Numerical modeling of 3D-printed concrete dams designed for pumped-storage hydropower

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Abstract. Pumped-storage hydropower (PSH), also called "the world´s water battery", represents one of the most sustainable, economical and efficient solutions for energy storage, being an excellent alternative for non-intermittent energy generation. This work aims to study new shapes of concrete dams for PSH using the possibilities opened by 3D printing technology. Solid shapes and hollow shapes were modelled, with different base and height dimensions. After selecting possible shapes, finite element modeling was performed using DIANA-FEA, analyzing stability and stresses due to water pressure and dead load. Within the framework of this analysis, concrete was considered as hardened in complete hydration. To verify the stress levels, a cracking index was used, allowing the evaluation of the efficiency of the shapes. The results indicated that the use of 3D printing can open several new possibilities for the design of concrete dams typically used for PSHs.

Keywords: concrete dam, pumped-storage hydropower, 3D printing.

1 Introduction

Conventional construction faces criticism for excessive design safety margins, resulting in bulky structural elements in addition to excessive construction waste. This excess weight of structural elements makes construction processes expensive and complicated. To make changes, 3D printing technologies on concrete have gained rapid development in recent years due to the advantages in structural optimization and economy with formwork in conventional construction. Practical engineering applications have proven the applicability of 3D printing in the large-scale construction of building components and compared to conventional manufacturing methods, this advanced technique has a number of advantages and offers almost unlimited potential for arbitrary geometric complexities. [1] The use of 3D printing technology in civil construction represents a great advance in reducing factors such as: waste of materials, cost and weight of the structure. Compared to conventional construction, construction with 3D printing is more efficient, economical, faster, automates processes, reduces the risk of workers' accidents and reduces environmental impacts. [2]

One of the possible applications of this technology would be the printing of dam walls of pumped-storage hydropower (PSH). This type of energy storage represents an excellent solution for non-intermittent energy demand as well as being a clean and sustainable source. Brazil, as reported in the Decennial Energy Expansion Plan (PDE), aims to maintain the participation of renewable energies in the energy matrix at high levels, meeting the goals of reducing greenhouse gases, as evidenced at the Copenhagen conference (COP-15). Bearing in mind the need to meet the sustainability goals and taking into account the privileged hydrography of Brazil, hydroelectric plants are the main source of energy in the country. [3]

Despite the large power generation capacity of Brazilian hydroelectric plants, the PDE pointed to the difficulty of meeting the instantaneous load variation in the short term. One of the alternatives for this service is the implementation of pumped-storage hydropower, which has the advantage of being able to generate energy in a non-intermittent manner. [4]

According to Canales et al. [5], renewable energy technologies have as their main limitation the unpredictability of natural sources, which have variable availability over time. The PSH addresses this problem and works as follows: this plant has two reservoirs at two different levels and water is pumped from the lower reservoir to the upper one when energy generation is greater than demand, and its drop is released for the generation of energy when there is an increase in demand.

This work aims to study new shapes of dam, modeling topologies commonly used in 3D printing, with hollow interior. The motivation comes from the need to optimize the construction of dam walls, looking for lighter shapes that have a good structural performance.

2 Methods

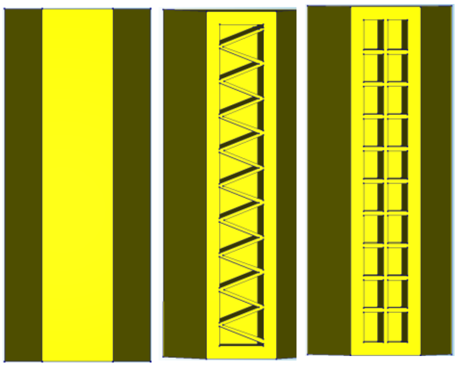
In order to present efficient and viable shapes of dams, a numerical modeling will be carried out using the finite element method and, as initial modeling, three forms commonly used in 3D printing and taken from the literature will be analyzed. In order to find the possible dimensions and compare the stress levels for different heights, each shape will be modeled at three different heights.

The design of the shapes will be carried out in the Autocad program to later be imported into the Diana FEA program, where the boundary conditions, material properties, mesh and, finally, the numerical analysis will be established.

After the modeling, a linear static analysis of the walls with simple concrete will be made to evaluate the stress distribution and integrity of the structure due to the acting forces. As a result, it will be possible to verify whether the structures withstand the loading of water pressure and self-weight.

