Structural Challenges and Innovative Solutions in the Novo Marapicu Reservoir Project

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Summary

The Novo Marapicu Reservoir Project, designed for CEDAE (Water and Sewage State Company of Rio de Janeiro), consists of six prestressed concrete reservoirs, each 40 meters in diameter and 15.8 meters high. Featuring a complex domed geometry, the reservoirs require post-tensioning at both the base and top to form a stiffness ring for structural integrity. Due to the extremely weak soil conditions, innovative engineering solutions were applied to minimize bending moments in the piles supporting the reservoirs and retaining wall. The retaining wall, designed with counterforts, was selected as an alternative to traditional traditional tieback systems and was further reinforced to support an upper access road and an intermediate service floor housing essential pipeline. The project showcases tailored engineering solutions to address construction challenges, ensuring stability and functionality within the spatial and operational constraints of a complex urban infrastructure.

1 INTRODUCTION

The Novo Reservatório Marapicu project is part of the strategic expansion of water supply infrastructure in the state of Rio de Janeiro. Located in Nova Iguaçu, it was designed to increase the supply capacity for the Baixada Fluminense region, the project will enhance the operational flexibility of the Guandu system. Designed to benefit over three million people in municipalities, while also supporting Rio de Janeiro's water supply.

The structural design was developed by Casagrande Engenharia, with construction carried out by OEC (Odebrecht Engenharia e Construção). The project was commissioned by the Companhia Estadual de Águas e Esgotos do Rio de Janeiro (CEDAE), the client and investor in the initiative.

The structural design phase of the project was initiated in March 2023, and the project exemplifies the integration of innovative engineering solutions and advanced technologies to tackle complex challenges. The project is currently in the construction phase, with work underway on the containment walls and galleries—critical elements for stabilizing the site and supporting the reservoir structure.

This project not only showcases the adoption of cutting-edge techniques such as BIM for improved coordination but also highlights the implementation of robust structural solutions to ensure safety, durability, and long-term reliability. The integration of innovative methodologies and meticulous engineering underscores the significance of this initiative in advancing regional water supply systems.

This paper will present the structural and geotechnical solutions developed for the Novo Marapicu Reservoirs, including their containment walls and galleries, while discussing the key premises and criteria considered during the project's design.

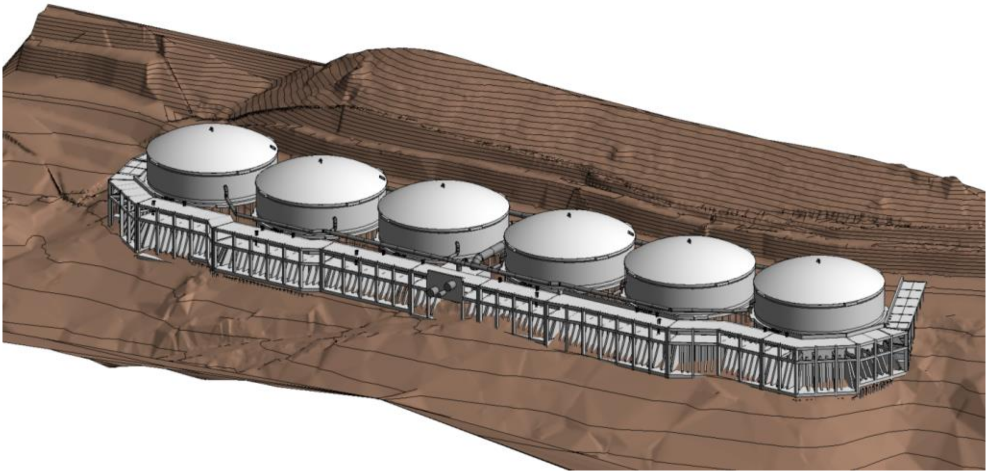


Fig. 1 - 3D View of the BIM Model

Fig. 2 - Construction in Progress - Retaining Walls Construction Phase

2 ORIGINAL DESIGN

The project involves the construction of six independent reservoir cells, each with an internal diameter of 38.0 m, a height of 9.0 m, and a maximum water depth of 8.0 m, providing a total storage capacity of 55,000 m³.

