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ESTUDO DE CASO: EFEITOS DOS TRANSIENTES EM ADUTORA POR GRAVIDADE

RODRIGO RIBEIRO FRANCO VIEIRA[1]; RODRIGO MÁXIMO SÁNCHEZ ROMÁN[2] E JOSÉ BONIFÁCIO MARTINS FILHO[3]

[1] Doutorando no programa de pós-graduação em Engenharia Agrícola, Universidade Estadual Paulista Júlio de Mesquita Filho, Faculdade de Ciências Agronômicas de Botucatu., CODEVASF 6 SR Av Comissão do Vale, s/n, Piranga, 48901-900, Juazeiro, Bahia – Brasil, rodrigo.vieira1965@unesp.br
[2] Professor associado no programa de pós-graduação em Engenharia Agrícola, Universidade Estadual Paulista Júlio de Mesquita Filho, Faculdade de Ciências Agronômicas de Botucatu. Avenida Universitária, 3780 Altos do Paraíso, 18610034 - Botucatu, SP - Brasil, rodrigo.roman@unesp.br
[3] Doutorando no programa de pós-graduação em Engenharia Agrícola, Universidade Estadual Paulista Júlio de Mesquita Filho, Faculdade de Ciências Agronômicas de Botucatu, R. Nícola Zaponi, 1427, Vale do Sol, 18606-12, Botucatu - SP – Brasil, boni.martins@outlook.com.

1 RESUMO

O estudo de transientes hidráulicos quando não realizados podem resultar em danos materiais e humanos. Sendo assim, é essencial propor soluções cabíveis para evitar tais danos, ainda em âmbito de projeto. Nesse contexto, o objetivo desse trabalho foi modelar os possíveis efeitos dos transientes hidráulicos em uma adutora por gravidade para o município de Campo Formoso-BA. A adutora por gravidade estudada tem extensão de 1.584 m e inicia em um reservatório elevado com fuste de 10 m de altura, descarregando em um reservatório com 3 m de altura. Para realização das modelagens hidráulicas foram utilizados os softwares EPANET para determinação de vazões e pressões e o Sistema UFC para modelar o efeito dos transientes em diferentes tempos de fechamento. Os resultados obtidos sugerem que os efeitos transitórios em redes por gravidades podem ser tão ou mais graves do que em sistemas pressurizados, a depender do caso, e que a assunção do tempo mínimo de fechamento de válvulas, calculado através da determinação do período da tubulação é um procedimento equivocado para a solução dos transientes hidráulicos, exigindo a simulação computacional.

Palavras-chave: golpe de aríete; válvulas hidráulicas; abastecimento rural, adutora por gravidade, transiente hidráulico.

VIEIRA, R. R. F.; SÁNCHEZ-ROMÁN, R. M.; MARTINS FILHO, J. B.
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2 ABSTRACT

The study of hydraulic transients when not performed can result in irreversible and human damage. Therefore, it is essential to propose reasonable solutions to avoid such damage, even at the project level. In this context, the objective of this work was to model the possible effects of hydraulic transients in a gravity pipeline for the municipality of Campo Formoso, Bahia State. The gravity pipeline studied has a length of 1584 m and starts in an elevated reservoir with a 10 m high shaft, discharging into a 3 m high reservoir. To carry out hydraulic modeling,

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EPANET software was used to determine flows and pressures, and the UFC system was used to model the effects of transients at different closing times. The results suggest that the transient effects in gravity networks can be as serious or more serious than those in pressurized systems, depending on the case, and that the assumption of the minimum valve closing time, which is calculated by determining the piping period, is an incorrect procedure for solving hydraulic transients, which requires computer simulation.

Keywords: water hammer; hydraulic valves; rural supply, gravity pipeline, hydraulic transient.

3 INTRODUCTION

Hydraulic transients, also popularly known as water hammers, are physical phenomena resulting from abrupt pressure variations inside a pipeline, either by activating or deactivating the pump assembly or by opening and closing valves and valves (TWYMAN, 2018; KERAMAT *et al.*, 2012). Smaller magnitude transients can also occur due to extremely slow changes in flow (VEIGA, 2014).

The most common method for calculating hydraulic transients is the method of characteristics (MOC) (Schimidt, 2016), which converts the equations of motion and continuity into ordinary partial equations (Gray, 1953; Streeter; Lai, 1962; Chaudhry, 1987). The boundary conditions of the steady state are computed to determine the value of pressure (H) and velocity (V) or flow (Q) in a given section of the conduit at the time of the transient Chaudhry (2014).

Overpressures resulting from hydraulic transients can result in deformation and collapse of the supply line (LOPES *et al.*, 2022). Therefore, these pressure variations must be considered when sizing the pipelines during the design phase.

The study of hydraulic transients is commonly carried out for urban water supply and sewage systems (SOARES; COVAS; RAMOS, 2013; SOARES; COVAS, 2015; STARCZEWSKA; COLLINS; BOXALL, 2014). However, in agricultural hydraulics (irrigation and rural water supply), transient phenomena, their diagnosis and appropriate solutions are still very incipient and scarce. These sectors, for various reasons—whether institutional, due to a lack of opportunity and others—have not yet awakened importance and need to adopt appropriate solutions, which, at present, become unacceptable given the tools available on the market, including some free ones.

In the case of gravity networks, control can be more difficult, and its solutions are aggravated by the general false idea that, because it is a pipeline of this nature, one should not worry about transients compared with systems pressurized by motor pump sets.

For booster systems (with pumps), the pressure wave has a value on a sonic scale and is not the displacement of the fluid in the pipeline (VIEIRA, 2019). In gravity networks, the transient phenomenon has a different behavior with respect to pressure waves than in a conventional pumping system, since the first wave is always at high pressure.

Culturally, agricultural hydraulics and irrigation systems are limited to the permanent regime, governed by Bernoulli's Theorem. Considering this theorem, it is impossible for the system energy (pressure) to be higher than the effective load plan, since energy is not created. However, hydraulic transients overcome this premise. This study aims to prove the complexity of gravity systems in terms of transients and to present a safer, more appropriate and economical solution, breaking the aforementioned paradigms of national agricultural hydraulics. In addition, the results demonstrate that the correct application of the characteristics method, which is performed via UFC software, allows the application of the most appropriate and economical solution in the dimensioning of the network. Considering the importance of supply systems for rural areas in Brazil, this work aimed to perform hydraulic modeling of the effects of possible transients in a gravity adductor for the municipality of Campo Formoso-BA.

4 MATERIALS AND METHODS

4.1 Description of the study area and pipeline

The gravity adductor that is the object of study of this work belongs to a rural supply system in the city of Campo Formoso, State of Bahia, designed by Codevasf 6th SR, linked to ART BA20210656087, which, from the district of Tuiutiba, supplies treated water supplied by EMBASA (Empresa Baiana de Águas e Saneamento) to five locations (districts) in that municipality: Baixio, Puxadeira, Cercadinho, Mandacaru and Vanvana.

The system has 2 pressurized adductors (Adductors 01 and 03); 1 gravity adductor (Adductor 02, object of the study); 5 elevated reservoirs and distribution systems; 3 pressure-breaking boxes; 1 hydropneumatic reservoir (RHO) for adductor 03; and valves, water meters and suction cups.

The flow rates calculated for supplying the five reservoirs are shown in Table 1.

