Numerical Analysis of Semi-Buried Cisterns Constructed with Precast Cementitious Plates

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Abstract. Semi-buried cisterns formed by cementitious plates represent an essential solution for water harvesting and storage in arid and semi-arid regions, being fundamental to ensuring water security and combating water scarcity, as presented in the governmental program One Million Cisterns. Therefore, this study proposes to explore preliminary strategies for numerical modeling using finite element methods and *Abaqus Simulia* software. The objective is to analyze in detail the structural behavior of these cisterns, aiming to optimize their design and performance. The adopted methodology involves a literature review to support the numerical modeling and compare the results with traditional analytical methods. The preliminary results indicate a promising possibility of reducing the walls' horizontal reinforcement compared to the current agencies' technical recommendations. Thus, preserving safety and durability conditions while implying lower-cost constructions and promoting the social development of the communities served. Therefore, this study represents a significant advancement in the understanding and optimization of semi-buried cisterns, emphasizing their importance and potential to address challenges related to water storage.

Keywords: Semi-Buried Cistern, Numerical Modeling, Social Development.

1 Introduction

1.1 Context and motivation

Brazil has the world's most populous and biodiverse semi-arid region (Brazilian Semi-Arid - SAB). However, in recent decades, clusters of desertification have emerged, a problem that could intensify from climate change (SILVA *et al*., [1]).

The Brazilian semi-arid region is one of the most populous arid zones in the world, covering approximately 969,589 km². One striking characteristic of this region is the low water availability during the dry season for human consumption, livestock, and agricultural practices. Thus, rainwater harvesting is a widely adopted technique, especially in arid and semi-arid areas where precipitation is scarce and occurs in limited and varied periods (COSTA and AQUINO [2]).

Therefore, alternative water sources, such as the immediate collection and use of rainwater, emerge as one of the solutions to meet water needs in different contexts. Implementing cisterns for immediate rainwater storage is an established and widespread practice. In this context, the National Program for Supporting Rainwater Harvesting and Other Social Technologies (Cisterns Program), funded by the Ministry of Social Development since 2003 (by Law No. 12.873/2013 [3] and regulated by Decree No. 8.038/2013 [4]), aims to promote access to water through the implementation of simple and low-cost social technologies.

The design of cistern projects requires special care and rigorous analysis at all stages, from conception to detailing of the reinforcements. To ensure the structure's durability and water tightness, it is essential to follow the minimum criteria established by current standards. One of the best ways to store water is in buried or semi-buried cisterns due to the lower incidence of light and heat.

Rainwater storage uses reservoirs, which can be classified according to their placement on the terrain:

- Supported Reservoirs: have the bottom in direct contact with the ground.
- Buried Reservoirs: are completely buried in the ground.
- Semi-buried Reservoirs: have part of the sides and the bottom in contact with the ground.
- Elevated Reservoirs: are built on columns to increase water pressure, when necessary.

Cisterns with precast cementitious plates (PCP) represent a simple technology that is low-cost to implement and maintain and easy to handle, suitable for semi-arid regions. According to ABNT [5], mortar is a homogeneous mixture of Portland cement, fine aggregate, and water, which may contain additions and additives to improve its properties. Cementitious materials, such as mortar and concrete, are widely used in constructing reservoirs of various dimensions due to their ease of molding, relatively low cost, durability, and low maintenance cost.

The motivation behind the idea of building cisterns using precast cementitious plates lies in the following:

- Making the cistern beneficiary an active collaborator of the program; he comes to value the benefit received, as he personally contributed to its construction, and better understands the function of each component.
- Transferring technological knowledge to the resident, enabling him to build new equipment for similar purposes, such as reservoirs for irrigating small areas, drinking troughs for animals, and small water tanks.

The advantages of the precast concrete construction system for reservoir works, whether supported or buried, include reduced maintenance needs, attractive aesthetics, high quality, and rapid construction. Thus, the PCP cistern is a cylindrical water reservoir, covered and semi-buried, designed to capture and store rainwater from runoff on house roofs. The reservoir, closed and partially buried in the ground up to approximately two-thirds of its height, is built near the family's residence, protecting the water from evaporation and atmospheric contamination. Details about the social technology can be observed in Figure 1.