The original design featured a flat slab supported by the perimeter walls and 25 interior columns. These columns were founded on a 60 cm thick piled raft foundation, which consisted of more than 180 root piles, ensuring adequate load transfer to the ground. Figure 3 illustrates the original conceptual design in detail.

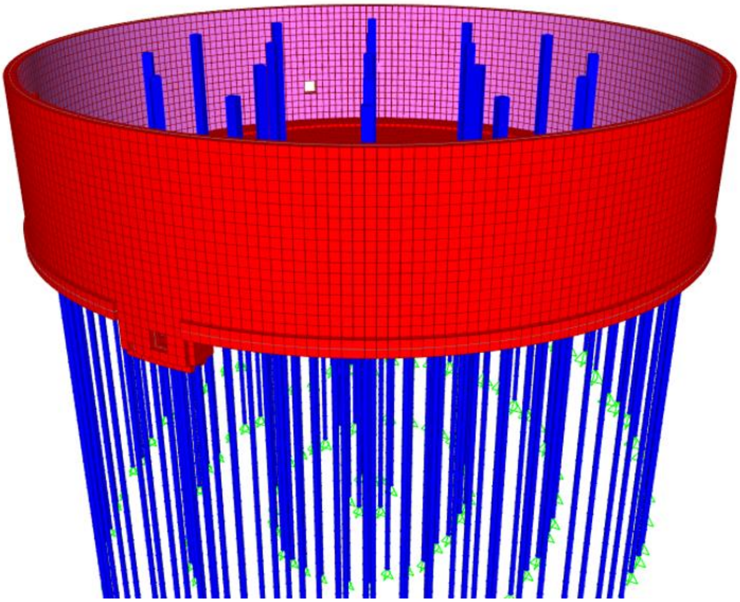


Fig. 3 – Original Design FEM Model

3 RESERVOIR FINAL DESIGN

Casagrande Engenharia developed an alternative conceptual design for the reservoirs while maintaining the originally planned capacity and diameter. The adopted structure has a cylindrical shape, featuring a 50 cm thick floor slab, 50 cm thick walls, and a spherical dome shell roof with variable thickness.
The reservoirs are supported by a system of root piles with a diameter of 410 mm, distributed along the entire perimeter of the structural walls. The pile length varies depending on the depth of the soil layer until reaching the bedrock. The minimum embedment in rock is 10 m, and the total pile length is determined based on the soil and landfill conditions.

