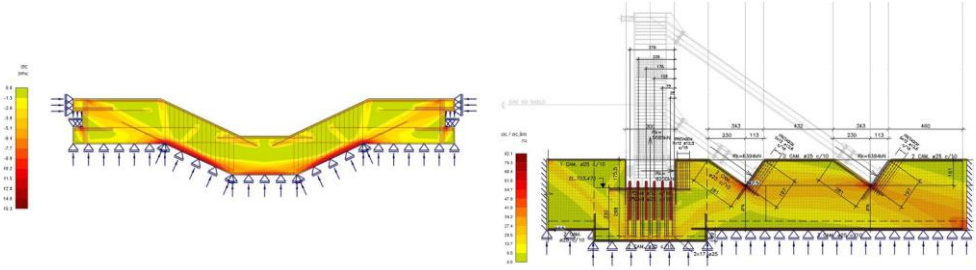

Fig. 11 Base slab typical cross-section (left) and longitudinal section in the region of the TBM's launch structure – Struts and Loads.

6 CONCLUSION

The construction of the Aricanduva Station for São Paulo's Metro Line 2 – Green represents a milestone in the conceptual design of urban infrastructure in Brazil. By employing unique structural solutions, such as the caterpillar-shaped cofferdam composed of 6 secant circular shafts, arch-shaped diaphragm walls, and arrow-shaped Y-panels, the project sets a benchmark for structural efficiency and cost-effectiveness.

The meticulous use of computational modelling, coupled with BIM integration, allowed for optimized soil-structure interaction analyses and precise detailing of critical components such as the TBM-supporting base slab. Furthermore, construction innovations like the sand jack system, "Jet Light" soil treatment, and post-tensioned connections for strut-to-Y-panel interfaces highlight the project's ability to blend creativity with practicality in addressing complex engineering demands.

This project underscores the transformative potential of innovation in structural engineering in Brazil. The Aricanduva Station not only redefines conventional construction methods but also sets a precedent for future infrastructure projects, inspiring engineers to explore new approaches that balance efficiency, resilience, and sustainability.

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