Brazilian savannah trees as bio-inspiration for hydraulic transient control in a penstock of a small hydropower plant

ABSTRACT

This study proposes an innovation, which is to use a non-circular and bio-inspired forced conduit (a new penstock with a cross section inspired by a tree trunk), to control the effects of hydraulic transients in Brazilian Small Hydropower Plants (SHPs). The aim is to demonstrate that natural structures, adapted to periodic environmental disturbances, are better at hydraulic transient control than traditional conduits. The proposed methodology includes the following steps: (1) problem identification; (2) potential biological model identification; (3) development of alternatives; (4) implementation and testing; and (5) solution selection. This research was conducted at the São Tadeu I SHP, in the city of Santo Antônio de Leverger/MT, Brazil. The following tree biological models from the Brazilian savannah (Cerrado) were used: the *Handroanthus capitatus* and *Strychnos pseudoquina* species. The proposed innovation improves the conduit of the traditional circular section and the relief valve solution of the criteria studied. The reason for this improvement was the reduction of wave speed in the non-circular section (from 1,126 to 583 m s^{-1}).

Keywords: Biotechnology; Cerrado; pipeline; tree trunk; tube geometry; wave speed reduction

1. Introduction

In the global electricity matrix, hydroelectric power accounts for 16.1% of the total, while in the case of Brazil, hydroelectric power contributes 56.8% (EPE, 2022). An analysis of the hydroelectric generation potential of the Brazilian park estimates a potential of 176 GW (EPE, 2020). The estimate includes Large Hydropower Plants (LHPs) and Small Hydropower Plants (SHPs, up to 30 MW), considering inventory studies completed and approved by the Brazilian Electric Energy Agency (ANEEL). The estimated potential may be greater than the availability of restricted water resources due to socio-environmental interference (e.g., national parks, indigenous reserves, quilombo areas, environmental protection areas, and others). Most of the Brazilian hydropower potential to explore is concentrated in the North and Central-West regions, highlighting the fact that most of the major inventoried projects are concentrated in the hydrographic regions of the Amazonia and Tocantins-Araguaia (EPE, 2020). In the Central-West region, Mato Grosso (MT) State has presented an increasing consumption of electric energy, by 5% per year, from 2007 to 2017. Over the specified period, the region witnessed a notable surge in energy production, registering a remarkable 194% increase, equivalent to an average annual growth rate of 6% (NIEPE, 2019). In alignment with this trajectory of growth, it has been forecast that the expansion will encompass the addition of two more hydropower plants and the establishment of 17 additional small hydropower plants. (AGER, 2021).

According to AGER (2021), concerning the generation units under construction, inspection activities suggest efforts by entrepreneurs to comply with the works schedule approved by ANEEL. These efforts include various aspects such as energy commercialisation, plant integration into the distribution network, establishing transmission facilities, securing financing for the enterprise, and other considerations. For operating power plants, different aspects can be cited, namely: plant performance (technical and operational conditions), dam safety, and significant incidents (safety conditions). Supervised actions have revealed instances of non-compliance and inadequate maintenance of goods and installations, as well as obstruction of hydraulic structures, such as the upper storage basin and pressure relief valve chamber in the city of Brasnorte, MT, and the tunnel in the city of Santo Antônio de Leverger, MT, observed during hydraulic transient performance tests (AGER, 2010; AGER, 2012; Guidicini et al., 2022). The resulting revenue is also in agreement with these points, as EPE (2019) mentions that over time, there have been many losses of hydroelectric plants that have affected the generation performance. Consequently, reducing its efficiency and exacerbating unavailability rates, until the point where deterioration reaches an irrecoverable stage, definitively interrupting the energy supply. The reversal of this trend can be achieved by the actions of repowering and modernising the generation units (EPE, 2019).

Requirements for modernisation and innovation in hydraulic transients is a topic that gives rise to problems in hydroelectric plants in MT. Some advances in this research area include the following: Anderson and Johnson (1990) studied the propagation speed of pressure waves and their relationship with Young's modulus in blood vessel walls. The findings suggest that even minor ovalisation in the tube can lead to significant decreases in both wave propagation speeds and Young’s modulus. Bending-induced changes in a cross-section shape with internal pressure increased the apparent elasticity of the tube wall (Anderson and Johnson, 1990). Another study focused on the research efforts of a new method to identify the presence of stiffness weakness along a pipe (Hachem and Schleiss, 2012). Wave speed and wave attenuation factors during transients are considered global indicators of local changes. The method was able to locate the stiffness weakness along the test tube and the error in position estimation varied up to 23% (Hachem and Schleiss, 2012). Aiming to achieve the ideal design of tunnels and compensation tanks at the Marun hydroelectric plant (a large hydroelectric dam in operation located in southwestern Iran), Fathi-Moghadam et al. (2013) developed hydraulic transient simulations linked to an optimisation technique. The emergency operating condition (maximum oscillation pressure) was studied. A genetic algorithm optimisation technique was used to select the optimal diameter for the inlet tunnel, penstocks, and surge tanks. The results revealed considerable savings in construction costs. Aiming to contribute to safety aspects of the Montbovon hydroelectric plant installation (located in Fribourg, Switzerland), Alligné et al. (2019) modeled hydraulic transient events in the interruption of discharge in the event of a pipe rupture (gate protection valve equipped with downstream air valve). The results showed that the pipe rupture simulation should consider: (1) the cavitation model in the gate protection valve; (2) the separation of the water column in the gate; and (3) air intake through air valves located downstream of the valve to obtain realistic results. In another study, the insertion of circular tubes into a pipeline with water hammer occurrences was tested (Kubrak and Kodura, 2020). In the research, three types of circular tubes — a thin-walled tube, a thick-walled tube, and a solid cylindrical tube — were evaluated. According to Kubrak and Kodura (2020), the results showed that by inserting a tube with a low modulus of elasticity can have a damping effect on the water hammer phenomenon, that is, it reduces the speed of the pressure wave and the maximum increase in water pressure.

In this context, there are opportunities for actions aimed at improving operation and maintenance (O&M) processes, adaptive management, and innovation focusing on pressure wave propagation speed. This study proposes an innovation, the use of a non-circular and bioinspired forced conduit section, to control the effects of hydraulic transients in a Brazilian Small Hydropower Plant (SHP). The main aim is to show that natural fluid support and transport structures, adapted to periodic environmental disturbances (burning and tipping) are better at hydraulic transient control than traditional conduits.

2. Theoretical background

This study does not aim to delve deeply into the fundamental subject matter of this research area. Instead, it provides concise presentations of the themes and suggests literature for those interested in further exploration of this field.

2.1. Biomimetics and bio-inspiration

Natural selection serves as a mechanism through which nature has processed, refined, and enhanced elements of the biological foundation over millions of years. Researchers can learn from these evolutionary refinements and use them intending to create new improvements in technology, thus this interdisciplinary synergy is the field of Biomimetics (Meyers et al., 2008).

According to Iouguina et al. (2014), the fields of biomimetics and bio-inspiration encompass a broad range of objectives and contexts. However, they are differentiated by their focus: biomimetics emphasises mechanical capacities, while bio-inspiration serves as an inclusive term encompassing bionics and biomimicry fields. Definitions of biomimetics include Schmitt, who officially coined the term biomimetics, a derivative of the Greek words bios (life) and mimesis (imitate). Another definition was given by Bar-Cohen which mentions that it represents the study and the imitation of the methods of the nature, projects and processes (Iouguina et al., 2014). These fields have shown promising results regarding energy systems. A study, which was inspired by insect wings to develop aeolian turbine archetypes, initiated turbine designs 35% more efficient than the conventional turbines (Cognet et al., 2017). In another study, the characteristics of the existing wave energy converters were analysed using biomimetics ideas in order to obtain hidden rules for improved designs (Zhang and Aggidis, 2018). More recently, efforts have been made to identify valuable biological entities, or cases of bionic design, which can inspire new wave energy converters (Zhang et al., 2022).

In general, the practical aspects of biomimetics can be accomplished by two approaches, solution-based and problem-driven (Fayemi et al., 2017). The solution-based approach describes the process of the biomimetic development for which the knowledge about biological systems are the kick-starters to a new technical project. On the other hand, the problem-driven approach is a biomimetic development process that determines a practical problem, in which an identified problem is the starting point for the process (Fayemi et al., 2017). The approaches can be further explored by interested researchers consulting the works of Vincent et al. (2006), Meyers et al. (2008), Iouguina et al. (2014), Fayemi et al. (2017), Ulhøi (2021), Wommer and Wanieck (2022) and Gebeshuber (2022).