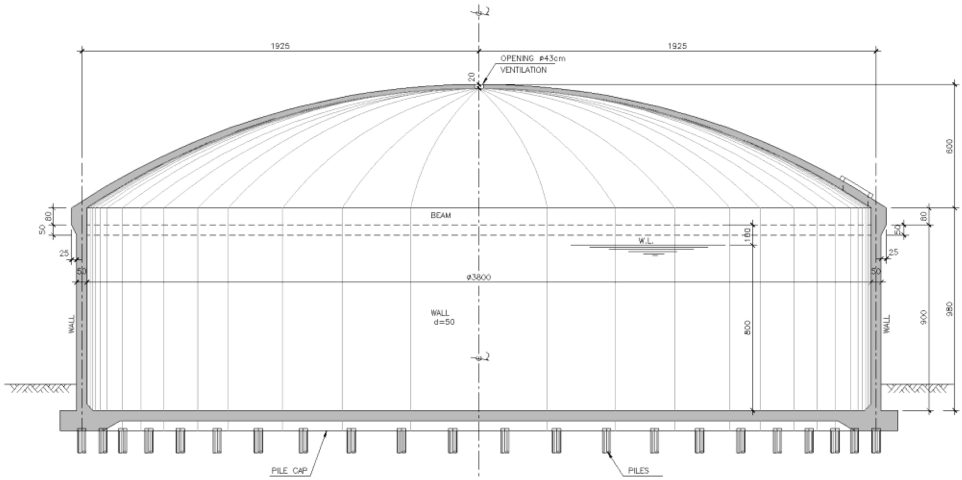


Fig. 4 - Elevation

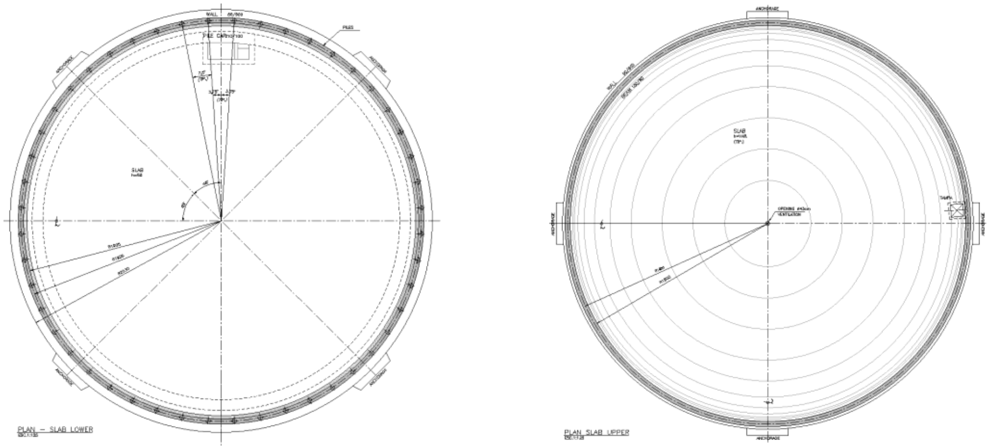


Fig. 5 - Plan of the Upper and Lower Slabs

The retaining walls were designed to withstand active earth pressure while ensuring overall stability. To optimize performance and prevent overturning and sliding, buried equilibrium beams were introduced, interlinked with the walls through tie rods. These beams have a cross-section of 1.50 m x 0.60 m and mobilize passive earth pressure as a stabilizing force. This solution reduces the load on the base piles and enhances the wall's stability.

The walls have variable heights ranging from 4.70 m to 17.50 m and extend approximately 370 m around the reservoirs. Transversely, the walls measure 8.0 m in width and include a rear equilibrium slab that balances the earth pressure. The equilibrium slab's extension varies between 1.00 m and 3.00 m. The wall thickness is 60 cm, with counterfort 50 cm thick, spaced on average every 3.0 m. The lower slabs, functioning as pile caps, vary in thickness depending on their level, ranging from 60 cm at the uppermost level to 150 cm at the lowest elevation.

The retaining wall includes a gallery structure composed of an intermediate slab and an upper slab. The upper slab accommodates maintenance vehicle traffic, while the intermediate slab supports reservoir pipelines and directs rainwater flow. To ensure proper drainage, the intermediate slab was designed with slopes that required a maximum fill thickness of 90 cm. Due to construction constraints, EPS (expanded polystyrene) was used as a lightweight fill material, reducing overload while accounting for concentrated pipe loads. Waterproofing layers, including an epoxy coating over the EPS fill, were applied to prevent water infiltration.

Expansion joints were incorporated longitudinally to mitigate potential damage from temperature effects and shrinkage. At the top of the filled regions, façade joints were included to accommodate additional structural movements.

To enhance stability further, equilibrium slabs and beams were installed on the inner side of the embankment. Passive earth pressure, activated only after significant displacement, was conservatively designed with a reduction coefficient of 0.25. To balance active and passive earth pressures, Ø34 mm monobars, each with a working load of 24 tf and a length of approximately 20 m, were installed following the recommendations of Tschebotarioff [1].

To ensure proper drainage of water in the backfill behind the retaining wall, a solution involving a sand filter wrapped in geotextile fabric was implemented. This filter system effectively channels water flow towards a drainage pipe, preventing water accumulation and reducing hydrostatic pressure on the wall.

This comprehensive approach ensures the retaining wall's durability, stability, and ability to handle the diverse challenges of the project.

3.1 BIM Integration in Project Development

The project is being developed using Building Information Modeling (BIM), which enhances coordination and collaboration throughout the design, construction, and maintenance phases. The use of BIM allowed seamless collaboration between structural, geotechnical, and hydraulic areas ensuring early clashes detection compatibility between components, and improved workflow management.