2.1 Geometry

For evaluation and comparison, three-dimensional models of three shapes of dam were made: one massive and two with a hollow interior (triangular truss and square lattice), as shown in Figures 1a, 1b and 1c. The isometric view of the massive dam is shown in Figure 2, showing the abbreviations of the dimensions, represented by the smaller base (b), larger base (B), height (h) and length (L). The dimensions of each model according to its height are presented in table 1.



(a) (b) (c)

Figures 1a,1b and 1c – Geometries of the dam walls modeled on Diana FEA. Massive shape (a), triangular truss shape (b) and square lattice shape (c).

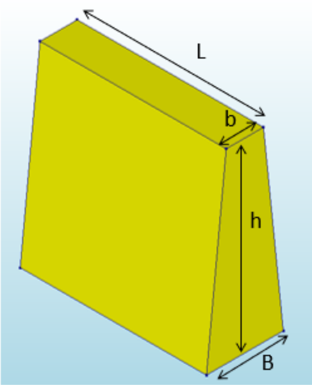


Figure 2 – Representation of the dimensions of the modeled massive dam wall

Table 1 – Dimensions of the dam walls according to its height

h (m)	B (m)	b (m)	L (m)
6	2,475	1,2	6
16	6,6	3,2	16
32	13,2	6,4	32

As shown in Figure 3, the following support restrictions were applied: the base was restricted in the x, y and z directions and the sides were restricted in the x and y directions. Regarding the applied load, it was applied dead weight to the structure and, in one of the sloping parts of the wall, it was applied a hydrostatic pressure. It is important to note that the program calculates the water pressure automatically, with the need to enter only the hydraulic head.

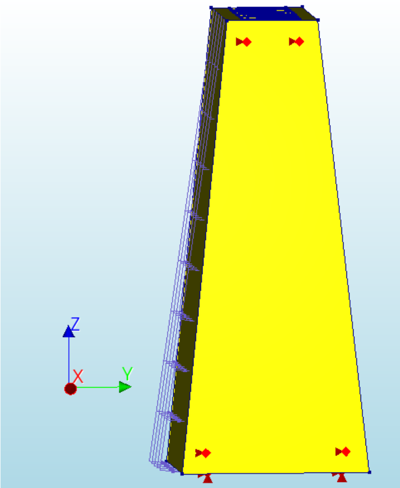
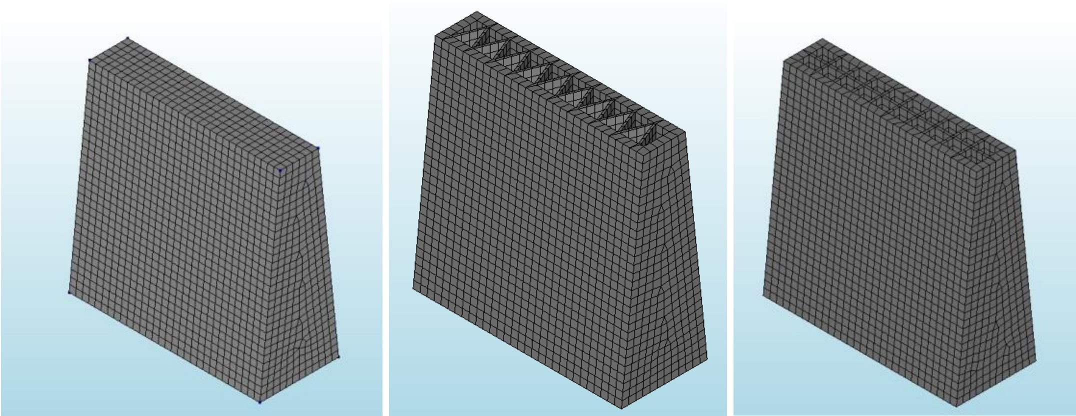


Figure 3 – Supports and loads of the model.

2.2 Mesh

The meshes of the models, shown in figures 4a, 4b and 4c, are formed by hexahedral elements with mesh size of 0.5 meters for dams with 16 meters in height and 0.3 meters for heights of 6 meters. For the finite element analysis, quadratic elements were defined.