Table 1. Calculated flows (Ls^{-1}) for elevated reservoirs 1, 2, 3, 4 and 5

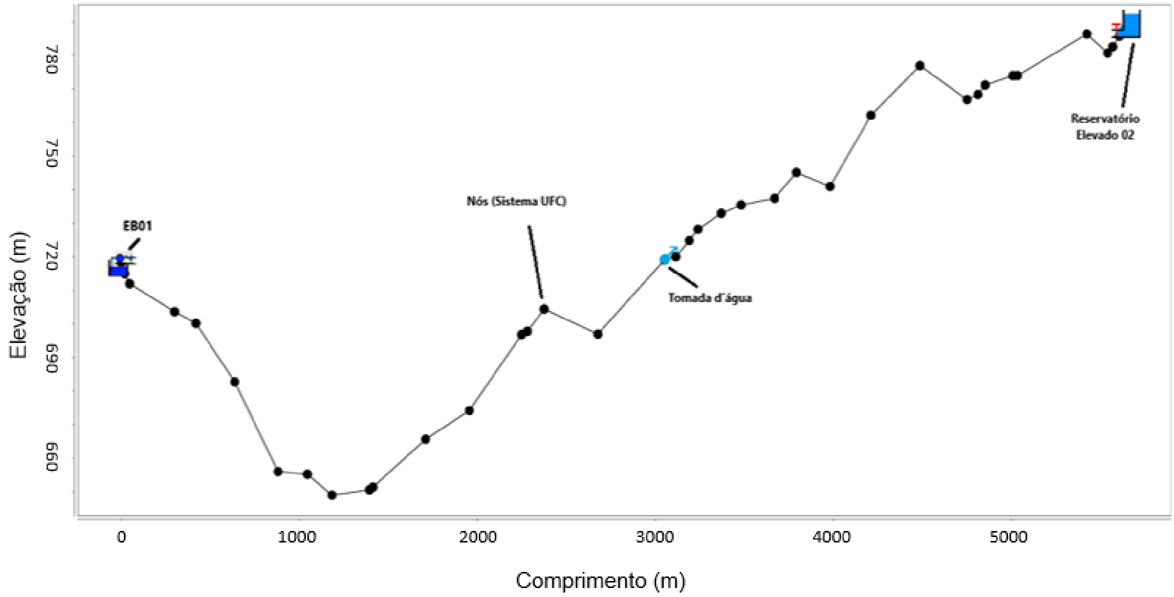
Reservoir	Q (Ls^{-1})
Elevated Reservoir 01	0.34
Elevated Reservoir 02	3.14
Elevated Reservoir 03	6.14
Elevated Reservoir 04	4.29
Elevated Reservoir 05	4.13

Source: prepared by the authors

The sum of the flow rates of reservoirs 03--05 is equal to 14.56 Ls^{-1}, which is exactly what is desired in adductor 02, the gravity section.

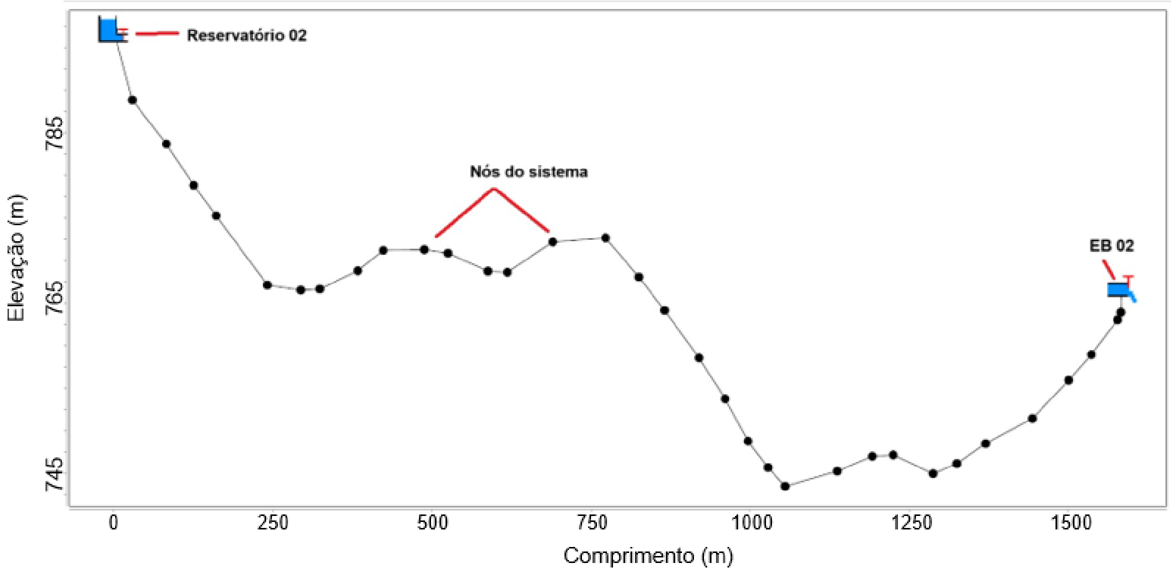
Figures 1, 2 and 3 show the sections of adductors 01, 02 and 03 A, respectively, indicating the pumping stations (EBPs or pumping stations), branch inlets, elevated reservoirs and the anticoup device required in adductor 03, a Hydropneumatic Reservoir (RHO).

Figure 1 Section EB 01 – elevated reservoir 02.



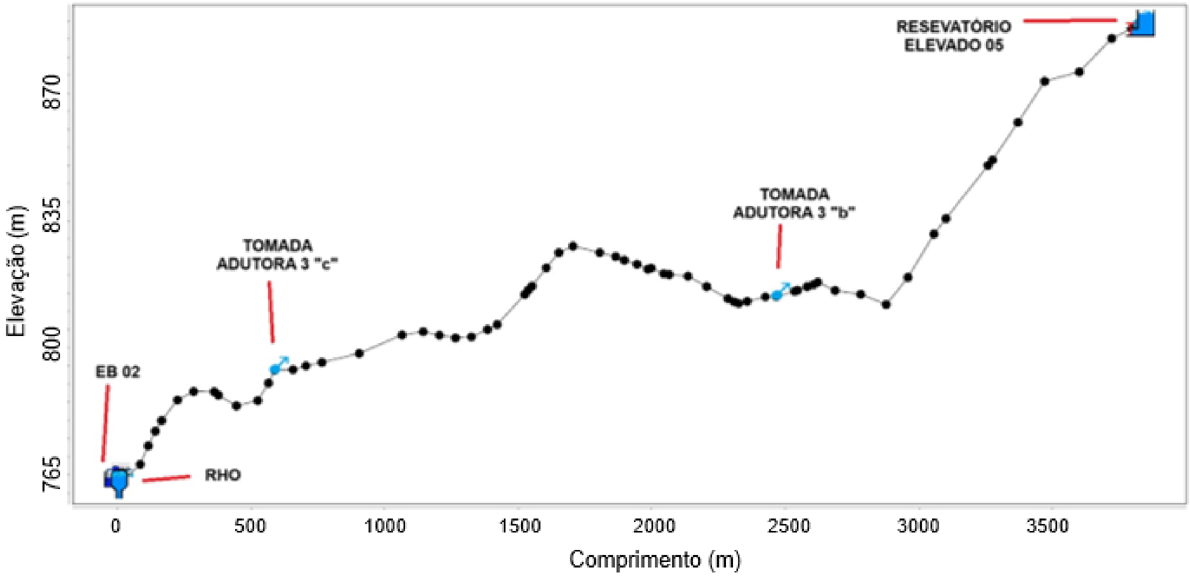
Source: prepared by the authors – UFC System.

