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Techno-Economic Analysis of BESS for Transient Pressure Control in Water Supply Rising Mains

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Abstract: This study analyzes the technical and economic feasibility of using Battery Energy Storage Systems (BESS) as an alternative to hydropneumatic tanks for controlling transient pressures in pumping systems. The methodology involved computational modeling of hydraulic transients in a 400 mm diameter ductile iron pipeline, with a total length of 10,346 meters, connected to a pumping station with a nominal flow rate of 200 LPS and a head of 285 meters. Two scenarios were compared: (i) the use of hydropneumatic tanks (HPT) combined with a bidirectional surge tank (BST); and (ii) the implementation of a BESS, enabling gradual pump shutdown. Results indicated that the BESS, by facilitating a 4-minute ramp-down, reduced the peak pressure by 155.31 mwc and maintained a minimum pressure of 1.7 mwc, successfully preventing vacuum formation. In contrast, the HPT solution reduced peak pressure by 134.44 mwc but resulted in a subpressure of -3.5 mwc, necessitating additional BST installation. Furthermore, the BESS demonstrated a lower total lifecycle cost compared to the HPT/BST alternative. The study concludes that BESS is an effective and innovative solution for mitigating hydraulic transients, offering superior technical performance and cost-effectiveness while enhancing the safety and reliability of water supply systems.

Key words: hydraulic transients, BESS, battery energy storage system, water hammer, pumping systems

1. Introduction

In hydraulic engineering, the safe operation of pumping stations and rising mains depends on the effective control of transient pressures. According to Azevedo Neto [1], during a power failure, the velocity of the pump sets decreases rapidly due to the loss of rotational inertia, leading to a sudden reduction in flow. The liquid column continues to move forward until its momentum is overcome by gravity. During this interval, a subpressure (negative pressure) occurs within the pipeline. Upon flow reversal, the column returns toward the pump until it encounters the closed check valve, causing fluid compression and resulting in overpressure. This transient pressure variation is known as a hydraulic transient or water hammer. Since the 20th century, hydraulic systems have utilized flywheels, consisting of a steel disc coupled to the shaft between the motor and the pump. The additional mass of this device increases the moment of inertia of the rotating parts, prolonging the deceleration time during power outages and thus mitigating transient pressures. However, flywheels present disadvantages, such as:

- Primary suitability for horizontal shaft pumps, with difficult application in vertical shaft pumps.
- Significant increase in steady-state electrical energy consumption.
- General limitation to relatively short rising mains.

Due to these drawbacks and advancements in the study of the phenomenon, flywheels have largely been replaced by newer devices, such as hydropneumatic tanks (HPT) and bidirectional surge tanks (BST), among others.

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According to Vianna [2], a hydropneumatic tank (HPT) is a vessel containing both water and compressed air, connected to the pipeline near the pumping station. When the pipeline is subjected to transient overpressure, the corresponding energy is transferred to the air inside the tank, which stores it as elastic energy through compression. Conversely, during subpressure events, the compressed air expands, releasing energy back into the system. There are two main types of hydropneumatic tanks. The classic type features a direct air-water interface. Because the air is pressurized, it tends to dissolve into the water over time, reducing its volume within the tank. Consequently, it requires the installation of an air compressor and level sensors to maintain the correct air-to-water ratio for proper operation. Fig. 1 illustrates this equipment.

The second type utilizes an internal bladder. In this configuration, there is no contact between the water and the compressed air. Thus, the air volume remains constant throughout the equipment's service life, eliminating the need for a compressor. Fig. 2 illustrates this design.

An alternative to HPTs for transient pressure control is the use of an alternative energy source that, in the event of primary power failure, can immediately energize the pump sets for a sufficient duration to allow a gradual ramp-down — similar to the effect provided by flywheels. In this context, Battery Energy Storage Systems (BESS) constitute a compelling alternative. A Battery Energy Storage System consists of a sophisticated mechatronic assembly comprising a high-density battery array with an integrated electronic system, governed by a battery management system, providing constant monitoring of critical parameters such as state of charge and state of health to optimize performance and extend the system's service life.