(a) (b) (c)

Figures 4a, 4b and 4c – Mesh of the dam walls modeled on Diana FEA. Massive shape (a), triangular truss shape (b) and square lattice shape (c)

2.3 Material properties

The material used was plain concrete and its properties are shown in table 1. For the tensile behavior, the linear model was used with post-crack behavior based on fracture energy (linear-crack energy). For compression, the elastic model was used.

Table 2 – Concrete properties

Property	Value
E	30 GPa
υ	0.2
ρ	2400 kg/m^3
f_t	3,0 Mpa
G_f	200 J/m

2.4 Static Linear Analysis

Static linear analysis is an analysis in which there is a linear relationship between applied forces and displacements. It is applied to structures where stresses remain in the linear elastic field in the material used. In this analysis, the stiffness matrix of the model is constant and the solution process is short compared to the nonlinear analysis of the same model. The linear analysis results provide a first impression of the structure's behavior in the field of pre-cracking.

2.5 Crack index

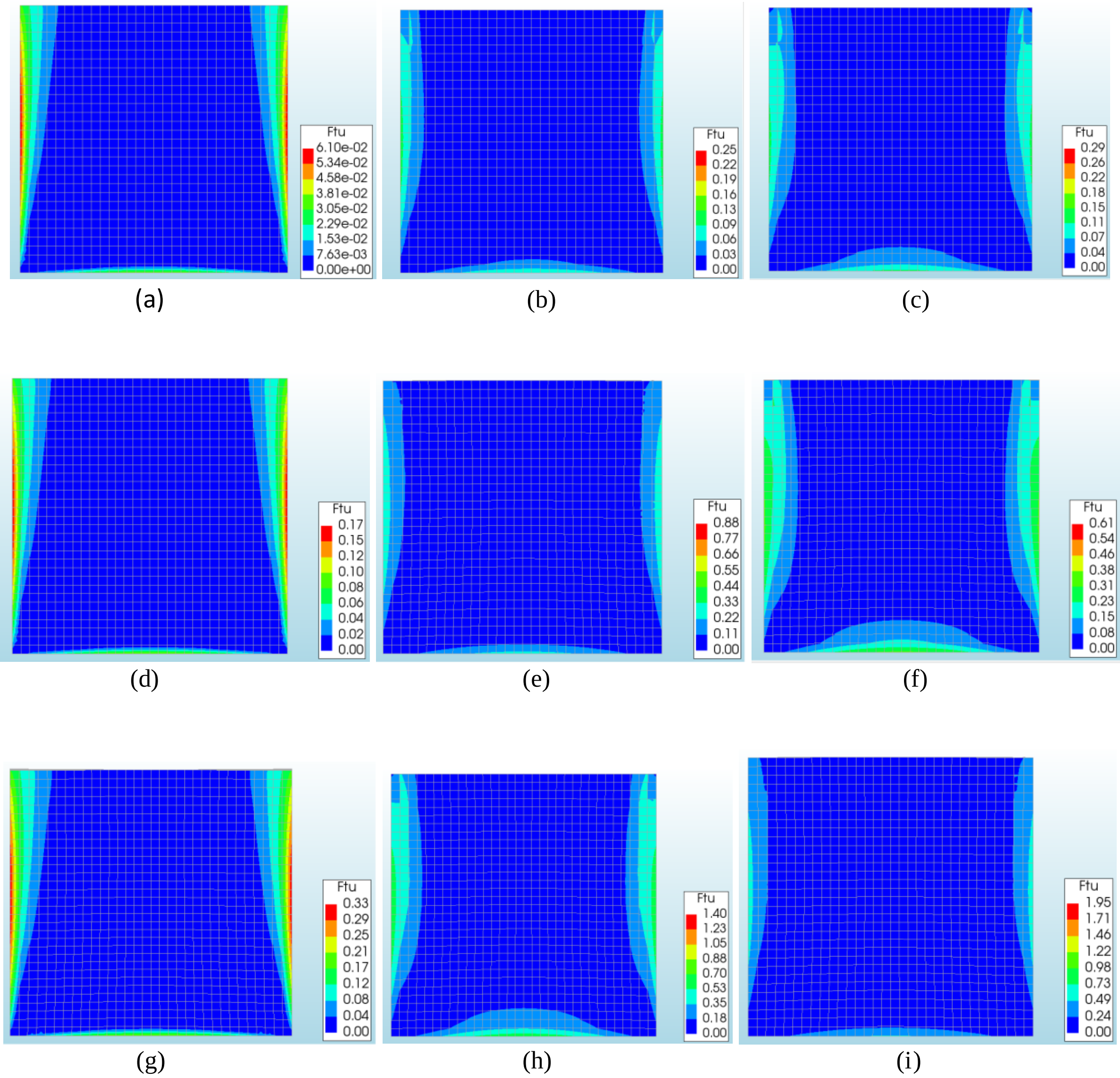
To assess the capacity of the structure to resist the solicitant efforts, the crack index was used, which indicates whether there will be crack formation or not. This index is calculated by the ratio between the maximum principal stress and the tensile strength of concrete, as shown in equation 1. This index takes into account Rankine's theory, which assumes that failure occurs when the maximum principal stress at any point reaches the value equals the maximum normal stress the material can withstand in the uniaxial tensile test. [6]