Figure 2 Section of elevated reservoir 02 – eb 02 (**case** study – gravity).



Source: prepared by the authors – UFC System.

Figure 3 Section – Pumping Station 02 – Elevated Reservoir 05 – with a hydropneumatic reservoir (RHO) and branches ("3b" and "3c").



Source: prepared by the authors – UFC System.

The total flow rate of the supply system is 17.50 Ls $^{-1}$, and for the section in question, by gravity, a flow rate of 14.56 Ls $^{-1}$ is desired, which will serve the downstream communities supplied by reservoirs 3, 4 and 5, and this is therefore the desired flow rate there. This flow, while maintaining the system's boundary conditions, occurs only if a control device is implemented, but specifically a flow limiting valve, because if this does not exist, the maximum flow rate would be 20.33 Ls $^{-1}$.

The simulations were carried out via the UFC System, software that performs simulations of water hammers in adductors, enabling the efficient sizing of hydraulic components to mitigate the risks of transients (LAHC, 2023).

4.2 Characterization of the studied system

The system is a gravity adductor with the following characteristics: total length (L) = 1,584 m and total geometric difference at Level Res Elev. 02 – EB 02 (Δ_{GEO}) = 30.27 m; Network – Section 01 - Pipe 01 - PVC IRRIGA LF PBS 150 mm PN 40 – 772.60 m; Section 02 - Pipe 02 - PVC IRRIGA LF PBS 125 mm PN 40 – 92.71 m; Section 03 - Pipe 03 - PVC IRRIGA LF PBS 125 mm PN 60 – 634.82 m; Section 04 - Pipe 04 - PVC IRRIGA LF PBS 125 mm PN 40 – 84.31 m; Desired flow rate (Q_1) = 14.56 Ls $^{-1}$;

The gravity pipeline starts at an elevated reservoir with a 10 m high shaft, discharging into a reservoir 3 m high from its base (inlet level). Importantly, the limit established for the simulated closing time in the UFC was the one in which the resistance of the pipeline was sufficient at all points of the pipeline to withstand the incident overpressure.

4.3 Cases analyzed

Two different cases were analyzed for the same pipeline, which, as described, had as a variable the closing time of the downstream valve, comparing the period of the pipeline and the minimum time that avoids damage caused by transients.

Thus, the modeling had three cases (flow rates), each with two variables (closing time according to the pipeline period—11.27 s—and according to the ideal minimum closing time), resulting in six analyses in total.

In all options, the transient effects were simulated considering the closure of the pipeline during the period and a longer closure time of the adductor until the one that would not cause any damage to the system was established. UFC software was used in all the simulations.

There are several important premises used in this study so that it would be possible to compare data from similar concepts.

Among these, the following stands out: the period of the pipeline of the section subject to analysis was calculated at 11.27 seconds via Equation 2. The total flow rate without control is that represented by Bernoulli's theorem, in which the maximum flow dissipates all the potential energy represented by the effective load plan (ELP) in the established network, which is calculated at 20.33 Ls $^{-1}$. The flow rate after the installation of the plastic valve “Function 49” – “F 49” - (BERMAD), 100 mm, was calculated at 20.16 Ls $^{-1}$ and was the result of the pressure drop imposed by this valve on the system. The pressure drop generated modified the boundary condition of the system, therefore altering its flow rate. In the third alternative, the application of another valve in series was considered, with the same model and diameter but with the flow limiting function (FR), which imposed a flow rate of 14.56 Ls $^{-1}$.

Valves generally require a minimum pressure of 10 mca to perform any given function (VIEIRA, 2019).

The combinations analyzed can be broken down as follows:

a) Case 1a - Total system flow - 20.33 Ls $^{-1}$ – without any control device with closing during the piping period (11.27 s);
b) Case 1b - Total system flow - 20.33 Ls $^{-1}$ - (with valve “F 49”) with closing at the minimum anti-coup time simulated in the UFC, 75 s;
c) Case 2a - Maximum flow with valve “F 49” - 20.16 Ls $^{-1}$ - and closing time in the piping period (11.27 s);
d) Case 2b - Maximum flow with “F 49” valve - 20.16 Ls $^{-1}$ - with closing at the minimum anti-coup time simulated in the UFC, of 76 s.
e) Case 3a - Desired flow rate with FR valve - 14.56 Ls $^{-1}$ - and closing time in the piping period (11.27 s);
f) Case 3b - Maximum flow with the “F 49” valve and FR valve - 14.56 Ls $^{-1}$ - with closing at the minimum anti-coup time simulated in the UFC, of 107 s.
g) Case 3c - Maximum flow with the FR valve - 14.56 Ls $^{-1}$ - with mechanical closing at 76 s.

4.4 Determination of physical parameters

4.4.1 Acoustic speed or velocity

Celerity is the speed of propagation of over- and underpressure waves in pressurized networks (AZEVEDO NETO; FERNÁNDEZ, 2015), whose equation is demonstrated below (STREETER; WYLIE, 1978; CHAUDHRY, 1987):

$$a = \sqrt{\frac{K}{\rho\left(1+\frac{K}{E}\frac{D}{e}\right)}} \qquad (1)$$

where “a” is the speed (ms $^{-1}$), K is the volumetric elasticity modulus of the fluid (in this specific case, water) (GPa), ρ is the specific mass of the liquid (kg m $^{-3}$), “E” is the elasticity modulus (or Young's modulus) of the pipe (GPa), D is the internal diameter of the pipe (m), and “e” is the wall thickness of the pipe (m).

4.4.2 Pipeline period

The period (in seconds) is the time it takes for the pressure wave to travel through the entire section of piping from the blockage point (valve, valve) and is governed by the following equation:

$\zeta = \frac{2L}{a}$(2)

Being:

ζ = Period (s)
a = Speed or velocity of the pressure wave (ms $^{-1}$);
L = Length of pipe (m).

The piping period for all the cases is 11.27 Ls $^{-1}$ since this is a function of the speed and length of the network, and the flow rate and velocity do not interfere with its result.

Therefore, maintaining the diameters, material and pressure classes of the pipes, the increase in flow, which implies an increase in the speed of the fluid, does not interfere in any way with the calculation of the piping period.

4.4.3 Equations for determining hydraulic transients

The calculation of hydraulic transients has the initial equations of the amount of movement (Equation 3) and the continuity or conservation of masses (Equation 4) (CARVALHO, 2011), and the algebraic solutions of these equations are very complex.

- Momentum equation:

$$\frac{\partial Hm}{\partial x} + \frac{Q}{AT^2}\frac{\partial Q}{\partial x} + \frac{1}{AT}\frac{\partial Q}{\partial t} + \frac{f\,Q\,|Q|}{2\,g\,D\,AT^2} = 0 \quad (3)$$

The term in modulus means that the flow can occur in both directions.
- Continuity or mass conservation equation:

$$\frac{\partial Hm}{\partial t} + \frac{Q}{AT}\frac{\partial Q}{\partial x} + \frac{a^2}{g\,AT}\frac{\partial Q}{\partial x} = 0 \quad (4)$$

where Hm is the manometric head (mca), ∂t is the elementary time interval (s), ∂x is the elementary distance between two sections of the pipeline (m), Q is the flow rate (m ^{3} s $^{-1}$), g is the acceleration of gravity (ms $^{-2}$), A_T is the area of the pipeline (m ^{2}), f is the coefficient of friction, dimensionless (Darcy–Weisbach), and a is the celerity (ms $^{-1}$).