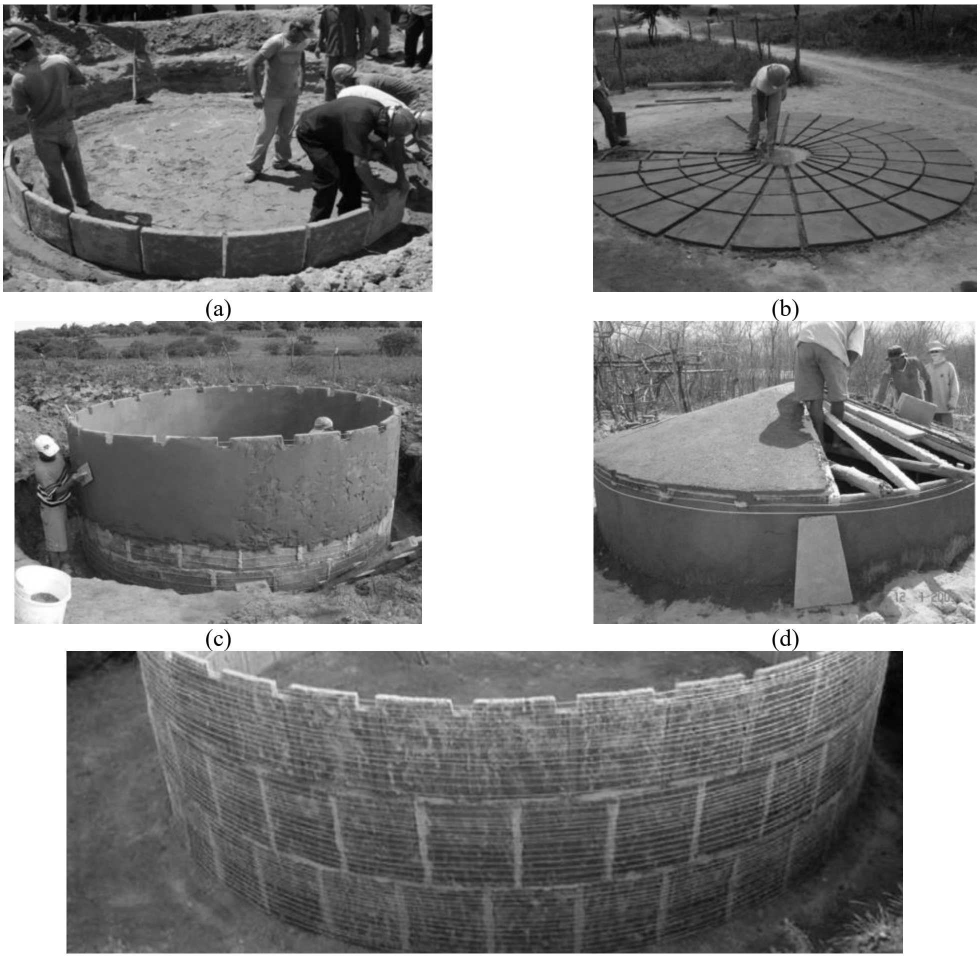
Potable water supply is a challenge in various areas of the country, and difficulties are faced in quantity and quality. Ensuring water supply becomes even more complicated in unfavorable circumstances like rainfall scarcity and high evaporation rates.

Semi-buried cisterns are covered and made of precast cement plates. They receive rainwater through a gutter system connected to the roofs. These reservoirs are built with readily available materials in all regions of the country without molds or additional technological equipment. Each type of produced piece results in reservoirs with different storage capacities, adapting to various needs. Their construction is easily carried out and does not require specialized labor or specific knowledge.

Thus, the motivation for this paper arises from the quest to find solutions to maximize resources and design conditions for semi-buried cisterns with precast mortar plates, contributing to the socioeconomic analysis of this important water storage system. A preliminary study on the structural analysis and design conditions of these PCP low-cost cisterns within the context of the 1 Million Cisterns Program (P1MC) promoted by ASA - Brazilian Semi-Arid Articulation (ASA [6]) was made. This will thoroughly examine how these plates behave under different loads and conditions of use, ensuring they meet the necessary safety and durability requirements for their application in cisterns destined for areas with limited resources. This will be done by reviewing available technical literature and analyzing these elements construction processes and structural performance.