In the context of hydraulic transient control, the BESS operates in direct synergy with a variable frequency drive (VFD). Once the system detects a power grid failure, this system allows an instantaneous commutation to the battery DC bus, with a switching latency of 200 milliseconds. Fig. 3 illustrates this system.

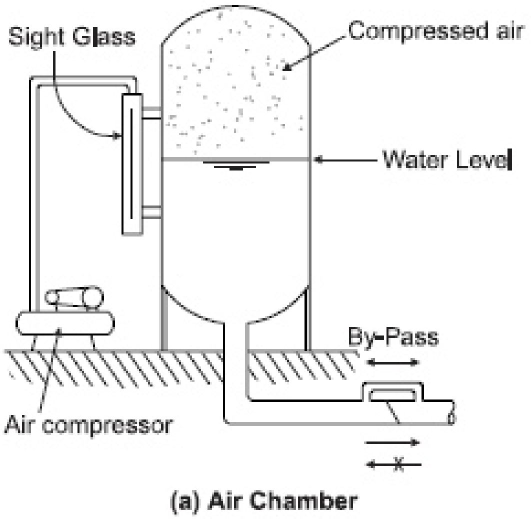

Fig. 1 Hydropneumatic tank classic type [3].

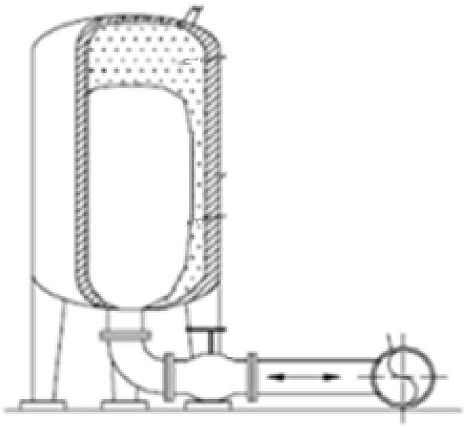

Fig. 2 Hydropneumatic tank with bladder [5].

Fig. 3 BESS – Battery Energy Storage System [6].

In this paper, an operational analysis under transient conditions is presented for a ductile iron rising main with a nominal diameter of 400 mm and a total length of 10,346 meters. The system is connected to a water pumping station with a nominal flow rate of 200 Lps and a total head (TDH) of 278 mwc. This techno-economic analysis addresses the operation and implementation costs of protection devices against overpressure and subpressure, as well as estimated operation and maintenance (O&M) costs, comparing the use of hydropneumatic surge tanks versus BESS.

2. Material and Methods

2.1 Methods

The methodology adopted in this study consisted of a computational analysis of the transient operation of a rising main. The objective was to compare the hydraulic performance and the costs associated with the implementation, operation, and maintenance of two alternatives for protection against excessive transient pressures: (i) the use of two hydropneumatic tanks (HPT), with one serving as a standby unit, and the installation of a bidirectional surge tank (BST) at an existing peak along the pipeline; and (ii) the installation of a BESS unit at the pumping station.

For the HPT, the installation cost included design and civil works for both tanks, hydraulic connections and valves, instrumentation, labor, and commissioning. For the BST, installation costs encompassed the design and execution of the mounting structure for the relief valve, hydraulic connections, instrumentation, and commissioning. Operation and maintenance (O&M) costs considered inspections according to NR-13 (Brazilian Regulatory Standard for pressure vessels) [7], applicable to a Class V tank, as well as eventual bladder replacement in case of abnormal pressure loss or relevant damage.

In Brazil, the selection and operation of HPT are heavily governed by Regulatory Standard NR-13 (NR-13). This standard, which draws its technical foundations and safety criteria from international codes such as the ASME Boiler and Pressure Vessel Code (Section VIII), establishes mandatory requirements for the structural integrity of pressure vessels, pipelines, and storage tanks. HPT classified as pressure vessels under these criteria, must strictly comply to NR-13 to mitigate risks of catastrophic failure. Compliance with this standard imposes several recurring obligations that significantly increase the Operational Expenditure (OPEX) of a water supply system:

- Mandatory Inspections: Similar to ASME recommendations but with legal enforcement in Brazil, vessels must undergo periodic internal and external inspections conducted by a “Qualified Legal Professional”, typically a certified mechanical engineer.
- Safety Device Calibration: Pressure relief valves and monitoring instruments require scheduled calibration and testing to ensure they operate within design limits, preventing overpressure events.
- Asset Management: Every vessel must maintain an updated “Safety Record Book”, containing detailed design data, hydrostatic test certificates, and all subsequent inspection reports.