4.4.4 Calculation of the pressure drop in the valve

For the simple calculation of pressure loss in the chosen valve, with a 3-way circuit, for a given flow rate, considering only the passage of fluid in the valve body, equation (3) must be applied:

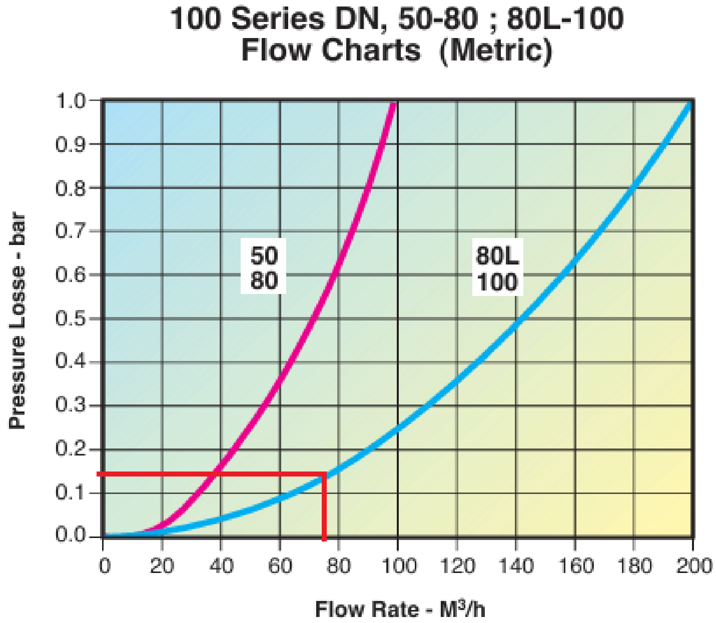
$$Hf = kQ^2 \rightarrow k = \frac{H_f}{Q^2} \quad (5)$$

Being:

Q = flow rate (m ^{3} h $^{-1}$);
Hf = Head loss (mca).

The “k” of the valve is a function of its diameter and material, and a 100 mm plastic valve, model “4 100”, type “Y” BERMAD, and “hyflow ” were used. From the pressure drop and flow points present in the technical catalog, the “k” of the valve is obtained to calculate the localized pressure drop (Vieira, 2019). The value of “k” for the chosen valve was obtained through the specific technical catalog, in which **Erro! Fonte de referência não encontrada.**, applying the maximum flow rate without control, of 20.33 Ls $^{-1}$, which is equivalent to 73.18 m ^{3} h $^{-1}$. For this flow rate, there is a pressure drop of 0.14 bar, which is equivalent to 0.14 × 10.20 = 1.428 ≈ 1.43 mca, considering a 3-way circuit (3 W). This relationship is translated through the horizontal and vertical red lines shown in **Erro! Fonte de referência não encontrada.**4.

Figure 4. Pressure loss BERMAD valve 4” 100 “Y”- Hyflow



Source: Bermad (2020)

Adopting the maximum flow rate without control, of Q = 73.18 $m^3 h^{-1}$ (or 20.33 Ls^{-1}):

$$k = \frac{H_f}{Q^2} = \frac{10.2 \times 0.43}{73{,}18^2} = 0.000267 \quad (6)$$

5 RESULTS AND DISCUSSION

5.1 Flow control – Application of a flow control (FR) valve

In the preparation of the original project, only a 3" plastic flow limiting valve (FR) with a three-way pilot (BERMAD, 2017) was applied, controlling the flow. This measure proved to be wrong, as this valve controls the flow of the system but not the harmful transient effects to it, and it is a gravity supply system; that is, the imposition of any device will alter the flow of the system on the basis of the theorem of conservation of mechanical energy (Bernoulli equation).

Despite the design flow being 14.56 Ls^{-1}, the fact that the network is gravity-fed, the incident flow dissipates all the energy in the system, resulting from the interaction between the nature of the pipes used, topography and control devices applied, including hydraulic valves.

The application of this function is valid for branched systems supplied by the same reservoir or common pumping station, but in theory, it would not be justified when only two points are connected, in this specific case, the elevated reservoir 02 and the supported reservoir EB02, since the flow is constant, with no variation in consumption along the network, since controlling transient effects would be more important than limiting flows. However, the flow (Q) and load (H) parameters are decisive for the magnitude of hydraulic transients (equations 3 and 4).

Thus, the flow rates analyzed in cases 1 and 2 were those calculated via EPANET, with and without transient control devices, since the flow rate was adjusted to the existing load losses in the network, whereas that of case 3 (14.56 L s^{-1}) was included directly in the UFC system for the water hammer analysis.

In cases “1b”, “2 b” and “3b”, controlled closing valves were used, or “Function 49” (BERMAD), aimed at protection against transients, which allows their gradual closing when the downstream reservoir is filled, this time being determined by the system itself in a safe and automatic manner, whereas for cases "3a", "3b" and "3 c", a flow limiting valve (FR) was added.

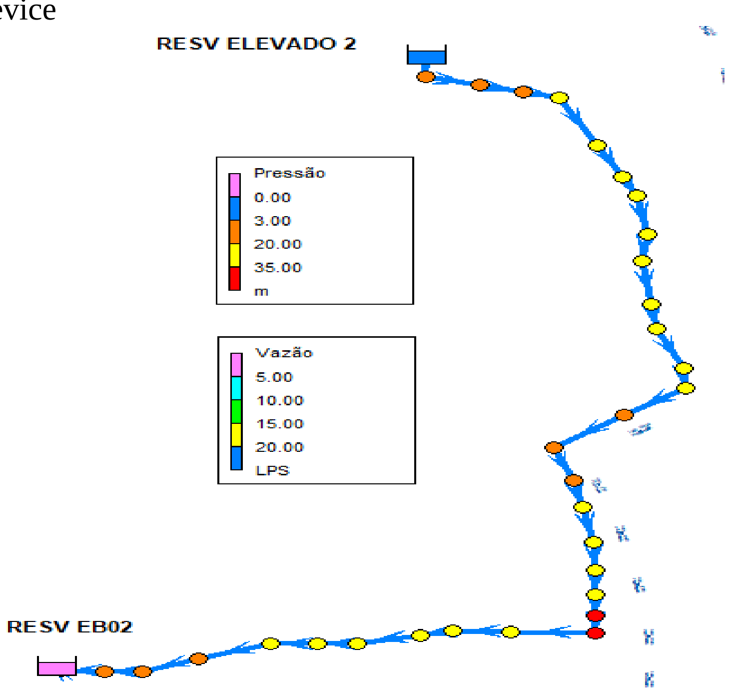
Before proceeding with the analysis of the transient effects for the maximum flow rate of the system, the EPANET software was used, except for case 3. The minimum closing time was established after simulations in the UFC system.

5.2 Case 1 - Maximum System Flow without Control

The flow rate indicated was 20.33 L s^{-1}, which is only the permanent regime, and this value represents the flow rate that dissipates all the energy in the system; that is, it is the maximum if no type of control is imposed, whether through orifices, registers or valves.

Figure 5 summarizes the route and flow of the adductor, and the arrows represent the direction of flow, considering that there is no flow or pressure control device (EPANET).