2.2. Natural structures of support and transport of fluids

Plant stems naturally serve as structures for sustaining and fluid conduits. The stems establish the connection between the roots and leaves, responsible for supporting the plant and carrying water and mineral salt from the roots to the leaves, as well as carrying the sugars (produced in the photo syntheses) from leaves to the roots (Meyers et al., 2008). Considering the basic idea of this research and the fact that the biome of interest is the Brazilian tropical savannah (Cerrado), it is essential to present some main characteristics. The Cerrado is characterised by having two well-defined seasons: dry and rainy. The severe climatic conditions of the Brazilian Savannah (Cerrado), which has frequent wildfires and water stress (periods of waterlogged soils and dry periods), have directed the evolution of its flora (Sartorelli and Campos Filho, 2017). The twisted appearance of its trees and bushes is a consequence of the occurrence of fire, and the thick bark of the trunks acts as a defence mechanism for the trees against fire (MMA, 2007; Simon and Pennington, 2012). Regarding this, plants have improved the ability to store water, nutrients and sprout after fire and collapse, which gives the biome high resilience (Sartorelli and Campos Filho, 2017). Tree species included low heights varying from 6 m to 8 m, thick corky bark, mostly blackened by fire, and root sprouting (Borges et al., 2014; Simon and Pennington, 2012). Covering more than 20% of Brazilian territory, the Brazilian savannah (Cerrado) is not as famous as the Amazon Forest, but it is also rich in biodiversity (Alencar et al., 2020). For example, photographic registers of Brazilian savanna biome samples (before and after the forest fire) are shown in Fig. 1.

Given the harsh environmental conditions of the Brazilian savannah, there is an expectation that its improvement could inspire the development of technologies capable of meeting similarly challenging requirements. There remains ample room for exploration regarding the Brazilian savannah, and those interested are encouraged to consult the works of MMA (2007), Simon and Pennington (2012), Borges et al. (2014), IBRAM (2016), Sartorelli and Campos Filho (2017), Sano et al. (2019), Alencar et al. (2020), Gomes et al., (2020), Silva et al., (2021).

2.3. Basic transient equation

The equation that relates the increase in pressure caused by disturbances (a sudden change of speed) in the flow of forced conduits can be derived by the movement´s equation in a volume of a pipe section where the outflow change occurs (Tullis, 1989). Equation 1 presents the relation between the pressure increase and speed disturbance, often referred to as Joukowsky's law (Stephenson, 1989).

$$\Delta H = \frac{-a\Delta V}{g} \tag{1}$$

Where: ΔH is the head rise; a is the wave speed; ΔV is the reduction in flow velocity; and g = 9.81 m s^{-2} is the acceleration due to gravity.

The a is a parameter that must be precisely evaluated for each system. This value depends on the density and the volumetric module of the liquid, elasticity, diameter and the thickness of the pipe is the wall and the presence of air or free gas (Tullis, 1989). The calculation of a is derived from the application of (1) the equation of continuity, (2) Joukowsky's law, (3) relation between ΔH and liquid´s bulk modulus (4) expansion of the pipe due to its tension-deformation properties (Tullis, 1989). Taking into account the expansion of the pipeline's length and diameter, as well as the fluid compression and its mathematical treatment, results in Eq 2.

$$\frac{g\Delta H}{a^2} = \frac{\Delta A}{A} + \frac{\Delta \rho}{\rho} \tag{2}$$

Where: ΔA is the increase of the pipe cross-section area; A is the pipe cross-section area; $\Delta\rho$ is the increase of mass density; and ρ is the fluid´s mass density.

According to Tullis (1989), the aim is to express the wave speed as a function of fluid and pipe properties which are readily obtainable. Then, inserting the bulk modulus of the liquid and the static pressure into Eq. 2 leads to Eq. 3. The term $(CK\Delta A)/(A\Delta p)$ is derived by the tension deformation pipe properties.

$$a^2 = \frac{K/\rho}{1 + (CK\Delta A)/(A\Delta p)} \tag{3}$$

Where: K is the bulk modulus of the liquid; C is the effect of pipe constraint; and Δp is the pressure increase.

To solve hydraulic transient problems, the Method of Characteristics is the most commonly used (Larock et al., 2000). The transient flow analysis is based on the equations of the amount of movement and continuity, as expressed by the derived partial Eqs 4 and 5. Eqs 4 and 5 were simplified by comparing the relative magnitudes of the various terms and eliminating those of lesser importance. More details are available in Tullis (1989).

$$g\frac{\partial H}{\partial x}+\frac{\partial V}{\partial t}+\frac{fV|V|}{2D}=0 \qquad (4)$$

$$\frac{\partial H}{\partial t}+\frac{a^2}{g}\frac{\partial V}{\partial x}=0 \qquad (5)$$

Where: x is the longitudinal coordinate; f is the friction coefficient; V is the average fluid speed; D is the internal pipe diameter; and t is the time.

The mathematical treatment of Eqs 4 and 5 considering simplifications is solved by the Finite Difference Method that results in Eqs 6, 7, ..., 11.

$$C+: H_{P,I} = C_P - BQ_{P,I} \qquad (6)$$

$$C-: H_{P,I} = C_M + BQ_{P,I} \qquad (7)$$

$$C_P = H_{I-1} + BQ_{I-1} - RQ_{I-1}|Q_{I-1}| \qquad (8)$$

$$C_M = H_{I+1} - BQ_{I+1} + RQ_{I+1}|Q_{I+1}| \qquad (9)$$

$$B=\frac{a}{gA} \qquad (10)$$

$$R=\frac{f\Delta x}{2gDA^2} \qquad (11)$$

Where: $H_{P,I}$ and H_I are piezometric heads in node I, in the present and past time, respectively; $Q_{P,I}$ and Q_I are the flow on node I, in the present and past time, respectively; and Δx is the distance between nodes.

Complementary information about the basic equations of the hydraulic transient can be found in Wylie and Streeter (1978), Watters (1979), Tullis (1989), Stephenson (1989), and Larock et al., (2000).

2.4. Boundary conditions

Afterwards, some boundary conditions of common small hydropower plants are briefly presented, such as reservoir, surge tank, sudden cross-section changes, turbine, butterfly valve and relief valve (Pejovic et al., 1987; Brekke, 2014).

In the boundary condition of the reservoir (node 1), which is considered to have a large storage capacity, the water level does not change during the transient and the head will remain constant $H_{P,I} = H_{R,I}$ = piezometric head at reservoir. Flow $Q_{P,I}$ will be calculated by Eq. 7 (Tullis, 1989).

Some reduction of costs can be obtained when the surge tank has a diameter smaller than the main pipe and some discharge is allowed. In these cases, Eqs 12, 13, ..., 20 represent the boundary conditions (Tullis, 1989).

$$H_{P,NT} = 0.5\left(-C_7 \pm \sqrt{C_7^2 - 4C_8}\right) \tag{12}$$

$$C_1 = X_{LT} + \frac{\Delta t}{2A_t}\left[\frac{(C_P + C_M)}{B} + Q_T\right] \tag{13}$$

$$C_2 = \frac{\Delta t}{(BA_t)} \tag{14}$$

$$C_3 = g\Delta t A_{TA} \tag{15}$$

$$C_4 = \frac{(C_P + C_M)}{B} - Q_T \tag{16}$$

$$C_5 = \frac{C_1}{C_3} \tag{17}$$

$$C_6 = \frac{C_2}{C_3} \tag{18}$$

$$C_7 = \frac{-B\left(C_4C_6 + 2\frac{C_5}{B} + C_2 + 1\right)}{(2C_6)} \tag{19}$$

$$C_8 = \frac{B(C_4C_5 + Z_{NT} + C_1)}{2C_6} \tag{20}$$

Where: $H_{P,NT}$ is the piezometric head on the surge tank; X_{LPT} and X_{LT} represent the water level on the surge tank, in the present and past time; Δt is the time step; A_{TA} is the cross-section area of the surge tank; Q_T is the flow on the surge tank; Z_{NT} is the topographic elevation of the surge tank. The term $Q_{P,NT}$ can be determined by Eq. 6. Complementary equations are necessary and more details are available in Tullis (1989).