For the BESS, the installation cost included design and civil works, electrical installations, labor, and commissioning. O&M costs were based on an estimated annual cost, as well as the potential replacement of a battery module if any anomaly is detected.

2.2 Rising Main and Pumping Station

The rising main is located in southern Brazil, and has the following characteristics:

- Pipeline Material: Ductile Iron
- Nominal Diameter (DN): 400 mm
- Outer Diameter (OD): 429 mm

- Inner Diameter (ID): 406.40 mm
- Total Length: 10,346 meters
- Static Head (Geometric Elevation): 195.81 meters
- Design Temperature: 25°C
- Wave Speed (Celerity): 1113.92 m/s

Fig. 4 shows the longitudinal profile of the pipeline.

The pumping station has the following characteristics:

- Installation Elevation: 556.70 m.a.s.l. (meters above sea level).
- Minimum Suction Water Level: 558.55 m.a.s.l.
- Configuration: Three (03) horizontal multistage pump sets.

Standard operation utilizes only one pump set. However, the system was designed to allow parallel operation of up to two units, when necessary, with the third unit available as standby. The selected pump set is the KSB Multitec A 150/5-12.2, with the following specifications:

- Rotation: 1750 rpm.
- Efficiency: 81.1%.
- Nominal Power: 360 kW.
- Moment of Inertia: 11.26 kgf.m².

The pump characteristic curve and the system curve, considering two pumps in parallel, resulted in an operating point of 200 Lps and total head of 278 mwc. This operational point was used for all transient simulations. Fig. 5 shows the referred characteristic curves.