Figure 5. Supply line, flow and flow direction, considering that there is no flow or pressure control device



Source: prepared by the authors EPANET

In this first case, it is pertinent to the permanent regime, without any control device, resulting in a pressure of only 5.52 mca on the control valve of the downstream reservoir, as expressed in **Erro! Fonte de referência não encontrada.**; that is, all the energy dissipated by the system resulted in the aforementioned flow.

This network, if operated without any type of control and subject to closure, even if it follows the calculated period (11.27 s), would result in the transient effects described below.

5. 2.1 Case 01a – 20.33 L s^{-1} - Applying the piping period (11.27 s)

The following can be observed in Figure 6:

a) Considering only the permanent regime, the pipeline (red line) easily supports the constant pressures in the piezometric line (green line).
b) However, with closure at 11.27 s, almost the entire pipeline experiences an overpressure rupture (dark blue line).
c) The maximum overpressure reached 93.57 mca;

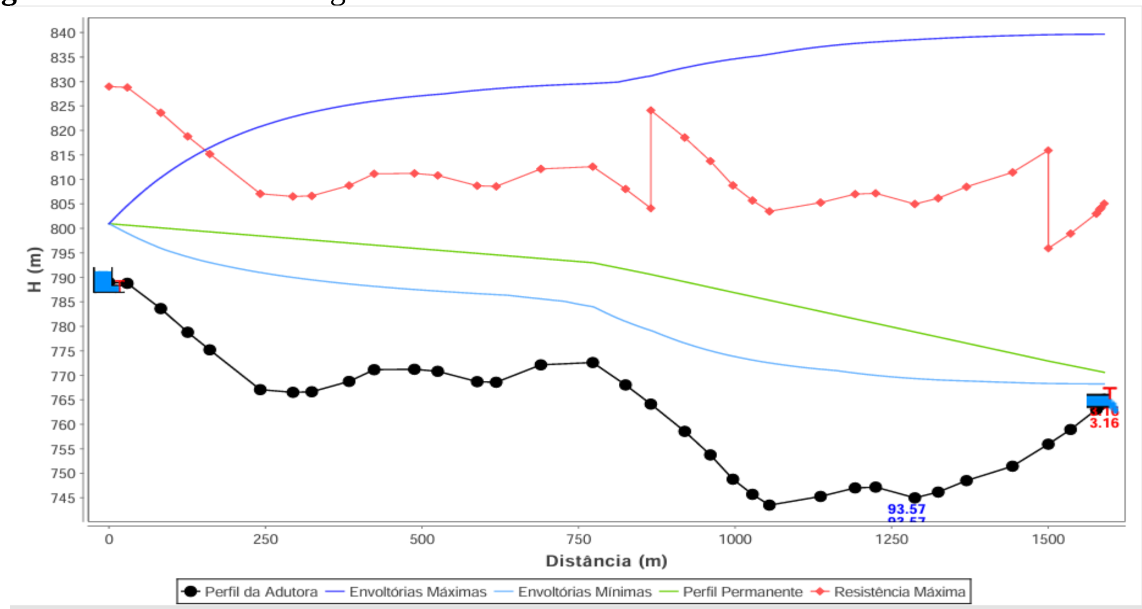
5.2.2 Case 01b – 20.33 L s $^{-1}$ – Applying a closing time of 75 s

The following can be observed in Figure 7:

a) Considering only the permanent regime, the pipeline (red line) easily supports the constant pressures in the piezometric line (green line).
b) With the closure at 75 s, the pipeline will not rupture due to overpressure (dark blue line); however, if the incident pressure is < 10 mca, it is not possible to apply a hydraulic valve;
c) Additionally, in this case, there will be no underpressure problem (light blue line) to be resolved.

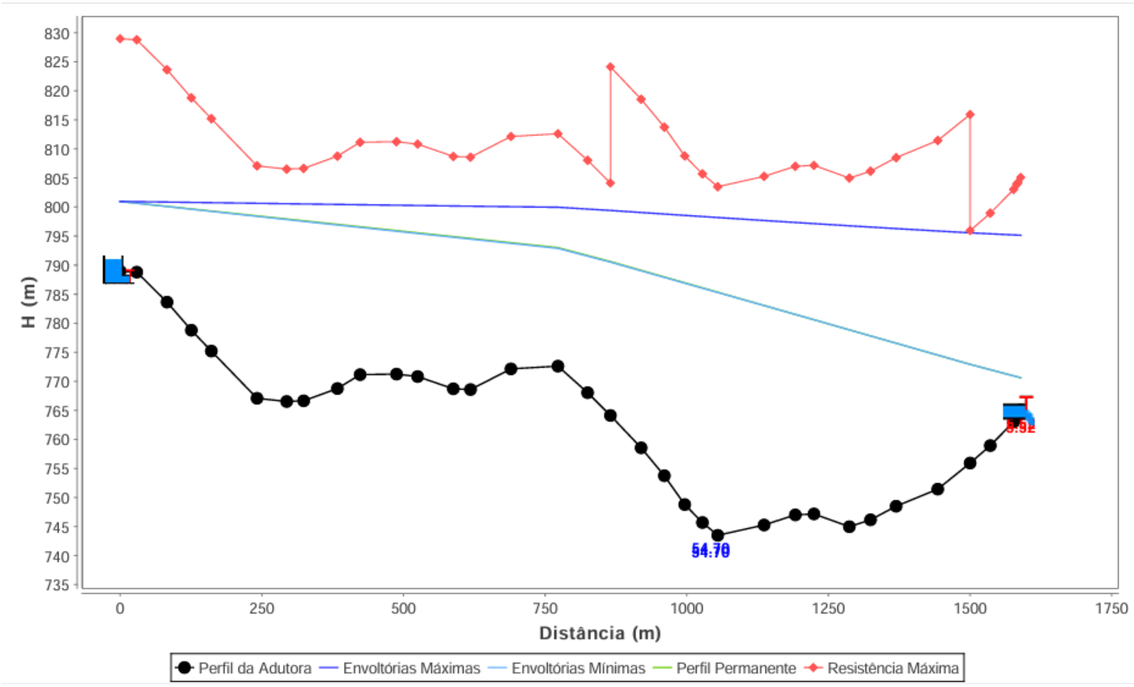
The maximum overpressure reached was 54.70 mca.

Figure 6. Case 01a - Closing in 11.27 seconds



Source: prepared by the authors – UFC System

Figure 7. Case 01b - Closing in 75 seconds



Source: prepared by the authors – UFC System

To achieve maximum flow while avoiding the effects of a water hammer, a reservoir closure period of 75 s would be necessary, which is unlikely to occur in practice if manual operation is used.

Even if a high-flow float is used to prevent the downstream reservoir from overflowing, it would be difficult to program it to close permanently within the required time because such elements do not have any type of regulation.

If the flow is interrupted within the period, the network will be subject to serious transitory effects and constant ruptures.

5.3. Case 2 - Maximum System Flow with Transient Control ("Function 49")

As this is a controlled option, a valve with controlled closing capacity must be provided to avoid harmful transient effects.

The maximum flow rate was then simulated in EPANET, including a plastic valve, with "Function 49", whose application resulted, after the total dissipation of the system's energy, in a flow rate of 20.16 L s $^{-1}$.