BIM integrates all stakeholders by providing a digital model of the entire project, which enables real-time collaboration and reduces the risk of errors. The approach also facilitates automatic quantity take-offs, scheduling, and ongoing monitoring of the construction process.

As construction progresses, the BIM model is updated weekly to reflect the current state of the project, evolving into an accurate "as-built" model. This continuous update process provides a reliable digital representation of the structure, which will be essential for future maintenance, operational planning, and decision-making. The BIM methodology was crucial for ensuring accuracy and efficiency, supporting the design of the structures.

3.2 Structural Solutions

3.2.1 Computational Modeling

The computational modeling process plays a critical role in the structural analysis of complex projects such as the Novo Marapicu Reservoir. To ensure the accuracy and reliability of the design, advanced computational tools are used to simulate the behavior of the structure under various loading conditions. For this project, the finite element method (FEM) was employed, using software such as CSI SAP2000 [2] to create a comprehensive three-dimensional model of the reservoir’s structure, including the walls, slabs, and prestressed tendons.

The reservoir's model was constructed to represent the real geometry and material properties of the structure. Elements such as slabs and walls were modeled using shell elements, while beams and piles were represented as frame elements, and the prestressing tendons were modeled as tendon elements. The models of the containment walls and galleries were designed with shell elements for walls, slabs, pile caps, and counterforts. Frame elements were used to model beams, columns, and piles. For the gallery structure, an additional model was created in the TQS software to facilitate a quicker verification of the built structure of the upper floors. These components were connected to accurately simulate the interaction between the different parts of the structure, including how the prestressed tendons exert forces on the slabs and walls.

Key factors such as the prestressing forces, soil-structure interaction, and internal stresses within the concrete were incorporated into the model. The prestressing tendons, with their specified diameters and prestressing force values, were precisely placed in the model. This allowed for accurate representation of the structural system’s response to the applied loads. The analysis considered different loading scenarios, including dead loads, wind loads, temperature effects, water pressure, and other live loads to ensure that the structure would perform safely and effectively throughout its lifespan.

Furthermore, the computational model was used to predict the structural behavior under service conditions, including the verification of required prestressed reinforcement. The model also facilitated the optimization of the design by providing insights into the distribution of stresses and potential failure points, allowing for refinement of the structure before construction. The ability to simulate different scenarios and their impacts on the overall structure was instrumental in enhancing the design's safety and performance.

To ensure the model's accuracy during the construction phase, the computational model is updated regularly, incorporating as-built data. This process allows the team to track progress and make necessary adjustments to the design if any discrepancies between the model and actual construction arise. This dynamic approach ensures that the model remains a reliable tool throughout the project’s lifecycle, enabling better decision-making and helping to mitigate risks associated with construction and structural performance.