The cross-section changes in a hydraulic system might cause a located head loss. In this case, one variable is known, the located head loss coefficient (K_l); three variables are unknown flow ($Q_{P,NL}$), piezometric head loss upstream ($H_{P,NL}$); piezometric head loss downstream (H_{PD}). The Eqs are 21, 22, ..., 25. Complementary material can be found in the work of Tullis (1989).

$$H_{P,NL} - H_{PD} = C_8 Q_{P,NL}^2 \tag{21}$$

$$C_8 = \pm \frac{K_l}{\left(2gA^2\right)} \tag{22}$$

$$Q_{P,NL} = 0.5\left(-C_9 \pm \sqrt{C_9^2 - 4C_{10}}\right) \tag{23}$$

$$C_9 = \frac{2B}{C_8} \tag{24}$$

$$C_{10} = \frac{\left(C_M - C_P\right)}{C_8} \tag{25}$$

For the turbine, there is a speed increase in the rotor as rotation and pressure are caused by the disturbance in the flow and there is a direct relation with the performance curves of the turbine (hill chart) and the controlling equipment of flow to the turbines (servomotor pistons). In this paper, the hydraulic condition studied is power failure during turbine operation with the rapid closure of the control valve. In this condition, the unit suddenly rejects the load during start-up (failure to start) or during steady-state operation (e.g. a short circuit of the transmission line). This is a normal operating condition, expected and executed as planned (Pejovic et al., 1987). The servomotor has its function guided by parameters as servomotor dead time, T_q; minimum closure time from the fully open position, T_f; cushioning time, T_h; and, total closure time, T_z (Fig. 2). According to Pejovic et al. (1987) and Brekke (2014), usual values of these parameters include:

- T_q : 0.3 until 0.7 s;
- T_f : 4 until 6 s;
- T_h : 4 until 6 s;
- Position of transition of the piston of the servomotor (y_h) : 0.1 until 0.2.

Brekke (2014), presents a procedure to calculate the increase pressure, when the turbine characteristics are known and the boundary condition can be resumed: (1) activation of the servomotor; (2) variation in the angular speed of the rotor; (3) change of outflow in the turbine; (4) pressure rise, as shown in Eq. 6. Representing these boundary conditions results in Eqs 26, 27, ..., 30. More details about turbine boundary conditions can be found in Wylie and Streeter (1978), Pejovic et al. (1987) and Brekke (2014).

$$H_{P,TU} = C_P - BQ_{P,TU} \tag{26}$$

$$H_{P,TU} = H_{TU}\left(\alpha^2 + \upsilon^2\right)\left(A_0 + A_1 x\right) \tag{27}$$

$$T = T_R\left(\alpha^2 + \upsilon^2\right)\left(A_0 + A_1 x\right) \tag{28}$$

$$\frac{T}{T_R} - \frac{P_G}{\alpha}\frac{C_{SI}}{T_R \omega_R} = \frac{\omega_R}{T_R}\frac{WR^2}{g}\frac{d\alpha}{dt} \tag{29}$$

$$T_f T_\alpha \frac{d^2 y}{dt^2} + T_\alpha^{'} \frac{dy}{dt} + \sigma(y-1) + \alpha - 1 + T_d \frac{d\alpha}{dt} = 0 \tag{30}$$

Where: $H_{P,TU}$ is the piezometric head on the turbine, in present time; $Q_{P,TU}$ is the flow on the turbine, in present time; HP_{TU} is the piezometric head on the turbine, in present time; H_{TU} is the piezometric head on the turbine, in past time; α is the speed ratio, dimensionless; υ is the velocity ratio, dimensionless; A_0, A_1, B_0 and B_1 are coefficients that depend upon the zone of operation; $x = \tan^{-1}(\upsilon/\alpha)$; T is the instantaneous torque on the turbine; T_R is the rated torque on the turbine; P_G is the power absorbed by the generator; C_{SI} is a conversion constant used in SI; ω_R is the velocity angular of the turbine; WR^2/g is the polar moment of inertia of the rotating parts; T_α is the ratio of the change in speed deviation to the change in relative servo velocity, dimensionless; y is the piston servomotor position, dimensionless; σ is the real part of complex valued frequency, dimensionless.

For a butterfly valve at the end of the pipe, the boundary condition is the equation for head loss across the valve (Tullis, 1989). After the butterfly valve is completely closed, its boundary condition is similar to that of a dead-end pipe. For the valve fully close its boundary condition is similar to dead-end pipe. At the closed position ($Q_{P,BV} = 0$), the piezometric head ($H_{P,BV}$) is found from Eq. 6 or 7 (Tullis, 1989).

The relief valve acts to control the limiting pressure values, preventing the exceeding of a pressure value of interest (set point pressure). The boundary includes Eqs 23, 31, 32 and 33, according to Tullis (1989). Complementary equations and relief valve technical data (e.g., discard coefficients, opening time, closing time) are necessary to fully understand this boundary condition. More information can be found in Wylie and Streeter (1978) and Tullis (1989).

$$H_{P,NV} = C_P - BQ_{P,NV} \tag{31}$$

$$H_{P,NV} = C_M + BQ_{PD} \tag{32}$$

$$Q_{P,NV} = Q_{PV} + Q_{PD} \tag{33}$$

Where: HP_{NV} is the piezometric head on the relief valve; $Q_{P,NV}$ is the upstream flow of the relief valve; Q_{PD} is the downstream flow of the relief valve; and Q_{PV} is the flow on the relief valve discharge. The term Q_{PV} can be found according to the characteristics of its relief valve (engineering data) and the piezometric head upstream and downstream of the valve.

2.5. Choosing a protection device

The hydraulic transient effects and the choice of the protection device will depend on the physical and hydraulic characteristics of the hydropower plant layout. A table showing a summary for choosing the protection device was proposed by Stephenson (1989). In any case regarding choosing the protection device, the main objective is to prevent serious damage to the installations. In general, it is desirable that the permissible maximum pressure is not exceeded in order to prevent damage or rupture; and, that the minimum pressure does not reach levels of cavitation, separation of the water column, as well as the potential event of buckling (Ramos, 2000). In agreement, Pejovic et al. (1987) mentions that there should be no vacuum in the tunnel or in the forced conduit in any period of time. If necessary, a protection condition can include one or several of the devices: (1) surge tanks; (2) relief valves; (3) governors; (4) deceleration of wicket gate closure; (5) air chambers; (6) bleeding in air; (7) non-circular conduit; (8) flexible hose; (9) check valves; (10) flow-control valves; (11) surge suppressors (Wylie and Streeter, 1978; Pejovic et al., 1987). In this case, the protection device alternative that ensures the minimum pressure load amplitude and the minimum occurrence of vacuum can be considered as the best option.

3. Study area

In this paper, the São Tadeu I Small Hydropower Plant (SHP), located in the municipality of Santo Antônio de Leverger, Mato Grosso State (MT), Brazil was adopted as a research case study. Figure 3 shows the location and the general layout of São Tadeu I SHP. Technical information can be found below according to (ANEEL, 2009):

- Nominal Power: 9.278 MW
- Number of turbines, type: 2, Horizontal Francis
- Nominal head: 200 m
- Nominal discharge: 5.47 $m^3\ s^{-1}$
- Nominal speed: 900 rpm
- Tunnel - length, base, arch: 2,460 m, 4.5 m, 5.0 m
- Penstock - length, diameter: 128 m, 1.75 m
- Surge tank - high, diameter: 162 m, 2.6 m.

As a justification for choosing the area, the following points can be considered: lack of information to help further studies and development of hydropower plant projects in MT, Brazil; the presence of typical SHP elements, which can be considered a valid representative of the SHP resource of MT, Brazil (ANEEL, 2009); occurrence of a structural problem related to the hydraulic transient, hydraulic rupture of the adduction tunnel during the pressurisation test (Assis, 2009; Guidicini et al., 2022).

The occurrence of hydraulic disruption in the adduction tunnel (that is, the load of chamber pressure of the tunnel that exceeded the resistance of the surrounding rocky bulk) during the pressurisation test generated ousting, in few hours, of all the volume of water that filled the tunnel (Assis, 2009; Guidicini et al., 2022). This caused serious damage to civil works and the equipment itself, delaying the start-up of the project by more than a year (Guidicini et al., 2022). Among the recovery measures implemented are: determining the extent of the new shielding; developing structural designs of the support bases and anchoring blocks of the new conduit; the hydraulic analysis of the forced conduit; and others (Guidicini et al., 2022). Moreover, the recurrence of leakage in the forced conduit expansion joint, observed during technical inspections, may be related to difficulties of the adductor system in dealing with hydraulic transients (AGER, 2013; AGER, 2017). Naturally, there is a need for studies to evaluate this relationship.

The hydraulic rupture of the adduction tunnel and the presence of leakage in the expansion joint associated with the desire to improve operation and maintenance (O&M) processes were motivating factors for this research.

4. Methodology

Based on the idea of solving a practical problem (effects of hydraulic transient in a hydropower plant adduction system), the problem-driven approach was adopted, according to Fayemi et al. (2017). The proposed methodology includes the following steps: (1) problem identification; (2) potential biological model identification; (3) development of alternatives; (4) implementation and testing; and (5) solution selection.