It is therefore concluded that the placement of the device and the loss of pressure generated (1.43 mca) reduced the flow from 20.33 L s $^{-1}$ to 20.16 L s $^{-1;}$ that is, the reduction was negligible, highlighting that it has an effect on the permanent regime.

One of the criteria for choosing hydraulic valves, in addition to the minimum incident pressure (10 mca), is the speed allowed in its body, which can reach 3.5 ms $^{-1}$ for metal valves and 5.5 ms $^{-1}$ for plastic valves (Vieira, 2019), and in the present study, this value was 2.57 ms $^{-1}$, which is within the allowed range.

This model has a chamber volume (CCDV – control chamber displacement value) of 0.62 L, which interferes with the filling and emptying of the control chamber, depending on the "Kv" of the pilot used.

Figures Figure and Figure show the transient effects when the valve closing occurs at the same calculated time as the pipeline period (11.27 s) and at the minimum time to cool the hydraulic transients (76 s), respectively.

5.3.1 Case 2a – 20.16 L s $^{-1}$ - Applying the piping period (11.27 s)

The following can be observed in Figure 8:

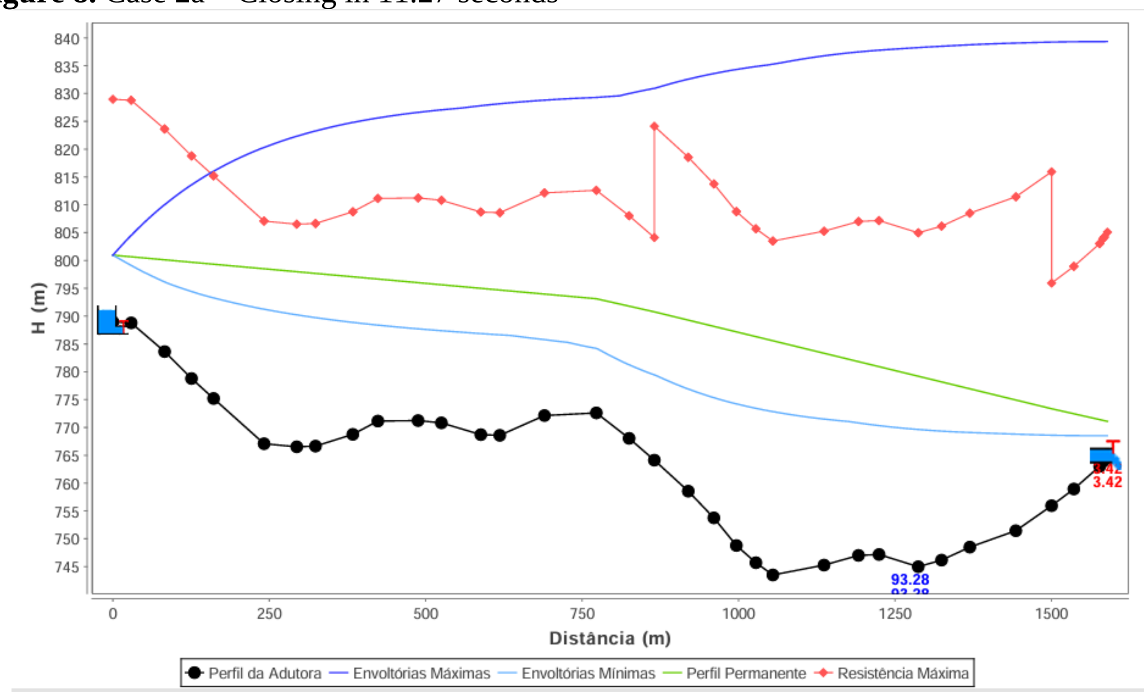
a) Considering only the permanent regime, the pipeline (red line) easily supports the constant pressures in the piezometric line (green line).
b) However, with closure at 11.27 s, almost the entire pipeline experiences an overpressure rupture (dark blue line).
c) The maximum overpressure reached 93.28 mca.

5.3.2 Case 02b – 20.16 L s $^{-1}$ with a closing time of 76 s

The following can be observed in Figure 9:

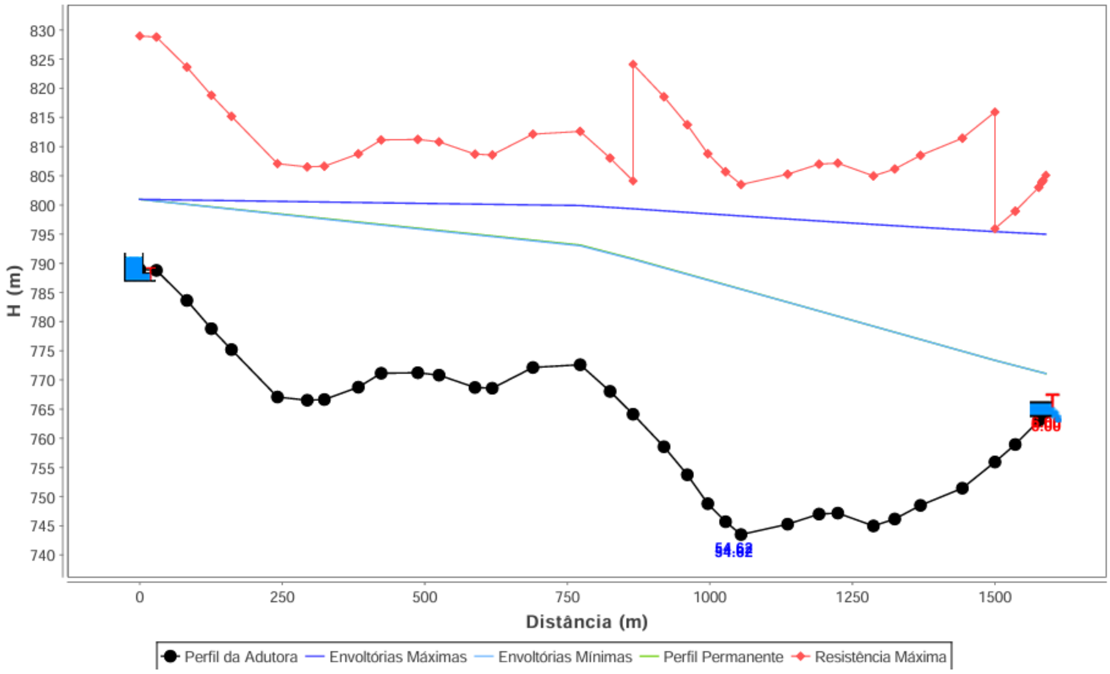
a) Considering only the permanent regime, the pipeline (red line) easily supports the constant pressures in the piezometric line (green line).
b) With closure at 76 s, the pipeline will not rupture due to overpressure (dark blue line).
c) Additionally, in this case, there will be no underpressure problem (light blue line) to be resolved.
d) The maximum overpressure reached was 54.62 mca.

Figure 8. Case 2a – Closing in 11.27 seconds



Source: prepared by the authors – UFC System

Figure 9. Case 2b – Closing in 76 seconds



Source: prepared by the authors – UFC System

5.4. Case 03 - System flow with flow control (FR valve)

In this option, a flow-limiting valve was used, as in case 3a, and then the "F49" valve was included; these options were simulated only in the UFC system, which allows the determination of flow rates in gravity networks.