Next, computational simulations are planned using ABAQUS Simulia structural analysis software, based on the finite element method (Dassault Systèmes [7]). The aim is to understand how cisterns built with precast mortar plates of 16 m³ behave and optimize their design. These simulations will allow determining the maximum storage capacity of these cisterns in the context of the proposed reinforcement reduction in Annex of Normative Instruction SESAN No. 09, of March 3, 2023 [8].

Thus, the intention is not only to understand structural behavior but also to contribute to the development of accessible and effective solutions for water storage in communities facing socioeconomic challenges and lack of access to basic resources.



(a) (b)

(c) (d)

(d)

Figure 1 - a) Positioning of the first row of plates; (b) Casting of the plates; (c) Coating of the walls; (d) Execution of the walls; (e) Detail of the arrangement of steel wires (ASA [6])

Therefore, this paper is justified by the relevance of social problems related to water storage, given the high demand for works that meet this urgent need. Hence, the investigation into implementing new technologies and construction methods, aiming at reducing waste and enhancing quality control, costs, and deadlines, becomes essential to improve society's quality of life, as such approaches contribute to expanding the capacity of basic infrastructure.

1.2 Method

The research methodology involves a brief review of the existing literature to establish the historical context, relevance to current developments, and the theoretical underpinnings on the subject. Subsequently, numerical structural modeling techniques, such as finite element analysis, are utilized to comprehensively study the structural behavior and properties of the cisterns under service conditions. The results obtained from a linear FEM model are compared to established theoretical models. Conclusions are drawn from the wealth of data and insights from the comprehensive analysis and discussion.

2 BRIEF THEORETICAL BACKGROUND

2.1 Types of Semi-buried cistern in the context of SAB

Two types of projects are being carried out in the SAB: the cistern project by the Ministry of Social Development (MDS) and the project developed by the Cooperar Project of the State of Paraíba, as seen in Figure 2. Table 1 presents the main parameters of the cistern.

(a) source: clickpb.com.br (b) source: paraiba.pb.gov.br

Figure 2 – Types of cisterns in the context of SAB: (a) - Ribbed inclined slab; (b) Flat Ribbed Slab.

Table 1 – Cistern main parameters for 16.0 m³ capacity

PARAMETER	MDS[1]	COOPERAR[2]
Internal radius	1.70 m	1.50 m
Depth	2.40 m	2.50 m
Buried depth	1.20 m	1.50 m
Plate thickness	0.04 m	0.06 m
Wire mesh	Ø 2.77 mm each 9 cm	#12 BWG wire 4 Ø plate
Cistern lid	Ribbed inclined slab	Flat Ribbed Slab

Sources: 1. Programa Cisternas — Ministério do Desenvolvimento e Assistência Social, Família e Combate à Fome (www.gov.br) ;
2. Downloads — Projeto Cooperar PB

2.2 Loads for Structural Analysis

Various forces and pressures must be considered when analyzing the tensile and compressive loads in the walls of a semi-buried cistern. These forces include hydrostatic pressure from the stored water, earth pressure from the surrounding soil, and the cistern's self-weight. In addition, the fundamental equations and how to determine these loads must also be considered. Equations (1), (2), and (3) present a simplified analytical model for estimating the stresses.

$$\sigma_h = K_a \gamma_s h_s + \rho_w g h_w \tag{1}$$

$$C = \frac{(K_a \gamma_s h_s) d_{ext}}{2} \tag{2}$$

$$T = \frac{(\rho_w g h_w) d_{int}}{2} \tag{3}$$

where: ρ_w is the density of water (typically 1000kg/m^3); g is the acceleration due to gravity (approximately 9.81m/s^2). h_w is the depth of water. σ_h is the horizontal pressure; K_a is the coefficient of active earth pressure; γ_s is the unit weight of the soil; h_s is the depth below the ground surface; C and T are the resultant forces of compression and tension on the cross-sectional area, respectively; d_{int} and d_{ext} are the internal and external diameters of the cistern. Understanding these equations and their applications allows engineers to design semi-buried cisterns that can withstand various loads, ensuring structural integrity and durability.

