XLIII CILAMCE
21-25, November, 2022
FOZ DO IGUAÇU - PR - BRAZIL

A Computational Model for the Analysis of Uplift Pressures and Fluid Flow in the Jucazinho RCC Dam

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Abstract. The Jucazinho dam is of the Roller Compacted Concrete (RCC) type, completed in 1998. The first flood was in 2004 with a 1,4m thick spill, causing deterioration of part of the dissipation basin. This situation triggered investigation services to assess the structural integrity of the structure. It was found that the drainage gallery presented several pathological manifestations arising from the water seepage through the concrete monolith. In 2017, there were maintenance and consolidation services throughout the dam structure, paying particular attention to cracks and the rehabilitation of the dam gallery. Several studies were carried out on the dam: (i) verification of the quality of the materials used throughout the structure; (ii) exceptional seismicity actions that could cause major problems preventing its use; (iii) global stability analysis. But the effects of seepage flow in the concrete were not deeply analyzed. These considerations justify the occurrence of existing manifestations and serve as a reference for monitoring the dam's safety. In order to analyze the water seepage that occurs in Jucazinho dam, the 2D Finite Element Method (FEM) was used using the ABAQUS software, considering: (i) flow through porous media with coupled fluid diffusion and stress analysis; (ii) finite elements with combined displacement and pressure degrees of freedom; (iii) the solver of non-symmetric equations; (iv) steady-state analysis. Following these considerations, this article presents a brief review of the literature on the subject and the knowledge of the physical parameters of the dam. Subsequently, it introduces the physical and mathematical formulations that characterize the problem to be studied in Jucazinho dam. With the numerical simulations the following results were achieved: (i) the equipotential and flow lines inside the monolith; (ii) the displacements and stresses for the fully coupled analysis. These parameters are important for future investigations and safety monitoring of the Jucazinho dam. Reference simulations performed without fluid flow in the confined medium demonstrate that the values obtained differ completely from the simulations that considered the water seepage inside the concrete, reaffirming the importance of considering flow analysis coupled with stress analysis.

Keywords: concrete dam, flow through porous media, finite element method, two-way coupled simulation, Coupled seepage–stress analysis.

1 Introduction

The Jucazinho dam, located in the municipality of Surubim, in the interior of Pernambuco, aims to regulate the flow of the Capibaribe River and supply neighboring municipalities. Its construction was completed in 1998 and had its first flood in 2004 with a 1.4m thick spill, which caused damage to the dissipation basin. In 2013, investigation services were carried out throughout the dam to verify the state of conservation of the entire hydraulic structure.[1]. In 2017, during a drought, maintenance and consolidation services of fissures and cracks on the upstream face and readjustment of the gallery were carried out [2].

The dam has been receiving investments in interventions, maintenance and with research aimed at the knowledge and behavior of the materials that make up the dam, also in other areas of engineering [2,3]. Despite Jucazinho receiving attention from public competent bodies, infiltrations still occur in the gallery, and it is not possible to differentiate whether the occurrence is with the same intensity identified in the works developed in 2013 [1].

Therefore, the present work aims to obtain a relationship between the main stresses and the behavior of the structure considering the structural mechanics coupled with the fluid mechanics through a numerical modeling in finite elements in the Jucazinho dam using the ABAQUS software.

The rest of the article is divided as follows: in the second chapter of the article is the theoretical framework where the governing equations and the main requesting actions are defined; in the third, the methodology is applied and the results obtained are discussed, describing the case study applied to the Jucazinho dam, description of the numerical modeling and the argumentation of the results. In the fourth chapter is the conclusion and finally the bibliographic reference.