5.4.1 Case 03a – 14.56 L s $^{-1}$ - Applying the piping period (11.27 s)

Figure 10 **Figure** shows that:

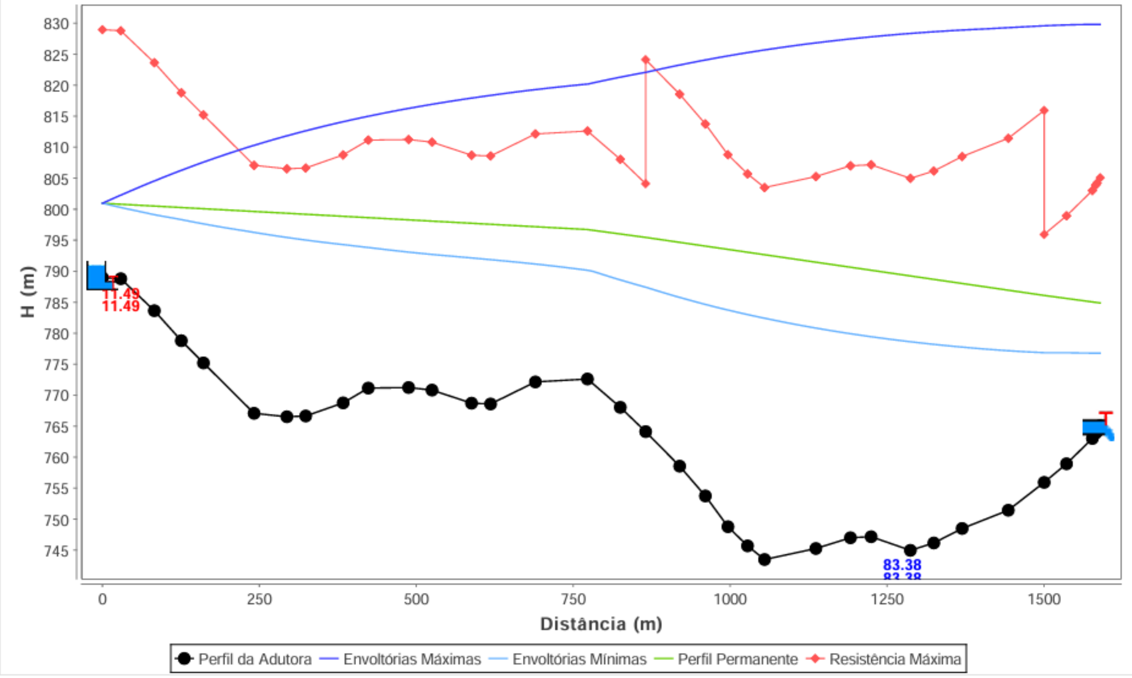
a) Considering only the permanent regime, the pipeline (red line) easily supports the constant pressures in the piezometric line (green line).
b) However, with closure at 11.27 s, almost the entire pipeline experiences an overpressure rupture (dark blue line).
c) The maximum overpressure reached 83.38 mca.

5.4.2 Case 03b – 14.56 L s $^{-1}$ - Applying a closing time of 107 s

The following can be observed in Figure 11:

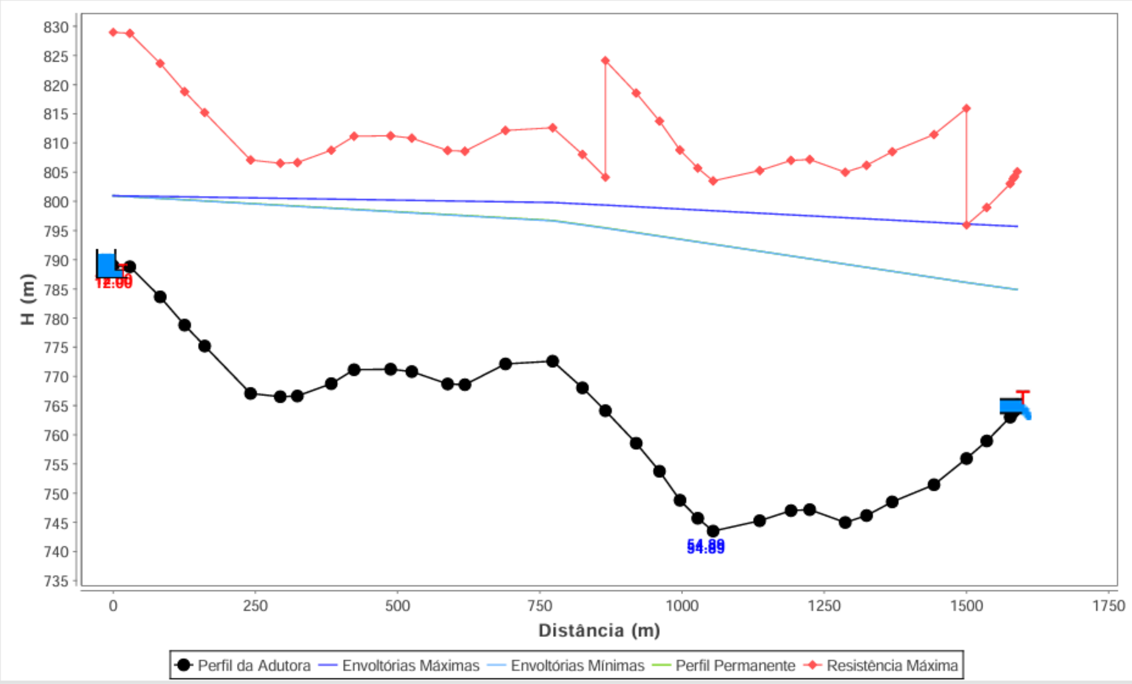
a) Considering only the permanent regime, the pipeline (red line) easily supports the constant pressures in the piezometric line (green line).
b) With closure at 76 s, the pipeline will not rupture due to overpressure (dark blue line).
c) Additionally, in this case, there will be no underpressure problem (light blue line) to be resolved.
d) The maximum overpressure reached was 54.89 mca.

Figure 10. Case 03a – Closing in 11.27 seconds



Source: prepared by the authors – UFC System

Figure 11. Case 03b – Closing in 107 seconds



Source: prepared by the authors – UFC System

Table 2 **Erro! Fonte de referência não encontrada.**shows a comparison between the three alternatives studied in terms of flow rates, closing time, maximum pressure and overpressure at the control valve (end of the pipeline) and piping costs only and total costs for each alternative. A 7th option called "3c" was simulated, in which the lowest flow rate (14.56 L s $^{-1}$) was used but with a mechanical closing time of

76 s, equivalent to cases 1b and 2b. In this case, a Function 49 valve was not provided, only the flow limiter.

Table 2. Data from the cases analyzed

Case	Tf (s)	Flow rate (L s $^{-1}$)	PPvc (mca)	Smax (mca)	Ctub (R$)	CT (R$)
1a	11.27	20.33	5.52	93.57	63,936.10	63,936.10
1b	75.00	20.33	5.52	54.70	48,164.76	52,764.76
2nd	11.27	20.16	6.01	93.26	65,571.68	65,571.68
2b	76.00	20.16	6.01	54.62	48,164.76	52,764.76
3a	11.27	14.56	19.78	83.38	62,643.98	67,243.98
3b	107.00	14.56	19.78	54.89	48,652.26	57,852.26
3c	76.00	14.56	19.78	58.65	48,944.76	53,544.76

Tf = closing time; PPvc = permanent pressure in the control valve; Smax = maximum overpressure; Ctub = piping cost; CT = total cost.
Source: prepared by the authors – Taken from the UFC System.