4.1. Problem identification

To identify the problem, bibliographic research on technical information was carried out and difficulties in operation and maintenance (O&M) processes in the study area were detected. Special attention was given to the hydraulic transient subject and conditions of extreme requirements of the adductor system. Furthermore, hydraulic simulations were used, such as the Visual Basic for Applications (VBA) programming environment, hosted in MS Excel software. The Method of Characteristics and the studies conducted by Wylie and Streeter (1978), Pejovic et al. (1987), Tullis (1989), Larock et al., (2000) and Brekke (2014) were used.

4.2. Potential biological model identification

According to Fayemi et al. (2017), to identify the potential biological model, a question about nature must be formulated to explore its progress in a given function. To formulate the question two points are important, the first is nature and the second is function. Considering nature and the biome in which the study area is inserted, nature can be represented by the Brazilian savannah (Cerrado). Considering the function, the history of O&M difficulties in the study area, and the routine of hydraulic transients wear down the tunnel, the penstock, and connections, leading them to work inefficiently (AGER, 2013; AGER, 2017; Guidicini et al., 2022). Thus, the function of interest is the adaptation to recurrent physical disturbance in fluid conductors. Therefore, a question was formulated: in open pastures, which fluid conductor would be better adapted to this recurrent physical disturbance? A simple answer to the question would be a Brazilian savannah tree trunk, known to be adapted to extreme environmental conditions such as felling, fire and water stress (Sartorelli and Campos Filho, 2017). To provide a precise answer to the question, significant effort in research is essential. Activities such as defining performance criteria to identifying the most effective conductor and conducting tests using a representative sample of plants are crucial. Two tree species were studied: *Handroanthus* *capitatus* (popular name is Ipê Amarelo) and *Strychnos pseudoquina* (popular name is Quina do Cerrado), as shown in Figs 1c and 1d. They were chosen due to the frequent occurrence in the Brazilian savannah and because these trunk trees are the potential biological model (Borges et al., 2014; Sartorelli and Campos Filho, 2017).

4.3. Development of alternatives

To develop alternatives, two approaches were adopted: the innovative approach and the traditional approach. For the innovative approach, the method used was the non-circular conduit to control the hydraulic transient and reduce the propagation speed of a pressure wave (Wylie and Streeter, 1978). Integrating this method with the natural fluid conduit (tree trunk), adapted to recurrent physical disturbances (fluctuating flood and drought conditions, occurrence of wildfires), leads to the alternative of replacing the traditional circular cross-section with a non-circular tree trunk cross-section. These trees have highly irregular trunks and can withstand significant changes in water flow. When in hydraulic transient, penstocks in hydroelectric plants also face extreme conditions (changes in water flow and pressure). This similarity is the main reason for choosing the highly irregular section alternative. The choice of quadrant prioritised the irregularity of the quadrant. For the sake of illustration, the development of alternatives is shown in Fig. 4.

For the traditional approach, the alternative relief valve was chosen, aligning with recommendations in the literature for the study area (Wylie and Streeter, 1978; Pejovic et al., 1987; Tullis, 1989; and Stephenson, 1989). The relief valve simulation was based on the following points: in the installation at the midpoint between the tunnel forced conduction transition and the butterfly valve; presence of a central adjustment device with control functions, function 1 (reaction time, $t_R = 0$ s), function 2 (opening time, $t_O = 2$ s), function 3 (closing time, $t_C = 15$ s); maximum allowable pressure equal to the pressure in the permanent flow plus 5%; and the globe valve discharge coefficient presented by Tullis (1989). The values of t_R, t_a and t_C were defined with an iterative trial and error process. Information techniques on the relief valve used for the simulation can be found in Bermad (2020).

4.4. Implementation and testing

Regarding implementation and testing, it was based on the understanding that the implementation is the simulation of replacing the traditional circular cross-section forced conduit with another non-circular cross-section conduit of equal area. Pressure propagation velocity (a) estimates were performed considering Eq. 3 and the calculation of ΔA for the non-circular section, according to research by Jenkner (1971), Wylie and Streeter (1978), Watters (1979) and Tullis (1989). The term ΔA was defined as the sum of the increase in the infinitesimal areas, as shown in Fig. 5 and Eqs 34, 35, 36 and 37.

$$\frac{\Delta A}{A\Delta p} = \frac{1}{eEA}\left(2\sum_{i=1}^{n}\sum_{j=1}^{2} d_{i,j}^{2} D_{i,j} + \frac{1}{60e^{2}}\sum_{i=1}^{n}\sum_{j=1}^{2} D_{i,j}^{5}\right) \tag{34}$$

$$\Delta D_{i,j} = \frac{\Delta p}{eE} d_{i,j} D_{i,j} \tag{35}$$

$$d_{i,j} = 0.5\left(b_{i,j} + B_{i,j}\right) \tag{36}$$

$$\Delta d_{i,j} = d_{i,j}^{2} \frac{\Delta p}{eE} \tag{37}$$

Where: i is a subscript that represents the infinitesimal element, $i = 1, 2, \ldots, n$; j is a subscript that represents the part of a non-circular section, $j = 1$ if quadrant is 1 or 2, $j = 2$ if quadrant is 3 or 4; $D_{i,j}$ is the infinitesimal length of wall pipe; $\Delta D_{i,j}$ is the increase in the infinitesimal length of wall pipe; $d_{i,j}$ is the average height of the infinitesimal element; $\Delta d_{i,j}$ is the increase in the average height of the element infinitesimal; e is the thickness of the pipe wall; E is the elasticity modulus; $b_{i,j}$ is the minimum height of infinitesimal element; and $B_{i,j}$ is the maximum height of the infinitesimal element. Details of the set of equations are available in Appendices A and B.

To carry out the tests, the estimated value of a was used to simulate the condition of power failure during turbine operation with the rapid closure of the control valve (load rejection). The following parameters were adopted for hydraulic simulation: time of minimum closing, $T_f = 5$ s; time of damping, $T_h = 0$ s; position of transition of the piston of the servomotor, $y_h = 0.16$; characteristic hill chart curves for the Francis turbine of Brekke (2014) adapted to the ANEEL (2009). The parameters used as references were from Pejovic et al. (1987), STE (2013) and Brekke (2014). The hydraulic simulations followed the same procedures used to identify the problem.

4.5. Solution selection

To choose the solution, the criteria of pressure amplitude (C_{R1}), vacuum incidence (C_{R2}) and graphical pressure analysis (temporal evolution at points of interest and adductor system envelope) were used, in alignment with Pejovic et al. (1987) and Cassano et al. (2020). The selected solution was the alternative that presented minor values of C_{R1} and C_{R2}, as Eqs 38, 39,

…, 41. The interest points are the tunnel near the reservoir (P1); the surge tank (P2); the tunnel-power transition, in the forced conduit (P3); and the butterfly valve (P4).

$$C_{R1} = N^{-1}\sum_{I=1}^{N}\left(P_{I,t,\max} - P_{I.t,\min}\right) \tag{38}$$

$$C_{11,I,t} = \begin{cases} 0, \text{if } H_{P,I,t} \geq Z(i) \\ 1, \text{if } H_{P,I,t} < Z(i) \end{cases} \tag{39}$$

$$C_{12} = \sum_{I=1}^{N}\sum_{t=0}^{t_{\max}} C_{11,I,t} \tag{40}$$

$$C_{R2} = 100\frac{C_{12}}{L} \tag{41}$$

Where: C_{R1} is the average pressure amplitude (kPa); I is the node identifier, $I = 1, 2, ..., N$; $P_{I,t,max}$ is the maximum pressure on node I, in time t_S; $P_{I,t,min}$ is the minimum pressure on node I, in time t_S; $H_{P,I,t}$ is the piezometric head on node I, in time t; $C_{11,I,t}$ is the identifier of the incident of the vacuum event on node I, in time t_S; t_S is the simulation time, $t_S = 0, \Delta t, 2\Delta t, ..., t_{max}$; C_{12} is the total number of incidences of the vacuum event, in time t_S; L is the length of the section; C_{R2} is the incident rate of the vacuum event. The t_{max} was defined using the period of oscillation of the chimney balance (T) and in condition $t_{max} \geq T$, according to Eq. 42.

$$T = 2\pi\sqrt{L_T A_{TN} / gA_{TN}} \tag{42}$$

Where: L_T is the length of the water column (tunnel and tank length); A_{TN} is the tunnel area.

For criterion C_{R1}, it is required to smooth variations, thus achieving smaller pressure transients and reduced levels of mechanical stress. Therefore, the lowest average pressure amplitude is desired, according to Eq. 38. To evaluate the performance according to criterion C_{R2}, a simplified model of equations that identifies, quantifies, and distributes the occurrence of vacuum events over time was proposed (Eqs 39, 40, and 41). Basically, it was considered that every time the piezometric line cuts the conduit, there is a vacuum event. The number of events was added up and distributed longitudinally and temporally. Naturally, there is room for further development, and more robust models can be created.