2 Theoretical Reference

2.1 Definition of Governing Equations

The main purpose of structural mechanical analysis is to obtain displacements and stresses under the action of specific loads in certain boundary conditions according to the structure studied. Every formulation of structural mechanics considers (i) the balance between external loading requests, (ii) the consideration of deformations and displacements that have occurred, (iii) and the boundary conditions that can be imposed on displacements or forces acting [4], as shown by eq. (1).

$$\begin{cases} \frac{\partial \sigma_{xx}}{\partial x} + \frac{\partial \sigma_{xy}}{\partial y} + f_x = 0. \\ \frac{\partial \sigma_{xy}}{\partial x} + \frac{\partial \sigma_{yy}}{\partial y} + f_y = 0. \end{cases} \quad (1a,1b)$$

Where σ_{xx}: is the stress in X, σ_{yy}: is the stress in Y, σ_{xy}: shear stress, f_x: Force in X and f_y: Force in Y. The formulation for the Finite Element Method (FEM) of structural mechanics was formulated based on differential equations and the variational method [4]. This concept was used in the numerical solution represented in eq. (2).

$$\left(\sum_{e=1}^{E}[K^e]\right)\vec{\delta} = \vec{P_c} + \sum_{e=1}^{E}\left(\vec{P_i^e} + \vec{P_s^e} + \vec{P_b^e}\right). \quad (2)$$

$$[K^e] = \iiint [B]^T\,[D]\,[B]dV. \quad (2a); \qquad \vec{P_s^e} = \iint [N]^T \vec{F} dS_1. \quad (2c);$$

$$\vec{P_i^e} = \iiint [B]^T\,[D]\vec{\varepsilon_0}dV. \quad (2b); \qquad \vec{P_b^e} = \iiint [N]^T \vec{f} dV. \quad (2d).$$

Where [N]: matrix of shape functions, [B]: matrix of partial derivatives of shape functions, [D]: Constitutive matrix, $\vec{F}$: Prescribed force vector and $\vec{\delta}$: Global displacement vector nodal.

The coupled analysis considers the mechanics of fluids (incompressible and inviscid) in a porous medium, considers the permeability of the material, the density of the fluid, the direction of flow according to the Darcy Law to obtain the head of water. The eq. (3) is based on the law of conservation of mass [5].

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial \emptyset}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial \emptyset}{\partial y}\right) + Q = \frac{\partial \theta}{\partial t}. \quad (3)$$

Where K_{xx} and K_{yy} are the hydraulic conductivity of the porous medium on the X and Y axes, Q is the volumetric flow rate per unit volume in units 1/s, $\emptyset$ is the water load distribution function in the infiltration area, ~~θ~~ is the content volumetric volume and the relationship $\emptyset$, which depends on the pore water pressure u_w as given in eq. (4) [6].

$$\emptyset = \frac{u_w}{\rho_w g} + h. \quad (4)$$

Where ρ_w is the density of water, g is the acceleration due to gravity and h is the maximum water level on the upstream face of the dam [6]. The MEF formulation of the coupled analysis was formulated conceptually similar to the one presented in the structural model [6]. The eq. (5) shows all terms for the numerical solution.

$$\left(\sum_{e=1}^{E}[H^e]\right)\emptyset = \sum_{e=1}^{E}[F^e]. \quad (5)$$

$$[H^e] = \iiint [B]^T\,[k]\,[B]dV. \quad (5a); \qquad [F^e] = \iiint [N]^T\,[Q]dV - \iint [N]^T v_n ds. \quad (5b);$$

Where [N]: matrix of shape functions, [B]: matrix of partial derivatives of shape functions, [k]: infiltration matrix, *F:* Prescribed force vector and $\emptyset$: Vector of water load in infiltration. The numerical solution is through iterative analytical methods that require the indication of the initial or residual velocity [6] this same procedure is used by ABAQUS [7].

The coupled verification will be based on Terzaghi's formulation, which considers the combination between the actions of effective stress and pore pressure, eq. (6) shows the basic principle of this formulation [8]. Where σ_{total} is the total effective stress, σ' effective stress and u_w the pore pressure.

$$\sigma_{total} = \sigma' + u_w. \quad (6)$$

In the modeling carried out in this work, the effective stress can be considered by the analysis performed in a structural static way and the total effective stress is carried out considering the action of the water flow in a porous medium. This article will only develop static analyzes based on structural mechanics and fluid mechanics in finite elements, which is not necessarily an exact solution, being an approximate numerical solution.

2.2 Information about the Jucazinho Dam

The article will study only one Overflow section of the Jucazinho dam, which has a crest extension of 442.0m, being at an elevation of 299.0m providing a maximum height of 63.2m, but in the spillway section the maximum elevation is 292. .0m and the maximum height of 57.1m. The upstream face is completely vertical and the downstream face with a slope of 0.8V:1.0H and its foundation is on a rocky stratum [1]. The drainage gallery is located internally near the upstream face and at the base of the foundation. Fig. 1 shows the dimensions of the dam section and Tab. 1 brings the physical and infiltration parameters adopted.