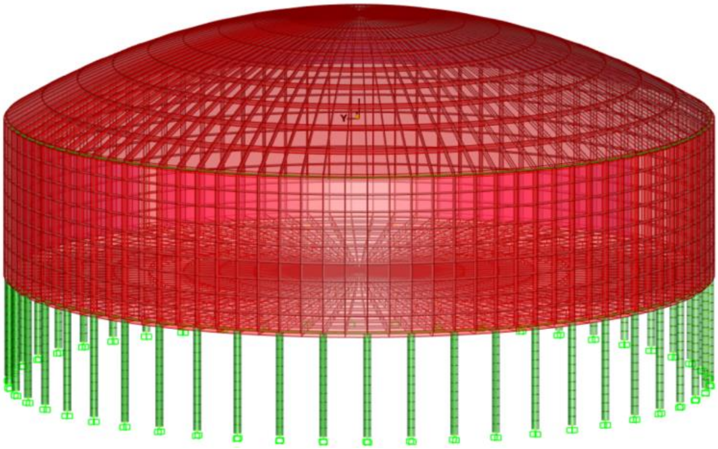


Fig. 6 - Computer modeling for structural analysis of reservoirs

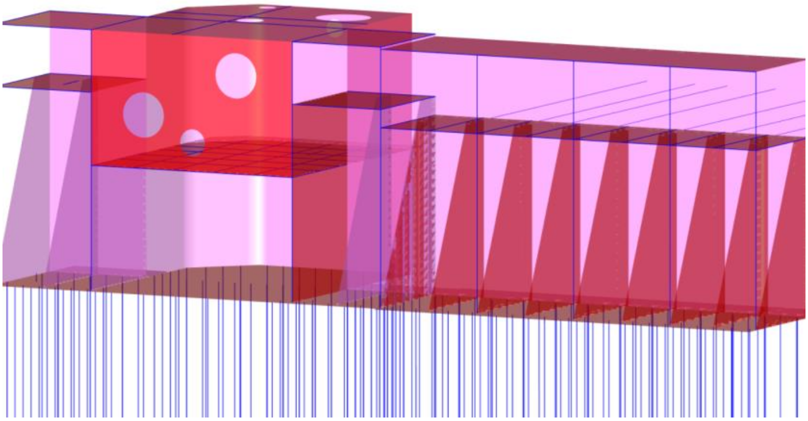


Fig. 7 - Excerpt from the computer model for the structural analysis of retaining walls and galleries

3.2.2 Prestressing

To manage the forces generated by water pressure at critical connection points (between walls and upper and lower slabs), post-tensioning with subsequent bonding was adopted. This solution was applied in both the upper and lower rings of the reservoir, where were used 22 prestressing tendons, each with a diameter of 15.2 mm. The initial prestressing force was set at 4,300 kN, considering losses due to friction, anchorage settlement, and a loss coefficient per meter, as well as progressive losses due to concrete creep, shrinkage, and steel relaxation, in accordance with ABNT NBR 6118 (2023) [3].

Two models—one with prestressing and one without—were used to evaluate the required steel areas to counterbalance the tensile stresses. The prestressing system was designed to resist the tensile forces generated by the water pressure, preventing cracking and maintaining the integrity of the structure.

The need for prestressing was verified using service load combinations. The required area of prestressing steel was estimated in such a way that the tensile forces were nullified.

It was necessary to include four anchorage points per ring, totaling eight anchorages in the upper beam and eight in the pile cap area. This increased number of anchorages was designed to reduce the cable length and, consequently, minimize prestress losses.

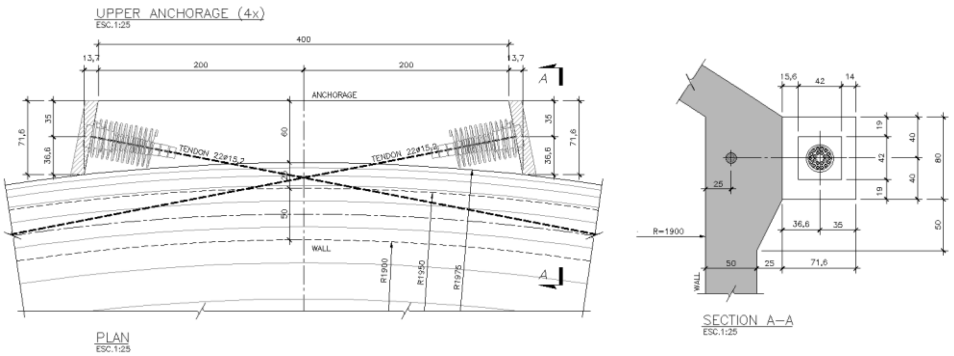


Fig. 8 - Detail of the Tendon Anchorages

3.2.3 Reinforcement in Opening Regions

In areas with openings for pipe passages, high tensile forces were expected. Additional reinforcement was necessary to handle these forces. For the critical regions, a reinforcement of 3×4Φ16 mm bars was designed to resist tensile forces of up to 1,000 kN over a length of approximately 20 cm.

3.2.4 Foundations and Load Capacity

The foundation system for the Novo Marapicu Reservoirs was meticulously designed to provide the required stability and load-bearing capacity, given the complex geotechnical conditions of the site. For each reservoir, 48 root piles with a diameter of Ø410 mm were strategically placed around the perimeter at 7.5° intervals. This distribution was carefully selected to ensure that the load carried by each pile did not exceed 1,200 kN (~120 tf), a limit determined by the geotechnical constraints of the site.