For graphical analysis, the selected solution was the alternative with the highest stationarity (unstable behaviour over time around a constant average) and the lowest amplitude, the option aimed to attenuate the effects of pressure pulses and fatigue, according to Pejovic et al. (1987) and Cassano et al. (2020).

5. Results

The results of this research are presented below. As the main problems were identified, following bibliographic research and hydraulic simulations, there are important pressure values in the tunnel forced conduction transition, incidence of vacuum events in the tunnel and in the forced conduit. The recurrence of leakage in the expansion joint, which was observed in AGER (2013) and AGER (2017), suggests fatigue due to high pressures and possibly hydraulic transients. The non-zero performance of criterion C_{R2} also suggests possible problems. Both indications need further investigation and adjustment with field data.

As a result of identifying the potential biological model, the trunk sections of the Ipê Amarelo and Quina do Cerrado tree species are shown in Fig. 6. The visual analysis in Fig. 6 indicates the Third and the Second quadrant as the ones with the highest irregularity, therefore they were selected to develop the alternatives. The current situation of the study area (Reference) and the set of alternatives developed (A1, A2, …, A7) can be observed in Fig. 7. As an alternative of the innovative approach, they have A1 alternatives, A2, …, A6. Alternative A7 was chosen from the traditional relief valve approach. In Table 1, descriptive information of the generated alternatives is presented, in Fig. 5. More information about infinitesimal elements of alternatives A1, A2, ..., A6 is available in Appendices A and B.

As results of the implementation and tests, we have the estimates of a and the performance of criteria (C_{R1} and C_{R2}), according to Table 2. Graphs with information on pressure envelopes and temporal evolution at the points of interest are presented in Figs 8 and 9.

The non-circular sections generated desirably important gains in the reduction of a, the reduction rate of a that ranged from 36.0 to 38.2%. This reduction was higher than the values found by Anderson and Johnson (1990), a reduction rate from 6.9 to 8.4%. A possible justification is related to the severe non-regularity of the proposed cross-section as opposed to the mild non-regularity tested by Anderson and Johnson (1990). The values of a were estimated, thus there is a requirement for experimental research for proper validation. The observation of C_{R1} for the tunnel indicates A1 (the lowest pressure amplitude, C_{R1} = 751.9 kPa) as the best alternative and A7 (the second largest pressure amplitude, C_{R1} = 795.5 kPa) showed an improvement compared to the Reference. On the other hand, the observation of C_{R1} for the forced conduit indicated A2 and A4 (lower pressure amplitude, C_{R1} = 2,016.1 kPa) as the best alternatives. A7 showed gain in relation to the Reference (pressure amplitude changed, from C_{R1} = 2,772.6 to 2,073.2 kPa). Therefore, the innovative approach overcame the traditional approach to C_{R1}.

For C_{R2}, in the tunnel, the best alternative was A7 (C_{R2} = 0.8 event 100 m^{-1} s^{-1}), alternatives A3 and A6 presented the worst performances (C_{R2} = 1.8 event 100 m^{-1} s^{-1}). Moreover, for C_{R2}, the observation of the forced conduit did not indicate vacuum occurrence for alternatives A1, A2, ..., A6. The A7 alternative intensified the vacuum occurrence (of C_{R2} = 0.04 for 0.1 event 100 m^{-1} s^{-1}). Therefore, for the $C_{R2,}$ the innovative and traditional approaches were equivalent. A traditional approach surpassed the innovative approach in the tunnel, but it was inferior in the penstock.

Regarding the graphical analysis, it can be observed that the innovative approach resulted in the reduction of maximum values and increase in minimum values in the tunnel and in the forced conduit (see Fig. 8: Reference; A1; A2; ...; A6) eliminating the occurrence of vacuum in the forced conduit. The stationarity was noted in the Hmax and Hmin lines, in the tunnel and in the forced conduit (see Fig. 8: A1; A2; ...; A6). In the traditional approach, a reduction in the maximum and minimum values in the tunnel and in the forced conduit was observed (see Fig. 8: A7). The advantage was the reduction of the requirements of maximum pressure of the forced conduit, the disadvantage was the increase in the occurrence of the vacuum also in the forced conduit (see Fig. 8: Reference and A7). In the traditional approach, there is no stationarity in the Hmax and Hmin lines (see Fig. 8: A7).

The graphical analysis of the temporal evolution of points of interest showed the occurrence of vacuum in P1 in all the alternatives developed. Alternative A7 was the one with the lowest number of vacuum events (see Fig. 9: A1, P1; A2, P1; ...; A7, P1). The observation of the point of interest P2 indicated no influence of alternatives A1, A2, ..., A6 on the pressure. In contrast, alternative A7 influenced the pressure (see Fig. 9: A1, P2; A2, P2; ...; A7, P2). For the point of P3 interest, the A4 alternative indicated minor amplitude of pressure and the A7 alternative the largest amplitude of pressure (see Fig. 9: A1, P3; A2, P3; ...; A7, P3). In none of the alternatives was the occurrence of vacuum in P3 observed. Thus, with regards protecting P3, alternative A4 was the best. In a similar way, for the point of P4 interest, alternatives A2 and A4 presented a minimum amplitude of pressure and the A7 alternative maximum amplitude of pressure (see Fig. 9: A1, P4; A2, P4; ...; A7, P4). Only in alternative A7 vacuum was the point of interest P4 observed. Alternatives A2 and A4 were selected because they consider protection of the point of interest P4.

Naturally, the innovative approach prevailed over the Reference, which was the expected result, because reducing *a* is one of the hydraulic transient control methods. Overall, the innovative approach outperformed the traditional approach in most criteria. The exception was observed when the tunnel protection was desired for the occurrence of vacuum and the protection of the forced conduit for maximum pressure requirements. The alternatives with better performances were A4, A2 and A1, two of these are the cross-section of the unmodified tree trunk. This suggests that the unmodified tree trunk section may overcome modified tree trunk sections and traditional pipe sections, although more studies are required for further proof.

Despite obtaining good results, some concerns are important for sustaining and continuing efforts in this research area. Currently, ways to reduce *a* include incorporating plastic tubes in the penstock and inserting circular tubes, according to works by Kubrak and Kodura (2020) and Kubrak et al. (2021). Evaluating the advantages and disadvantages of this innovation compared to existing alternatives is a concern and must be considered. Another aspect concerns the possible loss of additional energy inherent to the innovation when in permanent operation (as it is a non-circular pipe, greater turbulence, greater energy consumption, and greater unit head loss are expected). In other words, there is an expectation of less energy available for generating electrical energy. How important this loss of available energy will be and whether it can be economically sustained over time is relevant and deserves further investigation. At this point, acknowledging the manufacturing and installation costs is mandatory. Thus, is the cost of innovation (manufacturing, installation, and loss of available energy) lower than the O&M cost of conventional piping systems? These are key questions that require definite answers. Biomimetics and bio-inspiration researchers observe that nature, with its continuous evolution, has overcome greater obstacles than these at times. However, a reliable answer can only be derived from robust scientific evidence.

In an endeavor to facilitate this quest for answers, a comparative analysis was conducted between the load capacity of conventional circular piping and bioinspired non-circular piping. For the load available with the circular piping, São Tadeu I SHP project data were consulted, available in ANEEL (2009). For the load available with the bioinspired non-circular piping, data obtained from the first step (permanent regime, butterfly valve upstream of the turbine completely open) of the simulation of alternative A4 were used. These data were selected because it was the alternative with the best overall performance. The results were as follows: (1) for the circular pipe, the reference liquid head was 200.0 m; (2) for the bioinspired non-circular pipe, the reference liquid head was 198.1 m; (3) 0.95% available energy loss. These results were obtained through simulations and computational modelling, thus there is a requirement for ongoing research in this area and validation through experimental test data and modelling.

6. Summary and conclusions

An innovation aimed at improving operation and maintenance (O&M) processes in hydropower plants has been proposed. A set of alternatives utilising non-circular and bio-inspired sections for forced conduit was developed. The biological models used include Brazilian savannah tree species such as *Handroanthus capitatus* (popular name Ipê Amarelo) and *Strychnos pseudoquina* (popular name Quina do Cerrado). Simulated hydraulic transient tests in a small hydropower plant indicated that the bio-inspired non-circular section conduit surpasses the traditional circular section conduit and the relief valve solution in most of the studied criteria (pressure amplitude, vacuum occurrence, graphical analysis). The aim was to show that natural fluid support and transport structures, adapted to periodic environmental disturbances (burning and tipping) are better at hydraulic transient control than traditional conduits, confirmed using simulated tests (wave speed reduction ranged from 36.0 to 38.2%).