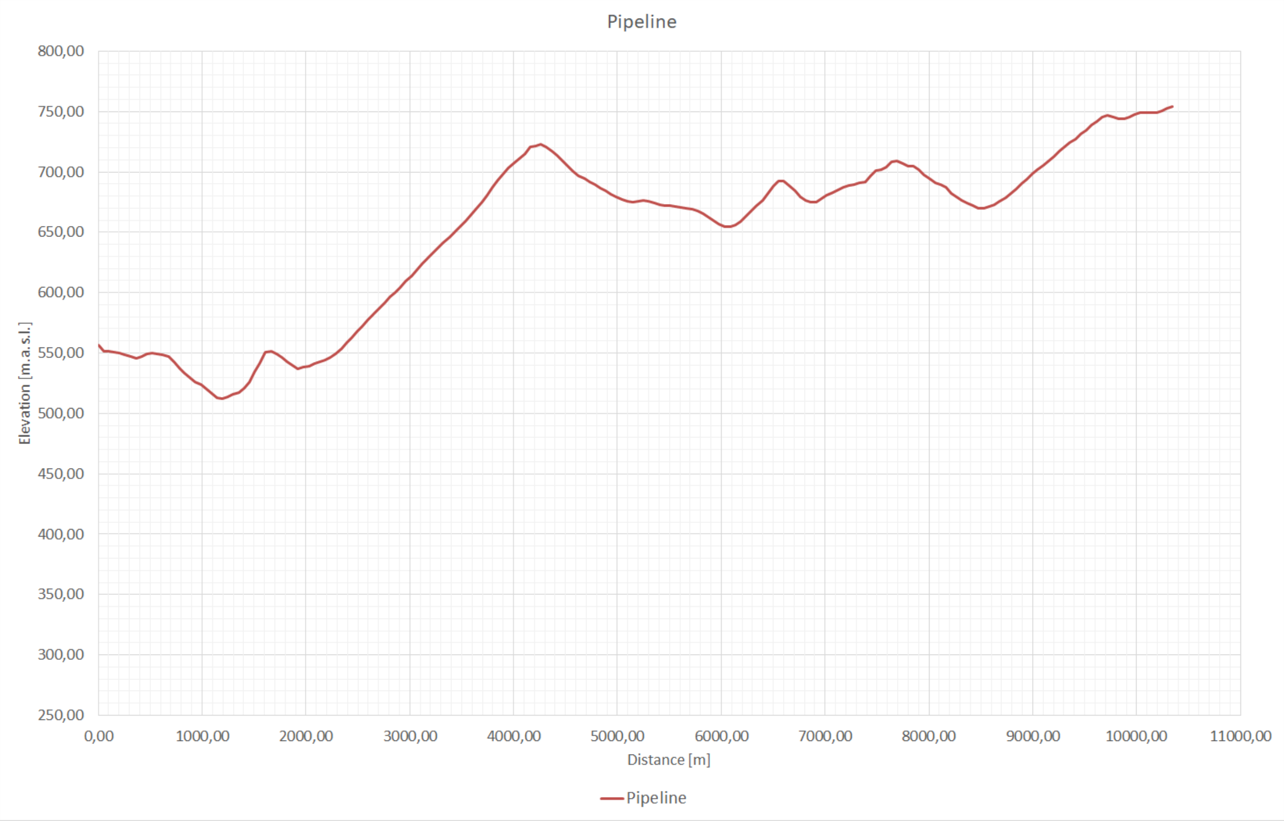

Fig. 4 Pipeline [6].

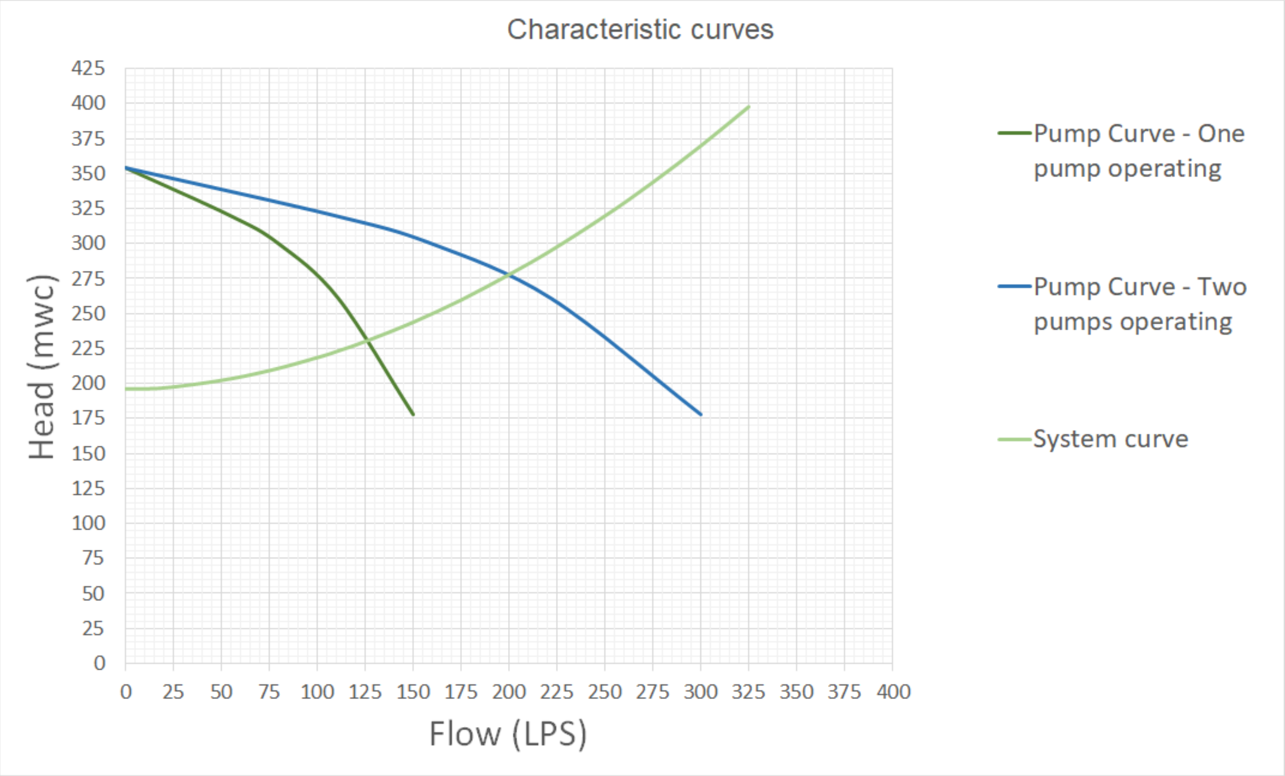

Fig. 5 Characteristic curves.