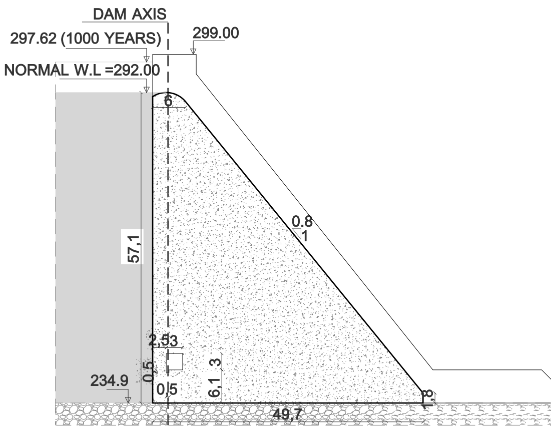

Figure 1. Overflow section of the dam [1].

Table 1. Seepage and Structural Properties of Jucazinho RCC dam [1].

Density (kg/m³)	**Elastic Modulus (Mpa)**	**Poisson's ratio**	**Permeability (m/s)**
2120	24463.95	0.2	1.00E-10
Void Ratio	**Gravity Acceleration (m/s2)**	**Density of the Water (kg/m3)**	
1	9.81	1000	

3 Applied Methodology and Discussion of Results

3.1 Description of Numerical Modeling

Numerical modeling of the dam was developed by the ABAQUS software in two ways: (i) the first simulation was the structural mechanics using the static module solver; (ii) the second was coupled analysis using the soil module solver. In both, the same amounts of elements and boundary conditions were used. The main difference between the two simulations is the type of solver and some small specifications that are indicated throughout the text.

The static verification used the CPS4R element that has 4 nodes with two degrees of freedom each, with reduced integration and used to obtain plane and continuous stresses. The soil model used the CPE4P element, which has 4 nodes with two degrees of freedom each, used to obtain the plane stresses and the pore pressure. [7].

In each of the two models there are a total of 1624 elements with 1718 nodes. A mesh convergence study was not developed since this investigation was carried out by Aguiar *et. al* [3] and this work adopted similar discretization.

The two simulations used the same boundary conditions: (i) foundation with restriction of horizontal and vertical movement and rotation at the nodes; (ii) the action of requesting the concrete's own weight and the action of the water buoyancy with the maximum height referring to the full reservoir.

In the coupled analysis, it is necessary to impose one more boundary condition referring to the requesting pore pressure [7], as it is part of the stress-strain relationships present in the governing equations and the numerical methods used, this pressure will act on the upstream face in a triangular shape similar to the thrust of water, while in the gallery a null value is indicated because there is a natural tendency of the flow of water go to that location. The two pressures are the Dirichlet boundary conditions and the difference between them is the water flow which is the Neumann boundary condition. [9]. The Fig. 2 shows in detail the discretization that was used for both simulations and the boundary conditions imposed and acting on the Jucazinho dam.

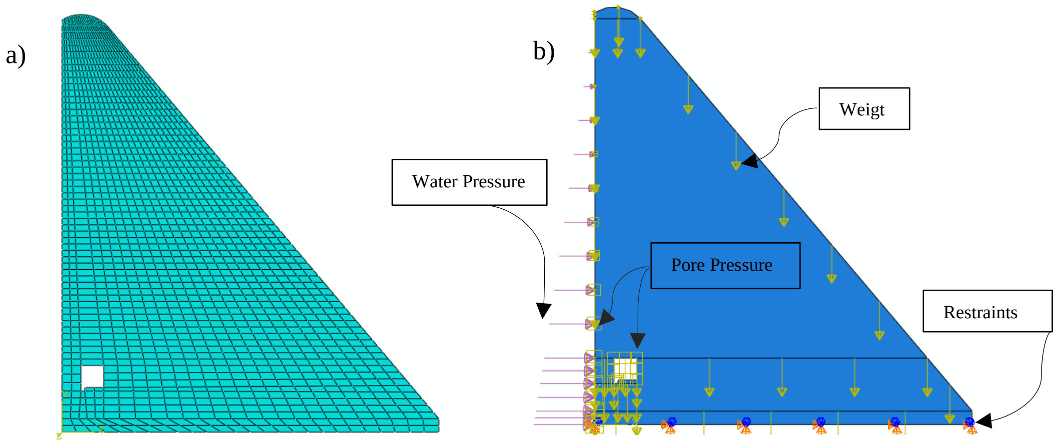

Figure 2. a) Finite element discretization; b) boundary conditions of selected section of the dam.