For the specific case study, the use of field data for the validation of the simulations would be of great value. In the case of confirming the reference simulation, it is suggested to investigate solutions that will ensure the non-occurrence of vacuum with respect to system pressure variations. Optimising the functions of the central relief valve adjustment device can be a viable way, while another way would be to combine hydraulic transient control methods.

The recommendations of this research include:

- A study of reliable ways to estimate wave speed (*a*) and alignment with experimental results.
- A study of methods to cancel external supports (anchoring) in pipes with a cross-section of unmodified tree trunks as internal pressures do not cancel out in all directions and senses.
- Accomplishment of experimental tests in order to contribute to the practical validation of the results found.
- Tests with other Cerrado species, using other combinations of quadrants, with combinations of conventional solutions, and with combinations between conventional and innovative solutions (for example, relief valves and bioinspired non-circular piping).

- Using economic criteria (including implementation costs) and multi-criteria methods to select the optimum solution.

Acknowledgements

The authors would like to express their gratitude to the Regulatory Agency for Delegated Public Services of the State of Mato Grosso (AGER) for providing the data, and to the Lancaster University Renewable Energy Group and Fluid Machinery Group.

Appendix A. Calculation of Δ*A* for the non-circular section

Figure A1a shows a unit long non-circular section of pipe of wall thickness *e* subject to an increased pressure Δ*p*, the quadrants (*j* = 1 and *j* = 2), infinitesimal element (*i* = 1, 2, …, *n*) and cross-section length $d_{t,i}$. Due to the axial and diagonal asymmetry, it was assumed that the deformation could be obtained from an infinitesimal element of rectangular shape under internal pressure, as shown in Fig. A1b. This rectangular section, when subjected to internal pressure, is deformed on its smallest side ($D_{i,j}$) according to the approach described in Jenkner (1971). The smallest side of the infinitesimal element, top for *j* = 1 and bottom for *j* = 2, borders the pipe wall; the other sides border neighbouring elements. Therefore, it was assumed that surface deformation occurs basically due to normal forces, as shown in Fig. A1c. The deformation caused by the normal force and stress, see Fig. A1d, can be estimated based on Jenkner (1971), Wylie and Streeter (1978) and Tullis (1989), according to Eqs A.1, A.2, ..., A.14.

$$\Delta D_{i,j} = \frac{\sigma_N}{E} D_{i,j} \tag{A.1}$$

$$\sigma_N = \frac{N}{e d_U} \tag{A.2}$$

$$\Delta p = \frac{F}{A_{i,j}} = \frac{F}{d_{i,j} d_U} \tag{A.3}$$

$$N - F = 0 \tag{A.4}$$

$$N = \Delta p d_{i,j} d_U \tag{A.5}$$

$$\sigma_N = \frac{\Delta p d_{i,j}}{e} \tag{A.6}$$

$$\Delta D_{i,j} = \frac{\Delta p}{eE} d_{i,j} D_{i,j} \tag{A.7}$$

$$\Delta d_{i,j} = d_{i,j} \frac{\Delta D_{i,j}}{D_{i,j}} = d_{i,j}^2 \frac{\Delta p}{eE} \tag{A.8}$$

$$\Delta A_N = \sum_{i=1}^{n} \sum_{j=1}^{2} d_{i,j} \Delta D_{i,j} + \left(D_{i,j} + \Delta D_{i,j}\right) \Delta d_{i,j} = 2 \frac{\Delta p}{eE} \sum_{i=1}^{n} \sum d_{i,j}^2 D_{i,j} \tag{A.9}$$

$$\frac{\Delta A_N}{A\Delta p}=\frac{2}{eEA}\sum_{i=1}^{n}\sum_{j=1}^{2}d_{i,j}^{2}D_{i,j} \qquad \text{(A.10)}$$

$$\Delta A_B=\frac{\Delta p}{60e^3E}\sum_{i=1}^{n}\sum_{j=1}^{2}D_{i,j}^{5} \qquad \text{(A.11)}$$

$$\frac{\Delta A_B}{A\Delta p}=\frac{1}{60e^3EA}\sum_{i=1}^{n}\sum_{j=1}^{2}D_{i,j}^{5} \qquad \text{(A.12)}$$

$$\frac{\Delta A}{A\Delta p}=\frac{\Delta A_N}{A\Delta p}+\frac{\Delta A_B}{A\Delta p} \qquad \text{(A.13)}$$

$$\frac{\Delta A}{A\Delta p}=\frac{1}{eEA}\left(2\sum_{i=1}^{n}\sum_{j=1}^{2}d_{i,j}^{2}D_{i,j}+\frac{1}{60e^2}\sum_{i=1}^{n}\sum_{j=1}^{2}D_{i,j}^{5}\right) \qquad \text{(A.14)}$$

Where: i is a subscript that represents the infinitesimal element, $i = 1, 2, \ldots, n$; j is a subscript that represents the part of a non-circular section, $j = 1$ if quadrant is 1 or 2, $j = 2$ if quadrant is 3 or 4; $D_{i,j}$ is the infinitesimal length of wall pipe; $\Delta D_{i,j}$ is the increase in the infinitesimal length of wall pipe; $d_{i,j}$ is the average height of the element infinitesimal; $\Delta d_{i,j}$ is the increase in the average height of the element infinitesimal; $A_{i,j}$ is the area of pipe in the infinitesimal element; ΔA_N is the increase in the transverse pipe cross-section due to normal forces; σ_N is the lateral unit stress; e is the thickness of pipe wall; E is the elasticity modulus; N is the Normal force; d_U is the longitudinal length of pipe (1 m); F is the force due to internal pressure; ΔA_B is the increase in the transverse pipe cross-section due to bending stress.

The effect of pipe constraint (C) considering the thick-walled pipes (if $D_{i,j}/e > 20$ then thin-walled pipe, otherwise thick-walled pipe). For pipes with functioning expansion joints along their length (Watters, 1979). The Eqs are A.15 and A.16.

$$\frac{D_{i,j}}{e}=\frac{0.01}{0.01575}=0.63 \qquad \text{(A.15)}$$

$$C=\frac{1}{1+\frac{e}{D_{i,j}}}\left[1+2\frac{e}{D_{i,j}}(1+\mu)\left(1+\frac{e}{D_{i,j}}\right)\right]=4.42 \qquad \text{(A.16)}$$

Where: μ is Poisson’s ratio for pipe material ductile cast iron, $\mu \approx 0.28$ (Tullis, 1989).

Appendix B. Non-circular section

The infinitesimal elements of the non-circular sections obtained in the research are shown in Fig. B1.

Notation

μ = Poisson’s ratio for pipe material (–)

σ = real part of complex valued frequency (–)

α = speed ratio (–)

υ = velocity ratio (–)

ΔA_B = increase in pipe cross-section area due to bending stress (m^2)

ΔA_N = increase in pipe cross-section area due to normal forces (m^2)

$\Delta d_{i,j}$ = increase in average height of the infinitesimal element (m)

$\Delta D_{i,j}$ = increase in infinitesimal length of wall pipe (m)

σ_{N} = lateral unit stress (Pa)

ω_R = velocity angular of turbine (rad s^{-1})

A = pipe cross-section area (m^2)

a = wave speed (m s^{-1})

A_0, A_1, B_0 and B_1 = coefficients that depend on the zone of operation

$A_{i,j}$ = area of pipe in the infinitesimal element (m^2)

A_{TA} = cross-section area of surge tank (m^2)

A_{TN} = tunnel area (m^2)

$B_{i,j}$ = maximum height of infinitesimal element (m)

$b_{i,j}$ = minimum height of infinitesimal element (m)

C = effect of pipe constraint (–)

$C_{11,I,t}$ = identifier of incident of vacuum event on node I, in time t_S (number of event)

C_{12} = total number of incidences of vacuum event, in time t_S (event s^{-1})

C_{R1} = average pressure amplitude (kPa)

C_{R2} = incident rate of vacuum event (event 100 m^{-1} s^{-1})

C_{SI} = conversion constant used in SI (–)

D = internal pipe diameter (m)

$d_{i,j}$ = average height of the infinitesimal element (m)

$D_{i,j}$ = infinitesimal length of wall pipe (m)

d_U = longitudinal length of pipe (1 m)

E = elasticity modulus (Pa)

e = thickness of pipe wall (m)

F = force due to internal pressure (N)

f = friction coefficient (–)

g = acceleration due to gravity (m s^{-2})

H_I = piezometric heads in node I, in past time (m)

$H_{P,BV}$ = piezometric head on valve butterfly (m)

H_{PD} = piezometric head loss downstream (m)