2.3 Computational Modeling

The analysis of transients in this study is grounded by the fundamentals laws of fluid mechanics: the conservation of mass and conservation of momentum.

Following the classical theoretical framework established by Parmakian [8], these principles are initially expressed in their integral forms. The continuity equation (1) represents the conservation of mass within a fixed control volume (VC), accounting for both fluid compressibility and pipe wall elasticity:

$$\int_{SC} \rho (V\,.n)dA + \frac{\partial}{\partial t} \int_{VC} \rho d\forall = 0 \qquad (1)$$

Simultaneously, the momentum equation (2) relates the sum of external forces acting on the fluid to the rate of change of momentum:

$$\sum F_x = \int_{SC} \partial V_x (V\,.n)dA + \frac{\partial}{\partial t} \int_{VC} \rho V_x d\forall \qquad (2)$$

For the practical application in long pipelines, these expressions are simplified into a set of partial differential equations. In terms of hydraulic head (H) and flow rate (Q), the governing equations of continuity and momentum for unsteady flow in pressurized pipelines are defined as show in equations (3) and (4), respectively. The *a* is the wave speed, *g* is the gravitational acceleration, *D* is the internal diameter, and *f* is the Darcy-Weisbach friction factor.

$$\frac{\partial H}{\partial t} + \frac{a^2}{gA}\frac{\partial Q}{\partial x} = 0 \qquad (3)$$

$$\frac{\partial Q}{\partial t} + gA\frac{\partial H}{\partial x} + \frac{fQ|Q|}{2DA} = 0 \qquad (4)$$

The previous equations were solved numerically using the Method of Characteristics (MOC) within the Voima Toolbox software, developed by Vianna [2, 4]. The MOC transforms the partial differential equations into ordinary differential equations along characteristics lines, enabling precise calculation of maximum and minimum pressure envelopes across the entire pipeline. The numerical solution respects the Courant-Friedrichs-Lewy stability criterion to ensure convergence and accuracy during the wave propagation.

Also, the software uses the solved equations to size the HPT and BST. The initial conditions included the physical properties of the 400 mm ductile iron pipeline (10,346 m length) and the steady-state operating parameters (200 Lps, 278 mwc), along with pump data, such as nominal power (360 kW), moment of inertia (11.26 kgf.m²), rotation (1750 RPM), and efficiency (81.1%).

2.3 Simulated Scenarios

The following technical scenarios were simulated:

- Scenario 1: Transient flow without any protection device.
- Scenario 2: Transient flow with an HPT installed near the pumping station. The HPT was sized using the MOC with the following parameters: Diameter: 2.0 m; Total Volume: 30 m³; Initial Air Volume: 15 m³.
- Scenario 3: Transient flow with the HPT (as in Scenario 2) and a BST installed at the peak at 4,265 meters (elevation 722.74 m.a.s.l.). The BST arrangement included a triple-function air valve (DN 100).
- Scenarios 4, 5, and 6: Transient flow with gradual pump shutdown (ramp-down) intervals of 1, 3, and 4 minutes, respectively, enabled by the BESS.

For the economic analysis, quotes were obtained from suppliers for all protection devices, and O&M costs were estimated over a 10-year horizon.

3. Results and Discussion

The results obtained from the computational simulation of the scenarios — both unprotected and protected — enabled an evaluation of the hydraulic behavior of the combined pipeline and pumping station system. The analysis identified two critical locations: a depression at distance 1,195.77 m, which generates a high-pressure point; and a peak at distance 4,263.18 m, which is susceptible to vacuum formation.

As the simulation software (Voima Toolbox) generates outputs with labels in Portuguese, the following color coding applies to all figures in this section: the black line represents the rising main profile (*perfil*); the green line represents the hydraulic grade line or HGL (*piezométrica*); and the red and blue lines indicate the maximum and minimum transient pressure envelopes (*carga máxima e mínima*), respectively. Additionally, the protection devices labeled in the figures as RHO (*Reservatório Hidropneumático*) and TAB (*Tanque de Alimentação Bidirecional*) correspond to the HPT (Hydropneumatic Tank) and BST (Bidirectional Surge Tank) discussed in this study.