3.2 Reference Results for Numerical Modeling

The reference values were obtained by CADAM software, which is a specific program for concrete dams based on the rigid body equilibrium method and beam theory to perform stress analysis, crack length calculation and safety factors [10]. This article focus in the stresses in the dam foundation, and Tab. 2 shows the reference results obtained in CADAM, where the coupling data refer to coupled analysis, where the mechanical and flow problem are solved simultaneously, considering the uplift pressures at the base of the dam.

Table 2. Data from CADAM.

	Normal force (kN)	Shear force (kN)	Uplift force (kN)
Uncoupled	-34,215.08	16,273.61	-
Coupled	-27,734.75	16,273.61	6,480.33

3.3 Discussion of Results

The initial verification of the simulations used the values obtained at the base of the dam, which are the data that will initially be compared with the reference values in Tab.2. The result of the distribution of support reactions on the Y axis obtained by ABAQUS along the dam foundation, both in static mode and in soils mode, can be seen in Fig. 3, another information contained is the pore pressure value obtained in the coupled simulation.

The models were validated through the values of the resultant of each curve contained in Fig. 3 compared to the reference values of Normal, Shear and uplift forces in Tab. 2. For the structural static analysis, the sum of all support reactions on the Y axis indicates the resultant of the normal force of the numerical modeling, the result of the shear force is the area of the graph, as recommended by the strength of the materials [11].

The comparison of coupled analysis values considered Eq. 3 to obtain the effective stress value. In the simulation, the total tension and pore pressure were obtained, and thus the results were compared. The procedure for normal and shear force was the same as for the structural analysis, but the pore pressure result was included to obtain the effective stress. The Tab. 3 contains the comparison and the error found between the reference values and the numerical models.

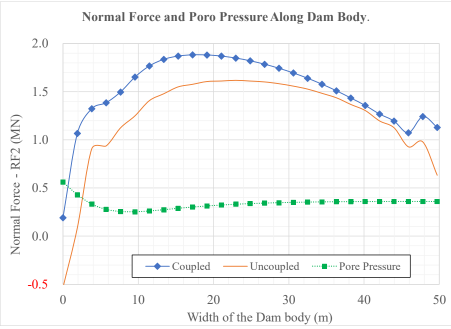

Figure 3. Distribution Forces along Dam Body.

Table 3. Verification and Validation of Results.

	Uncoupled		Coupled	
	Resultant Force (kN)	**Error**	**Resultant Force (kN)**	**Error**
Normal	32,950.27	3.70%	31,360.54	13.07%
Shear	16,005.60	1.65%	15,167.36	6.80%
Uplift	0.00	0.00	9,178.77	-

With the validation of the simulations, the stresses in X, Y, XY and the main one in the foundation were observed, where the static and coupled distributions were compared. In all stress contours, the coupled curves presented the highest values compared to the static one, as they are total stress values, but the contour distribution pattern in both analyzes followed the same behavior throughout the foundation.

This difference between the tensions occurs precisely with the consideration of the pore pressure in this region of the dam because it is an area that is inside the phreatic surface, there is an action of the water infiltration flow and therefore, it must be considered pressure exerted by the water. Fig. 4 shows the stress distribution along the dam foundation comparing the results of the static and coupled analyses.

In the entire cross-section of the dam, when comparing the values of the maximum principal stresses obtained in the two analyses, it was noticeable that in the coupled solution the stress distribution occurs throughout the section being in the form of compression, but in small regions near the top and from the base of the gallery, the values are traction, unlike the static solution that presented only compression values in a small region of the heel and in the other points of the cross section the values was null.