3 NUMERICAL SIMULATION

The analyzed cistern has an internal diameter of 3.40 m and a total height of 2.40 m. The cementitious plates are 4.0 cm thick with an additional 2.0 cm coating on each side, resulting in a total thickness of 8.0 cm. The bottom plate of the cistern also has a thickness of 8.0 cm. These measurements follow the specifications of the MDS [8]. The main mechanical properties were adopted 15GPa, 0.2, 10MPa, and 1.5MPa for the Elasticity Modulus, Poisson, Compressive Strength, and Tensile Strength of the Mortar, respectively. For steel wires, the nominal values provided by the manufacturer were adopted.

Regarding the reinforcements, they are positioned around the cementitious plates, 2 cm away from the outer surface of the cistern wall. The reinforcements are evenly spaced in 26 turns along the height of the wall.

The cistern is subjected to several forces, including pressure from the water stored in the reservoir, soil pressure, and the weight of the cistern lid. The water pressure creates vertical pressure at the bottom of the reservoir and a radial pressure on its walls. Assuming the specific weight of water is 10 kN/m³, the pressure at the bottom of the reservoir is calculated to be 24 kN/m². Meanwhile, the horizontal pressure on the walls increases linearly from zero at the top to 24 kN/m² at the bottom, resulting in a final calculated value of 33.6 kN.

The pressure from the soil acts in the opposite direction of the water pressure on the outer surface of the semi-buried cistern. This soil pressure is exerted only on the lower half of the cistern walls. It varies linearly from zero at the midpoint to 24 kN/m² at the bottom, with a calculated total value of 33.6 kN, based on a specific weight of 20 kN/m².

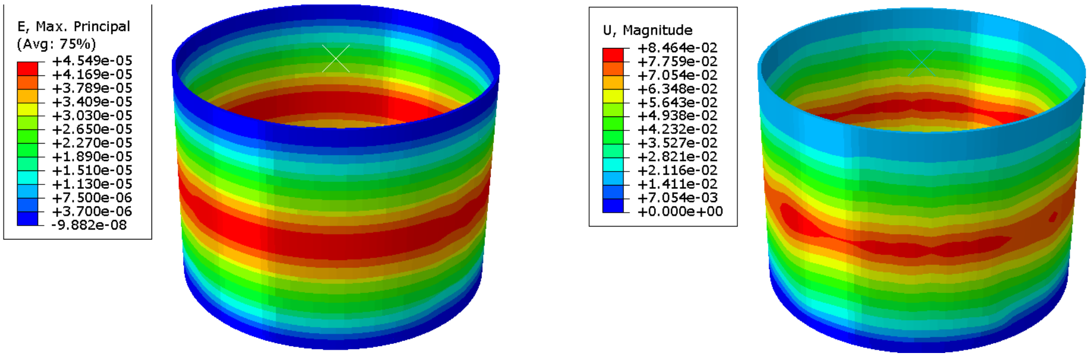
Finally, for analytical purposes, the cistern lid is assumed to be inclined at a 30° angle, resulting in horizontal and vertical force components at the top of the structure. Given that the lid is constructed of mortar with a specific weight of 24 kN/m³ and a thickness of 8 cm, the horizontal and vertical forces are calculated to be 17.43 kN and 10.06 kN, respectively. The calculated forces are 24.40 kN and 14.08 kN. These forces were applied at the top of the reservoir. According to the technical construction specifications, the top of the cistern is reinforced to withstand the lid's forces without causing excessive stress and deformation in this region.

The modeling and numerical analysis were conducted using the commercial software Simulia Abaqus, which employs the Finite Element Method (FEM). The finite element mesh consists of C3D8R elements from the internal ABAQUS library, comprising an 8-node solid element with linear interpolation and reduced integration. A mesh with a global element size of 8.0 mm was utilized. The loading was applied incrementally, with soil and water loads distributed on the cistern surfaces, and the lid load was modeled as located on the top of the walls. Boundary conditions were applied at the lower end of the walls and throughout the bottom plate of the cistern, restricting any translational movement in all three directions.