The results demonstrate that it is important to relate the final cost of the alternatives to the magnitude of the water hammer, as is evident when comparing cases 1 and 2 with case 3, in which there was flow control in all options. Referring to Bernoulli's theorem, a lower flow rate was set in the same pipeline than in the other pipelines, implying a higher final pressure in the control valve area (19.78 mca).

According to equations 3 and 4, the flow rate (Q) and load (H) directly affect the value of the hydraulic transients, and in this case, the load (H) was more important than the flow rate (Q), which, in this case, had a lower value. Therefore, it is not possible to define which of the two parameters has the greatest influence on the phenomenon, requiring appropriate simulation.

All alternatives in which the closing time of 11.23 s was used proved to be more expensive in the “piping” item because of the need to apply materials with a higher pressure class or resistance to rupture, since the maximum overpressures were the highest in all of them.

The use of Function 49 valves (alternatives 1b, 2b and 3b) resulted in lower overpressures and, consequently, the need for more economical piping. Assuming mechanical operation in option 3c, to simulate the transient effects with a closing time equivalent to options 1b and 2b, the difference between them was small. However, considering the total costs, this approach ranks 3rd among the cheapest; however, in practical terms, it is highly unlikely that closing will be achieved in this precise time.

In all alternatives, compliance with the piping period (11.27 s) always proved to be the most expensive because of the need to apply pipes with a higher pressure class.

Cases 1b and 2b, with flow rates of 22.30 Ls $^{-1}$ and 22.16 Ls $^{-1}$ for closing times of 75 and 76 s, respectively, would be the least expensive due to the relatively high flow rates considering the same implemented structure.

Considering that the network was not changed in any of the alternatives with respect to diameter, the established differential was the closing time and the incident overpressures, implying adjustments in the pressure class of the pipelines.

Tables 3 to 5 detail the costs of the cases studied.

Table 3. Comparative costs - cases 1a and 1b

Item	unit price	Alternative			
		case 01a		case 01b	
		qty .	p. total	qty .	p. total
PVC pipe ILF PBL 150 mm PN 40*	185.00	23	4255.00	134	24790.00
ILF PBL PVC pipe 150 mm PN 60*	252.00	112	28224.00	0	0.00
PVC pipe ILF PBL 150 mm PN 80*	303.43	0	0	0	0.00
ILF PBL PVC pipe 150 mm PN 125*	329.17	0	0.00	0	0.00
PVC pipe ILF PBL 125 mm PN 40*	130.28	0	0.00	42	5471.76
PVC pipe ILF PBL 125 mm PN 60*	179.03	0	0.00	100	17903.00
PVC pipe ILF PBL 125 mm PN 125*	223.10	141	31457.10	0	0.00
subtotal pipes			63936.10		48164.76
Plastic valve 4" 100 Y "Function 49" 03 WAYS MOD 50-40-69**	4,600.00	0	0.00	1	4600.00
Plastic valve 4" 100 Y "FR" 03 WAY**	4,600.00	0	0.00	0.00	0.00
Total			63936.10		52764.76

*unit: 6 m tube; **unit: piece.
Source: prepared by the authors

Table 4. Comparative costs - cases 2a and 2b

Item	unit price	Alternative			
		case 02a		case 02b	
		qty .	p. total	qty .	p. total
PVC pipe ILF PBL 150 mm PN 40*	185.00	22	4070.00	134	24790.00
ILF PBL PVC pipe 150 mm PN 60*	252.00	112	28224.00	0	0.00
PVC pipe ILF PBL 150 mm PN 80*	303.43	6	1820.58	0	0.00
ILF PBL PVC pipe 150 mm PN 125*	329.17	0	0.00	0	0.00
PVC pipe ILF PBL 125 mm PN 40*	130.28	0	0.00	42	5471.76
PVC pipe ILF PBL 125 mm PN 60*	179.03	0	0.00	100	17903.00
PVC pipe ILF PBL 125 mm PN 125*	223.10	141	31457.10	0	0.00
subtotal pipes			65571.68		48164.76
Plastic valve 4" 100 Y "Function 49" 03 WAYS MOD 50-40-69**	4,600.00	0.00	0.00	1	4600.00
Plastic valve 4" 100 Y "FR" 03 WAY**	4,600.00	0.00	0.00	0.00	0.00
Total			65571.68		52764.76

*unit: 6 m tube; **unit: piece.
Source: prepared by the authors.

Table 5. Comparative costs - cases 3a, 3b and 3c

Item	unit price	Alternative					
		case 03a		case 03b		case 03c	
		qty .	p. total	qty .	p. total	qty .	p. total
PVC pipe ILF PBL 150 mm PN 40	185.00	28	5180.00	134	24790.00	134	24790.00
PVC pipe ILF PBL 150 mm PN 60	252.00	106	26712.00	0	0.00	0	0.00
PVC pipe ILF PBL 150 mm PN 80	303.43	0	0	0	0.00	0	0.00
ILF PBL PVC pipe 150 mm PN 125	329.17	0	0.00	0	0.00	0	0.00
PVC pipe ILF PBL 125 mm PN 40	130.28	0	0.00	32	4168.96	26	3387.28
PVC pipe ILF PBL 125 mm PN 60	179.03	16	2864.48	110	19693.30	116	20767.48
PVC pipe ILF PBL 125 mm PN 125	223.10	125	27887.50	0	0.00	0	0.00
subtotal pipes			62643.98		48652.26		48944.76
Plastic valve 4" 100 Y "Function 49" 03 WAYS MOD 50-40-69	4,600.00	0	0.00	1	4600.00	0	0.00
Plastic valve 4" 100 Y "FR" 03 WAY	4,600.00	1	4600.00	1	4600.00	1	4600.00
Total			67243.98		57852.26		53544.76

*unit: 6 m tube; **unit: piece.
Source: prepared by the authors.

The transient effects in gravity networks can be as serious or more serious than those in pressurized systems, depending on the case, and the use of the “Function 49” valve resulted in total savings of between 14% and 20% in total investments, comparing alternatives “a” and “b” for each case. Case 3c was not considered, as its implementation in the field is unlikely.

6 CONCLUSIONS

The fact that a water main is gravity driven does not imply that transient phenomena are negligible; in contrast, they may be subject to total rupture, and it is wrong to design without analyzing hydraulic transients via computer systems, just as in discharge water mains.

The sizing of adductors and the prediction and control of hydraulic transients can lead to savings in investments, in addition to operational safety.

Flow control through flow-limiting valves does not necessarily imply a reduction in pressure envelopes and may even generate others of greater value.

The mere calculation of the pipeline period (Equation 2) to define a valve closing time—as presented in much of the literature on hydraulics—to avoid the harmful effects of transients has proven to be a mistaken strategy that should not be adopted indiscriminately. The only way to define this parameter is through computational analysis with appropriate software.

When analyzing the closure in the time pertinent to the period of the alternatives (11.27 s), it is clear that the effective load plan presented by Bernoulli's theorem was overcome by the overpressure, which denotes the difference between the permanent and transient regimes.

The adoption of “Function 49” proved to be much more than mere high-level hydraulic technicality for controlling the water hammer in the gravity network studied, as it is a question of saving on the necessary investments, allowing maximum use of the network for the same implemented structure, since the closure of the reservoir will obey the hydraulic system naturally and without interference, in a self-regulating manner.

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