Fig. 5 shows the distribution of the maximum principal stresses of the static and coupled models. The principal stress values obtained in the coupled analysis are higher due to the effects of water infiltration in the dam body acting from the upstream face towards the gallery, being great evidence that the infiltration flows and the internal water pressures resulting in compressive stresses.

The coupled simulation indicates the flow direction and its magnitudes. In places with low pore pressure, there will be little difference between the stresses obtained with the static simulation, but on the upstream face and on the dam foundation, which is in contact with the bedrock, there is a great performance of pore pressure, any verification at these locations should consider Terzaghi's formulation [8]. The Fig. 5c shows the entire pore pressure contour obtained in the coupled simulation.

Parametric analyzes were performed on the dam axis, shown in Fig. 1, where the first refers to the total displacement and the second to the principal stresses, Fig. 6 demonstrates the results found in both analyses. In Fig. 6a, it is verified that the displacement of the static and coupled form increases with the height of the dam, but that there is a difference in values between the two numerical models. The displacements of the coupled verification are smaller than the static ones, around 37% along the entire height of the dam, between the heights 6m to 9m there is a discontinuity of values due to the existence of the gallery, the displacement at the crest was 1.41mm for the static one and 1.02mm for the coupled one.

In the analysis of principal stresses on the dam axis, shown in Fig.6b, the stress of the static model acts only from the foundation to the base of the gallery, while from the top to the crest the value is null. In the coupled model the stress varies from compression to tension along the axis with a discontinuity in the gallery region. Pore pressure tends to act in a triangular fashion along the entire axis, with maximum intensity at the foundation and zero at the dam crest, but there is a relief of tension in the gallery region. Of the stresses observed in the axis of the dam, the pore pressure is the one with the highest absolute value, so it should not be neglected in any verification.

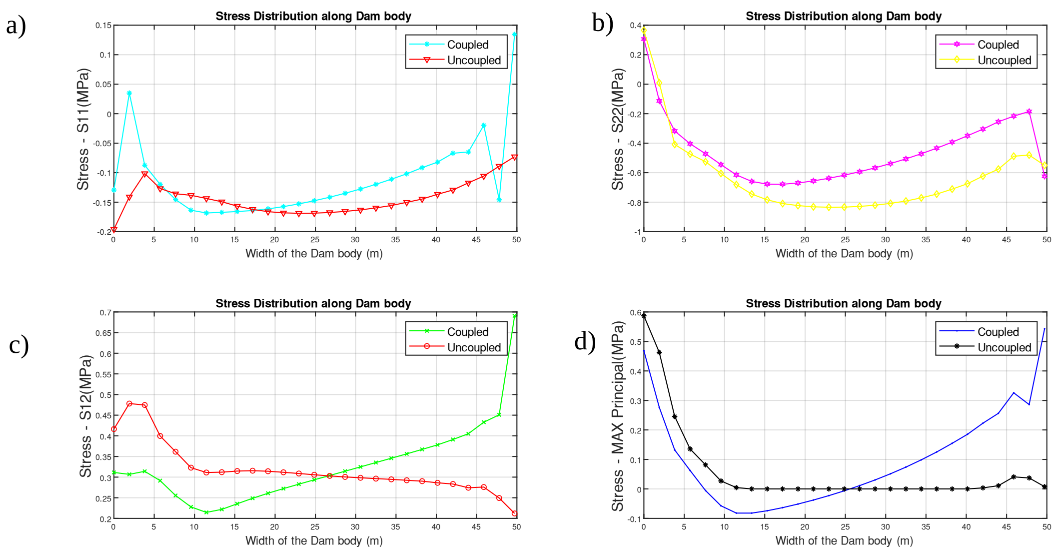

Figure 4. Stress Distribution along Dam body, a) Stress S11 (MPa), b) Stress S22 (MPa), c) Stress S12 (MPa), d) Maximum Principal Stress (MPa).