$$F_{tu} = \frac{\sigma_1}{f_t} \tag{1}$$

where σ_1 is the maximum principal stress and f_t is the concrete tensile strength.

3 Results and discussion

After the linear analysis using the finite element method performed by the program, the crack index maps of each model of dam wall were obtained, as shown in Figures 5a to 5i. As expected, there was a concentration of tensile stress at the extremes of the edges and base of the walls. Figures 5a to 5i present the results of the linear static analysis, presenting the side view (where the water pressure is acting) of the maps of the crack indexes in each model.



Figures 5a to 5i – Crack index maps of modeled dam walls. Massive shape with 6 m of height (a), triangular truss shape with 6 m of height (b), square lattice shape with 6 m of height (c), Massive shape with 16 m of height (d), triangular truss shape with 16 m of height (e), square lattice shape with 16 m of height (f), Massive shape with 32 m of height (g), triangular truss shape with 32 m of height (h), square lattice shape with 32 m of height (i),

For the comparison of the stress distribution in each dam wall, table 2 presents the cracking indexes according to each height and shape.

Table 2 - Height, size of mesh elements, maximum main stress and cracking index of each dam wall

Shape	**Height (m)**	**Mesh (m)**	**σ1 (Mpa)**	**Ftu**
Massive	6	0,3	0,183	0,06
Massive	16	0,5	0,51	0,17
Massice	32	1	0,99	0,33
Triangular truss	6	0,3	1,05	0,35
Triangular truss	16	0,5	2,64	0,88
Triangular truss	32	1	5,85	1,95
Square lattice	6	0,3	0,87	0,29
Square lattice	16	0,5	1,83	0,61
Square lattice	32	1	4,2	1,4

It is important to note that the massive structure presents the best behavior in stress distribution, with the maximum stress of this structure having a lower value than in structures with a hollow interior. However, this structure has a greater mass than the hollow structures, as shown in Table 3. For a height of 6 meters, the difference between the solid structure and the hollow structures is approximately 45 tons, with an effective volume of concrete 30% smaller. This represents a significant loss of weight, showing that these shapes are extremely efficient.

Table 3 - mass and volume of each dam wall

Shape	**Height (m)**	**Volume (m^3)**	**Mass (t)**	**Effective volume of concrete (%)**
Massive	6	66,2	158,8	100,0
Massive	16	1254,4	3010,6	100,0
Massice	32	10035,2	24084,5	100,0
Triangular truss	6	47,0	112,9	71,1
Triangular truss	16	891,9	2140,6	71,1
Triangular truss	32	7135,4	17125,0	71,1
Square lattice	6	47,6	114,3	72,0
Square lattice	16	903,4	2168,2	72,0
Square lattice	32	7227,2	17345,3	72,0

As the hollow structures obtained good results, with a crack index below 1 at heights of 6m and 16m, they are viable and efficient options, being lighter, cheaper and faster to execute. It is also noticed that the structure with a square lattice interior has a better result than the structure with a triangular truss interior.

4 Conclusions

From the results obtained, it is concluded that the shapes with hollow interior represent an excellent alternative for a dam wall form for PSHs. These shapes are remarkably light and withstand well the stresses required for structures with 6 meters of height.

In order to evaluate the use of fibrous concrete and the post-cracking behavior of the dam wall, the next steps are to carry out the model with this type of material, modifying the fracture energy (Gf), constitutive laws and using the nonlinear analysis.

For an initial analysis, truss and lattice structures proved to be excellent ways to use 3D printing in the construction of dam walls and represent a good alternative for reducing the use of materials and having a faster execution.

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