$H_{P,I}$ = piezometric heads in node I, in present time (m)

$H_{P,I,t}$ = piezometric head on node I, in time t_S (m)

$H_{P,NL}$ = piezometric head loss upstream (m)

$H_{P,NT}$ = piezometric head on surge tank (m)

$H_{P,NV}$ = piezometric head on relief valve (m)

$H_{P,TU}$ = piezometric head on turbine, in present time (m)

HP_{TU} = piezometric head on turbine, in present time (m)

H_{TU} = piezometric head on turbine, in past time (m)

I = node identifier, $I = 1, 2, ..., N$

i = subscript that represents the infinitesimal element, $i = 1, 2, \ldots, n$

j = subscript that represents the part of a non-circular section

K = bulk modulus of the liquid (Pa)

K_l = located head loss coefficient (–)

L = length of the section (m)

L_T = length of the water column, tunnel and tank length (m)

P_G = power absorbed by generator (W);

$P_{I,t,max}$ = maximum pressure on node I, in time t_S (kPa)

$P_{I,t,min}$ = minimum pressure on node I, in time t_S (kPa)

Q_I = flow on node I, in past time ($m^3\ s^{-1}$)

$Q_{P,BV}$ = flow on valve butterfly ($m^3\ s^{-1}$)

Q_{PD} = downstream flow of relief valve ($m^3\ s^{-1}$)

$Q_{P,I}$ = flow on node I, in present time ($m^3\ s^{-1}$)

$Q_{P,NL}$ = flow on located head ($m^3\ s^{-1}$)

$Q_{P,NV}$ = upstream flow of relief valve ($m^3\ s^{-1}$)

$Q_{P,NT}$ = upstream flow of surge tank ($m^3\ s^{-1}$)

$Q_{P,TU}$ = flow on turbine, in present time ($m^3\ s^{-1}$)

Q_{PV} = flow on relief valve discharge ($m^3\ s^{-1}$)

Q_T = flow on surge tank ($m^3\ s^{-1}$)

T = instantaneous torque on turbine (Nm);

t = time (s)

T_α = ratio of the change in speed deviation to the change in relative servo velocity (–)

t_C = closing time (s)

T_f = time of minimum closure from the total opened position (s)

T_h = time of damping (s)

t_{max} = is maximum simulation time (s)

t_O = opening time (s)

T_q = closure time of servomotor (s)

t_R = reaction time (s)

T_R = the rated torque on turbine (Nm);

t_S = simulation time, $t = 0, Dt, 2Dt, ..., t_{max}$ (s)

T_z = time of total closing (s)

V = average fluid speed ($m\ s^{-1}$)

WR^2/g = polar moment of inertia of rotating parts ($kg\ m^2$)

x = longitudinal coordinate (m)

X_{LPT} = water level on the surge tank, in present time (m)

X_{LT} = water level on the surge tank, in past time (m)

y = servomotor piston position (–)

y_h = position of transition of the servomotor piston (–)

Z_{NT} = topographic elevation of surge tank (m)

ΔA = increase in transverse pipe section (m^2)

ΔH = head rise (m)

Δp = pressure increase (Pa)

Δt = time step (s)

ΔV = reduction in flow velocity (m s^{-1})

Δx = distance between nodes (m)

$\Delta \rho$ = increase in mass density (kg m^{-3})

ρ = fluid mass density (kg m^{-3})

References

AGER. (2010). *Ager-MT supervises generation and distribution of electric energy in the State*. http://www.ager.mt.gov.br/-/ager-mt-fiscaliza-geracao-e-distribuicao-de-energia-eletrica-do-estado

AGER. (2012). *ELECTRIC POWER: Inspection of Ager-MT points out irregularities in energy distribution and generation*. http://www.ager.mt.gov.br/-/energia-eletrica-fiscalizacao-da-ager-mt-aponta-irregularidades-na-distribuicao-e-geracao-de-energia?inheritRedirect=true

AGER. (2013, Abril 24). Report of inspection RF - PCH São Tadeu I - 0005/2013 - AGER. Protocolo n.: 121292/2013 (Process AGER-PRO-2022/02307, Process AGER-TER-2022/04906), Regulatory Agency for Delegated Public Services of the State of Mato Grosso (AGER).

AGER. (2017, May 30). Report of inspection RF - PCH São Tadeu I - 0014/2017 - AGER. Protocolo n.: 169835/2017 (Process AGER-PRO-2022/02307, Process AGER-TER-2022/04906), Regulatory Agency for Delegated Public Services of the State of Mato Grosso (AGER).

AGER. (2021). 2021. *Annual activity report 2021* (Report No. 2). Regulatory Agency for Delegated Public Services of the State of Mato Grosso (AGER).

Alencar, A., Shimbo, J. Z., Lenti, F., Marques, C. B., Zimbres, B., Rosa, M., Arruda, V., Castro, I., Ribeiro, J. P. F. M., Varela, V., Alencar, I., Piontekowski, V., Ribeiro, V., Bustamante, M. M. C., Sano, E. E., & Barroso, M. (2020). Mapping three decades of changes in the Brazilian savanna native vegetation using landsat data processed in the Google Earth engine platform. *Remote Sensing*. 12, 924. https://doi.org/10.3390/rs12060924

Allighé, S., Nicolet, C., Chabloz, P., & Chapuis, L. (2019). Dynamic closing modelling of the penstock protection valve for pipe burst simulations. *Earth and Environmental Science*. 405, 012021. https://doi.org/10.1088/1755-1315/405/1/012021

Anderson, E. I. A., & Johnson, G. R. (1990). Effect of tube ovalling on pressure wave propagation speed. Proceedings of the Institution of Mechanical Engineers, Part H: *Journal of Engineering in Medicine*, 204(4), 245–251. doi:10.1243/pime_proc_1990_204_263_02

ANEEL. (2009). *Implementation follow-up of PCH São Tadeu I, São Tadeu Energética Ltda. – MT: Process 48500.0001190/2003-95*. http://www.consultaesic.cgu.gov.br/busca/_layouts/15/DetalhePedido/DetalhePedido.aspx?nup=48700004681201428

Assis, A. P. (2009, December 12). Technical report on the accident that occurred in the tunnel of PCH São Tadeu I on November 11, 2009. Protocolo n.: 139641/2006 (Process AGER-PRO-2022/02307, Process AGER-TER-2022/04906), Regulatory Agency for Delegated Public Services of the State of Mato Grosso - AGER, Cuiabá, Mato Grosso, Brazil.

Ateliê Perola Negra. (2022, July 16). *Disc made with chamfered rustic wood trunk*. https://img.elo7.com.br/product/zoom/434CF1F/bolacha-tronco-de-madeira-rustica-chanfrada-decoracao-festa-tronco-pra-fotos.jpg

B&B Objetos. (2020, August 5). Natural board - Ipe disc. https://img.elo7.com.br/product/zoom/31C4353/tabua-natural-bolacha-de-ipe-ipe.jpg

Bermad. (2020). *700 Sigma series: Engineering Data*. https://catalog.bermad.com/BERMAD%20Assets/Waterworks/700%20Series%20-%20SIGMA%20-%20EN-ES/-%20App%20Eng.%20tools/Engineering/WW_700-SIGMA_Engineering_English.pdf?_gl=1*72e0uf*_ga*MTY3NzkzNDI5NC4xNjkzNzQ3Njk3*_ga_WB72NLMX0D*MTY5Mzc0NzY5Ny4xLjEuMTY5Mzc0Nzc2OC4wLjAuMA..

Bomfim, E. (2015, October 19). Ipê Amarelo. *Edenilson Bomfim*. https://flic.kr/p/A1LKTn

Borges, H. B. N., Silveira, E. A., & Vendramin, L. N. (2014). Tree flora of Mato Grosso: plant typologies and their species, Entrelinhas.