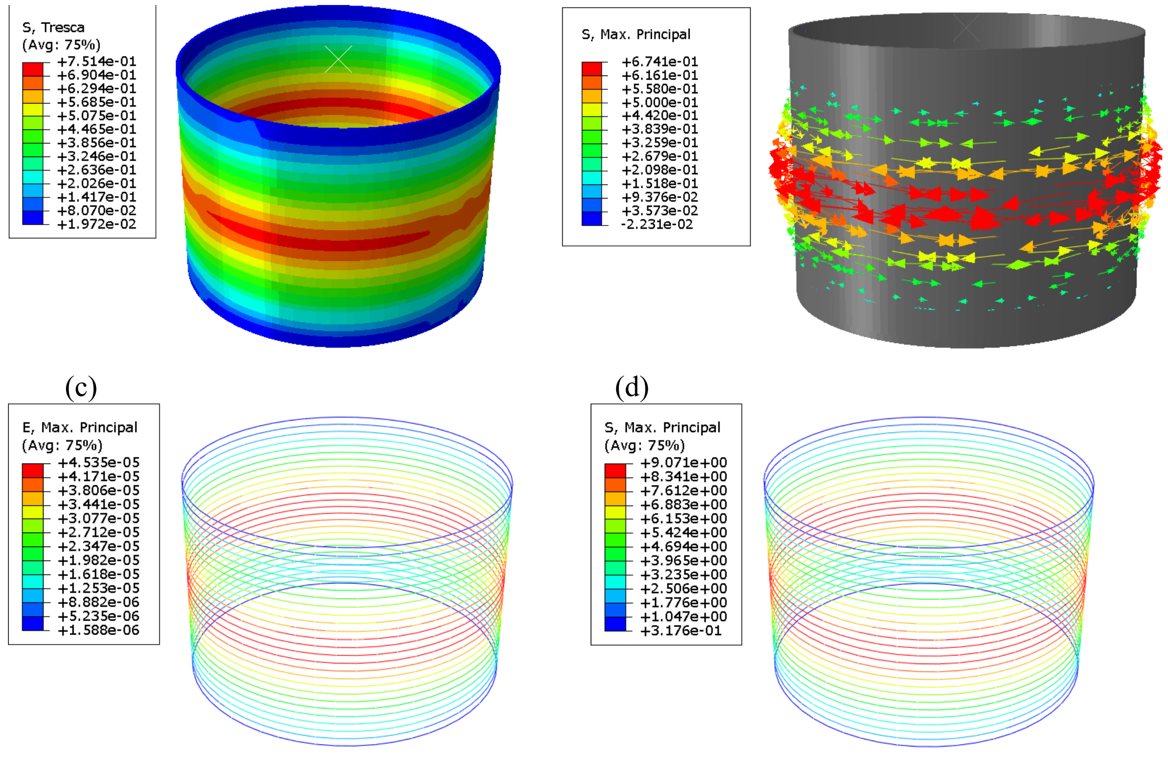
4 RESULTS AND DISCUSSION

In Figure 3 (a) and (b), it is possible to visualize the values of strain and displacement in the cistern plates. It is observed that the water pressure is predominant and causes elongation along the length of the cistern. The strain limits due to tensile effects are low, with a maximum value of 4.549e-5. Figure 3 (c) and (d) show the stress distribution in the cistern plates. The highest stress concentrations appear at the center of the cistern, where soil compression is absent, and the tensile effect due to water pressure is predominant. The maximum stress acting in the section is equivalent to 0.7514 MPa. Finally, Figure 3 (e) and (f) illustrate the strain and stress values in the steel wires. Due to the steel and mortar bond, the materials have the same strain limits; however, the steel wires are responsible for absorbing higher stress levels. They exhibit a maximum stress of 9.071 MPa, 12 times higher than the stresses experienced in the mortar plates.

Figure 4 compares, for the most stressed section, the analytical responses (obtained using the expressions from Table 2) and numerical responses (FEM – Abaqus) along the height of the cistern. The most stressed point for both models is the cistern's average height (1.2 m). The simplified analytical model yielded a maximum stress in the cementitious plates of 0.5 MPa, while the numerical model showed 0.7514 MPa, indicating a difference of 50.3%. Despite this difference, in both cases, the calculated tensile strength of the concrete (1.5MPa / 1.4 load factor security) = 1.07 MPa) is higher than the calculated stresses. The difference in results may be related to the fact that the analytical model did not account for the vertical force caused by the cistern lid. Additionally, the definition of the properties might also lead to changes in behavior.