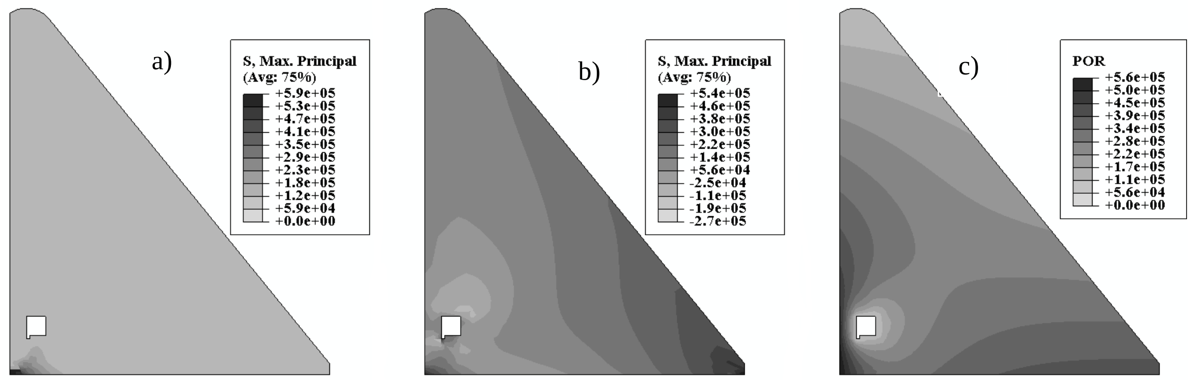

Figure 5. Section of the Dam Stress, a) Maximum Principal Stress - Uncoupled (Pa), b) Maximum Principal Stress - Coupled (Pa), c) Pore Water Pressure (Pa).

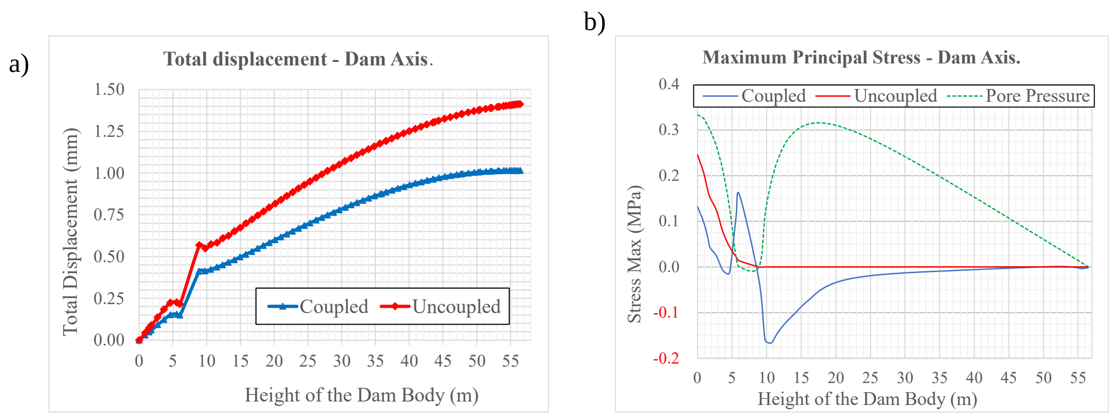

Figure 6. Analysis Dam Axis; a) Total Displacement (mm), b) Maximum Principal Stress and Pore Pressure (MPa).

4 Conclusions

The article presented the comparison between two identical two-dimensional simulations, which used different physical behaviors, in order to prove the importance of considering the infiltration of water in the body of an RCC dam. The simulation values were validated with the CADAM software, which is specific for concrete dam calculations.

With this, it can be identified that the foundation is the region in which the stresses of the coupled model are greater than that of the uncoupled model and that this difference occurs precisely because the presence of uplift pressure is more intense. In addition, it was found that the main stresses in the coupled model are also higher and act entirely on compression due to the action of infiltration flows and water pressure inside the concrete.

The displacements in both models are different, but they show the same tendency of behavior along the dam body and that the absolute displacement of the coupled model tends to be smaller than the static one, being strongly influenced by the pore pressure action that acts inside the dam body.

The knowledge of the water pressure distribution in the pores along an RCC dam is important to verify the behavior of stresses and displacements, as these can be increased or minimized depending on the location. The coupled simulation obtained more consistent results, as it uses boundary conditions that are closer to reality than the static modeling.

As an indication of future work, it is recommended the development of transient analyzes according to the change in the water level upstream and the inclusion of constructive layers.

Acknowledgements. The authors gratefully acknowledge the contributions of National Department of Works against Drought (DNOCS) and Geotechnique Company for their information about the dam project.

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