Brekke, H. (2014). *Hydraulic turbines: design, erection and operation*. https://www.ntnu.no/documents/381182060/1267681377/HYDRAULIC+TURBINES_Hermod+Brekke+-+2015.pdf

Cassano, S., Nicolet, S., & Sossan, F. (2020). Reduction of penstock fatigue in a medium-head hydropower plant providing primary frequency control. *2020 55th International Universities Power Engineering Conference* (*UPEC*), 1–6. https://doi.org/10.1109/UPEC49904.2020.9209857

Cognet, V., Courrech du Pont S., Dobrev, I., Massouh, F., & Thiria, B. (2017). Bioinspired turbine blades offer new perspectives for wind energy. *Proc. R. Soc. A*. 473, 20160726. https://doi.org/10.1098/rspa.2016.0726

EPE. (2019). *Generation expansion: repowering and modernization of hydroelectric power plants; gains in efficiency, energy and installed capacity*. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-432/EPE-DEE-088_2019_Repotencia%C3%A7%C3%A3o%20de%20Usinas%20Hidrel%C3%A9tricas.pdf

EPE. (2020). *National Energy Plan 2050*. https://www.epe.gov.br/sites-pt/publicacoes-dados-abertos/publicacoes/PublicacoesArquivos/publicacao-227/topico-563/Relatorio%20Final%20do%20PNE%202050.pdf

EPE. (2022). *Energy and electrical matrix*. https://www.epe.gov.br/pt/abcdenergia/matriz-energetica-e-eletrica

Fathi-Moghadam, M., Haghighipour, S., & Samani, H. M. (2013). Design-variable optimization of hydropower tunnels and surge tanks using a genetic algorithm. *Journal of Water Resources Planning and Management*. 139(2), 200–208. https://doi.org/10.1061/(ASCE)WR.1943-5452.0000243

Fayemi, P. E., Wanieck, K., Zollfrank, C., Maranzana, N., & Aoussat, A. (2017). Biomimetics: process, tools and practice. *Bioinspiration & Biomimetics*. 12, 011002. https://doi.org/10.1088/1748-3190/12/1/011002

Gebeshuber, I. C. (2022). Biomimetics – Prospects and Developments. *Biomimetics*. 7, 29. https://doi.org/10.3390/biomimetics7010029

Gomes, L., Miranda, H. S., Soares-Filho, B., Rodrigues, L., Oliveira, U., & Bustamante, M. M. C. (2020). Responses of plant biomass in the brazilian savanna to frequent fires. *Frontiers in Forests and Global Change*. 3, 507710. https://doi.org/10.3389/ffgc.2020.507710

Guidicini, G., Mello, F.M., & Carvalho, N.S. (2022). *Pathology of hydraulic tunnels: accidents and incidents in Brazil*, Oficina de Textos, São Paulo.

Hachem, F. E., & Schleiss, J. (2012). Effect of drop in pipe wall stiffness on water-hammer speed and attenuation. *Journal of Hydraulic Research*. 50(2), 218–227. http://dx.doi.org/10.1080/00221686.2012.656838

IBRAM (2016). Cerrado trees. https://www.ibram.df.gov.br/images/%C3%81rvores%20do%20Cerrado.pdf

Iouguina, A., Dawson, J. W., Hallgrimsson, B., & Smart, G. (2014). Biologically informed disciplines: a comparative analysis of bionics, biomimetics, biomimicry, and bio-inspiration among others. *International Journal of Design & Nature and Ecodynamics*. 9(3), 197–205. https://doi.org/10.2495/DNE-V9-N3-197-205

Jenkner, W. R. (1971). Über die Druckstossgeschwindigkeit in Rohrleitungen mit quadratischen und rechteckigen Querschnitten. *Schweizerische Bauzeitung*. 89, 99–103. http://doi.org/10.5169/seals-84747

Junior, O. (2021, August 23). City Hall of Franco da Rocha. *Fighting the fire in Juquery State Park*. https://www.flickr.com/photos/prefeituradefrancodarocha/51397707348/

Kubrak, M., & Kodura, A. (2020). Theoretical analysis of the reduction of pressure wave velocity by internal circular tubes. In M. B. Kalinowska, M. M. Mrokowska & P. M. Rowiński (Eds.), *Recent Trends in Environmental Hydraulics: 38th International School of Hydraulics*, (pp. 117–126). GeoPlanet: Earth and Planetary Sciences. https://doi.org/10.1007/978-3-030-37105-0_10

Kubrak, M., Malesinska, A., Kodura, A., Urbanowicz, K., Bury, P., & Stosiak, M. (2021). Water Hammer Control Using Additional Branched HDPE Pipe. *Energies*. 14, 8008. https://doi.org/10.3390/en14238008

Larock, B. E., Jeppson, R. W., & Watters, G. Z. (2000). *Hydraulics of Pipeline Systems*. CRC Press LLC.

Meyers, M. A., Chen, P. Y., Lin, A. Y. M., & Seki, Y. (2008). Biological materials: structure and mechanical properties. *Progress in Materials Science*. 53, 1–206. https://doi.org/10.1016/j.pmatsci.2007.05.002

MMA. (2007). *Biodiversity of the Cerrado and Pantanal: areas and priority actions for conservation*, Ministry of the Environment (MMA).

NIEPE. (2019). *Strategic Plan for the Development of Renewable Energies in Mato Grosso, PEDER-MT 2050*. https://www.unido.org/sites/default/files/files/2020-04/Plano%20Estrat%C3%A9gico%20para%20o%20Desenvolvimento%20de%20Energias%20Renov%C3%A1veis%20em%20Mato%20Grosso%20PEDER-MT%202050.pdf

Pejovic, S., Boldy, A. P., & Obradovic, D. (1987). *Guidelines to hydraulic transient analysis*. Gower Technical Press Ltd., Brookfield.

Pereira, B. A. S. (2022, August 1). Strychnos pseudoquina A.St.-Hil. *Taxonomic Hierarchy* http://reflora.jbrj.gov.br/reflora/floradobrasil/FB8680

Ramos, H. (2000). *Guideline for design of small hydropower plants*. http://www.civil.ist.utl.pt/~didia/FCT2009/book-SHP.pdf

Sano, E. E., Rodrigues, A. A., Martins, E. S., Bettiol, G. M., Bustamante, M. M. C., Bezerra, A. S., Couto Jr., A. F., Vasconcelos, V., Schüler, J., & Bolfe, E. L. (2019). Cerrado ecoregions: A spatial framework to assess and prioritize Brazilian savanna environmental diversity for conservation. *Journal of Environmental Management*. 232, 818–828. https://doi.org/10.1016/j.jenvman.2018.11.108

Sartorelli, P. A. R., & Campos Filho, E. M. (2017). *Regeneration plants guide natural from the Cerrado and Atlantic forest.* Agroicone.

Silva, P. S., Nogueira, J., Rodrigues, J. A., Santos, F. L. M., Pereira, J. M. C., DaCamara, C. C., Daldegan, G. A., Pereira, A. A., Peres, L. F., Schimit, I. B., & Libonati, R. (2021). Putting fire on the map of Brazilian savanna ecoregions. *Journal of Environmental Management*. 296, 113098. https://doi.org/10.1016/j.jenvman.2021.113098

Simon, M. F., & Pennington, T. (2012). Evidence for adaptation to fire regimes in the tropical savannas of the Brazilian Cerrado. *International Journal of Plant Sciences*. 173(6), 711–723. https://doi.org/10.1086/665973

STE. (2013, January 1). Operating instructions. Protocolo n.: 139641/2006 (Process AGER-PRO-2022/02307, Process AGER-TER-2022/04906), Regulatory Agency for Delegated Public Services of the State of Mato Grosso (AGER).

Stephenson, D. (1989). *Developments in water science: Pipeline design for water engineers*, 3 ed. Elsevier Science Publishers B.V.

Tullis, J. P. (1989). *Hydraulic of pipelines: pumps, valves, cavitation, transients*. John Wiley & Sons.

Ulhøi, J. P. (2021). From innovation-as-usual towards unusual innovation: using nature as an inspiration. *Journal of Innovation and Entrepreneurship*. 10(2), 1–21. https://doi.org/10.1186/s13731-020-00138-0

Vergueiro, M. (2020). Government of Mato Grosso. *Cerrado - Mato Grosso*. https://www.flickr.com/photos/governodematogrossoimagem/50191530073/

Vincent, J. F. V., Bogatyreva, O. A., Bogatyrev, N. R., Bowyer, A., & Pahl, A. K. (2006). Biomimetics: its practice and theory. *Journal of the Royal Society Interface*. 3, 471–481. https://doi.org/10.1098/rsif.2006.0127

Watters, G. Z. (1979). *Modern analysis and control of unsteady flow in pipelines*. Ann Arbor Science Publishers Inc.

Wommer, K., & Wanieck, K. (2022). Biomimetic research for applications addressing technical environmental protection. *Biomimetics*. 2, 182. https://doi.org/10.3390/biomimetics7040182

Wylie, E. B., & Streeter, V. L. (1978). *Fluid transients*. McGraw-Hill Inc.

Zhang, H., Aggidis, G. A. (2018). Nature rules hidden in the biomimetic wave energy converters. *Renewable and Sustainable Energy Reviews*. 97, 28–37. https://doi.org/10.1016/j.rser.2018.08.018

Zhang, H., Sheng, W., Zha, A., Aggidis, G. A. (2022). A Preliminary Study on Identifying Biomimetic Entities for Generating Novel Wave Energy Converters. *Energies*. 15, 2485. https://doi.org/10.3390/en15072485