(a) (b)



(c) (d)

(e) (f)

Figure 3 – FEM Model Results: (a) Mortar Plates - Strain (Max. Principal) (b) Mortar Plates – Displacement (m) (c) Mortar Plates - Stress (Tresca) (MPa) (d) Mortar Plates - Stress (Max. Principal) (MPa) (e) Steel Wires - Strain (Max. Principal) (f) Steel Wires - Stress (Max. Principal) (MPa).

According to Figure 4, the numerical model shows that the most stressed steel wires are in the central region, with a maximum stress of 9.07 MPa. This stress is significantly lower than the yield strength of the steel used (500/1.15 = 435 MPa). Given this substantial difference in results, it can be identified that the properties of the steel are not being fully utilized. Additionally, as shown in Figure 4, it can be observed that the stresses acting on the steel wires at the top and bottom of the cistern are lower than those at the height of 1.2 meters. For design purposes, it is appropriate to either increase the spacing or reduce the diameter of the steel in the upper and lower third regions. For example, instead of using steel with a diameter of 2.77 mm, steel of type N18 BWG, which has a diameter of 1.24 mm, can be used, thus reducing material and costs.

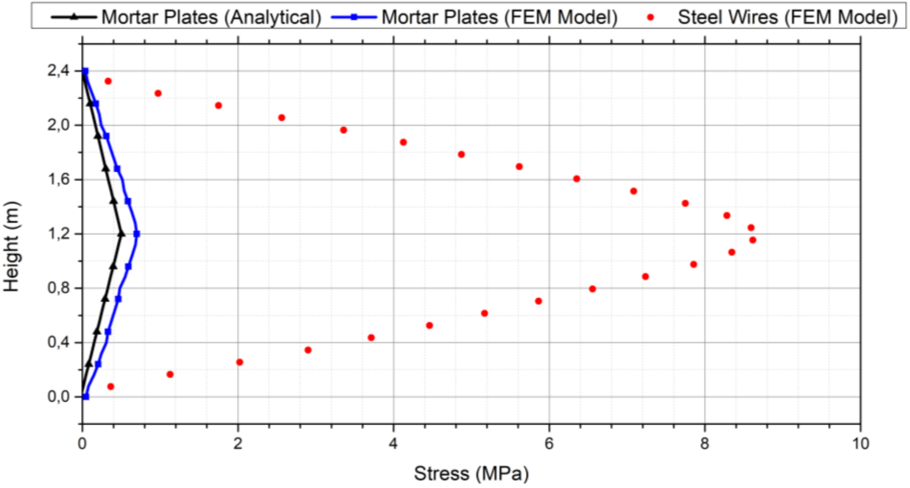


Figure 4 – Stress Distribution

5 Conclusion

PCP semi-buried cisterns are essential for water security and combating scarcity in arid and semi-arid regions. Thus, this work presented preliminary approaches for developing numerical models to evaluate the behavior of these cisterns.

The theoretical linear model and numerical model exhibited similar stress distributions, albeit at different stress levels. However, the simplified analytical model proved inadequate for characterizing the behavior of the cistern walls. The findings suggest that the stresses acting on the steel wires are below the material's yield strength, indicating a reduced need for horizontal steel in the cistern walls compared to current technical codes. Therefore, transitioning from the current 2.77 mm diameter steel wires to #18 BWG steel with a 1.24 mm diameter at one-third of the upper and lower ends of the cistern could be advantageous, as the stresses in these regions are lower. Specifically, at one-third of the upper and lower ends of the cistern, the steel wire primarily serves to mold the PCP previously coating the walls. This reduction in steel elements could lead to cost savings and broader social benefits by allowing for the expansion of the cistern program to benefit more people while still maintaining the safety and durability of the structural elements. It appears that the current cistern designs are based on empirical practices and use more steel wire than necessary.

This study advances our understanding and improvement of the structural performance of cisterns with cementitious plates. It demonstrates the fundamental role and ability of these cisterns to foster social development by enhancing the resilience of local communities in water storage conditions.

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7 Authorship statement

The authors hereby confirm that they are the sole liable persons responsible for the authorship of this work and that all material that has been herein included as part of the present paper is either the property (and authorship) of the authors or has the permission of the owners to be included here.

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