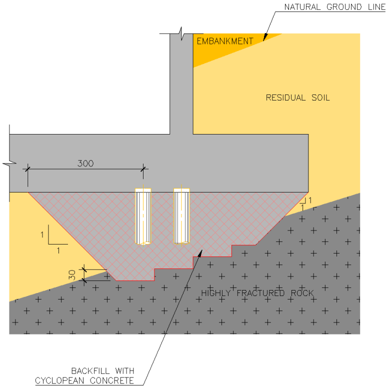
The lengths of the piles were calculated using the semi-empirical Aoki & Velloso [4] method, which was further refined by Monteiro (1997) [5]. This method was employed to estimate the necessary embedment length in rock, ensuring that the foundation system could adequately support the loads applied to the reservoirs. Given the degree of rock fracturing at the site, the method considered the stratigraphic profile obtained from the geotechnical surveys, allowing for a more precise evaluation of the pile lengths required for proper foundation stability.

In calculating the required pile embedment, the typical practice for similar projects was followed, assuming a conservative approach regarding the pile diameter in rock. For the design, the diameter of embedment in rock was considered to be 305 mm, in line with standard industry practices. This consideration was essential for determining the geotechnical load-bearing capacity and ensuring the structural integrity of the foundation system.

The calculation of the pile's load-bearing capacity confirmed that a minimum embedment length of 10 meters in rock was necessary for each pile to achieve the required foundation performance. This length was then added to the length of the pile in the soil, which varies depending on the ground conditions, to determine the total pile length. This approach ensures that the piles provide sufficient support for the entire reservoir structure, considering both the rock and soil layers in the region.

By combining advanced geotechnical analysis with a carefully designed foundation system, the project ensures that the reservoirs' structures are stable and capable of supporting the substantial loads imposed by both the weight of the reservoirs and external forces such as water pressure. The adopted foundation system is a critical aspect of the overall structural design, providing the necessary stability and reliability for the long-term operation of the Novo Marapicu Reservoirs.

The foundation of the retaining wall comprises 1,272 piles, distributed to resist the forces from the wall and the surrounding soil pressure. To avoid large moments and shear forces on the piles, a cyclopean concrete base was adopted. This base ensured that the foundation system could efficiently bear the loads from the wall while distributing them uniformly across the piles, preventing excessive localized stresses.



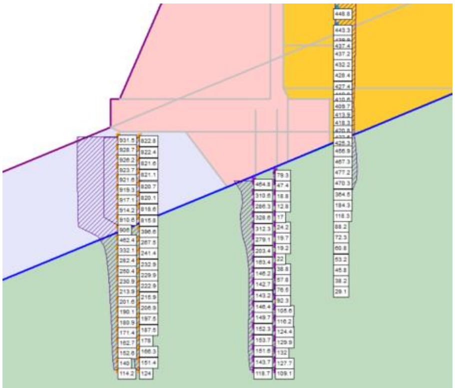


Fig. 9 - Detail of the Cyclopean Concrete

4 CONCLUSIONS

The Novo Marapicu Reservoir project represents a remarkable engineering achievement, addressing critical water supply demands for the Baixada Fluminense region. Combining structural, geotechnical, and innovative design solutions, the project showcases the integration of advanced computational modeling, meticulous planning, and practical execution to overcome complex challenges. The design evolution improved construction feasibility and structural performance, supporting the project's development.

The reservoirs' foundation system was meticulously designed to ensure stability, considering geotechnical constraints and utilizing robust root piles embedded in fractured rock. The retaining walls and galleries showcase structural innovation, incorporating prestressed tendons, equilibrium beams, and efficient drainage systems to ensure safety and functionality. Furthermore, the use of BIM technology throughout the design and construction phases facilitated coordination, enabling real-time updates and the creation of an accurate as-built model.

This project highlights the importance of collaborative effort, with contributions from multidisciplinary teams ensuring the successful delivery of innovative and sustainable solutions. It also underscores the essential role of advanced engineering practices in enhancing infrastructure resilience and functionality.

The Novo Marapicu Reservoir serves not only as a crucial component of the Guandu water system but also as a benchmark for future infrastructure projects in the region, demonstrating how strategic design and construction methodologies can meet the growing demands of modern urban centers.

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