Scenario 1 (unprotected) resulted in a maximum overpressure of 440.62 mwc at 1,195.77 m and a maximum subpressure of -153.91 mwc at 4,263.18 m. The pressure envelopes, alongside the hydraulic grade line and the longitudinal profile, are shown in Fig. 6.

Scenario 2 (HPT near the pumping station) yielded a maximum pressure of 315.36 mwc at 1,195.77 m and a maximum subpressure of -10.67 mwc at 4,263.18 m. The pressure envelopes, alongside the hydraulic grade line and the longitudinal profile, are shown in Fig. 7.

Scenario 3 (HPT plus BST at the peak) further improved results, with a maximum pressure of 306.18 mwc and a reduced subpressure of -3.48 mwc at 4,263.18 m. The pressure envelopes, alongside the hydraulic grade line and the longitudinal profile, are shown in Fig. 8.

Regarding the BESS alternatives (Scenarios 4, 5, and 6), the performance was directly linked to the shutdown duration. Scenario 4 (1-minute ramp-down) still resulted in significant subpressure (-44.83 mwc). Scenario 5 (3-minute ramp-down) brought subpressure closer to atmospheric limits (-4.89 mwc). Finally, Scenario 6 (4-minute ramp-down) proved the most effective, with a peak pressure of 285.31 mwc and a minimum pressure of 1.73 mwc, successfully eliminating all negative pressures along the entire pipeline. The results for Scenarios 4, 5, and 6 are detailed in Figs. 9, 10, and 11, respectively.

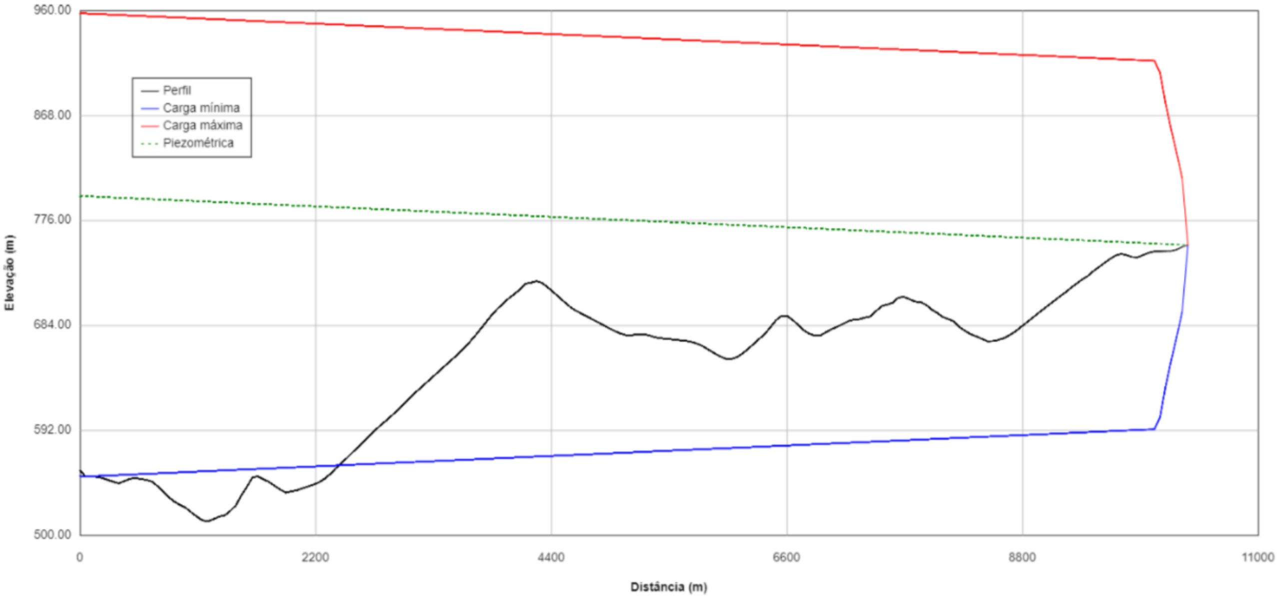

Fig. 6 Scenario 1.

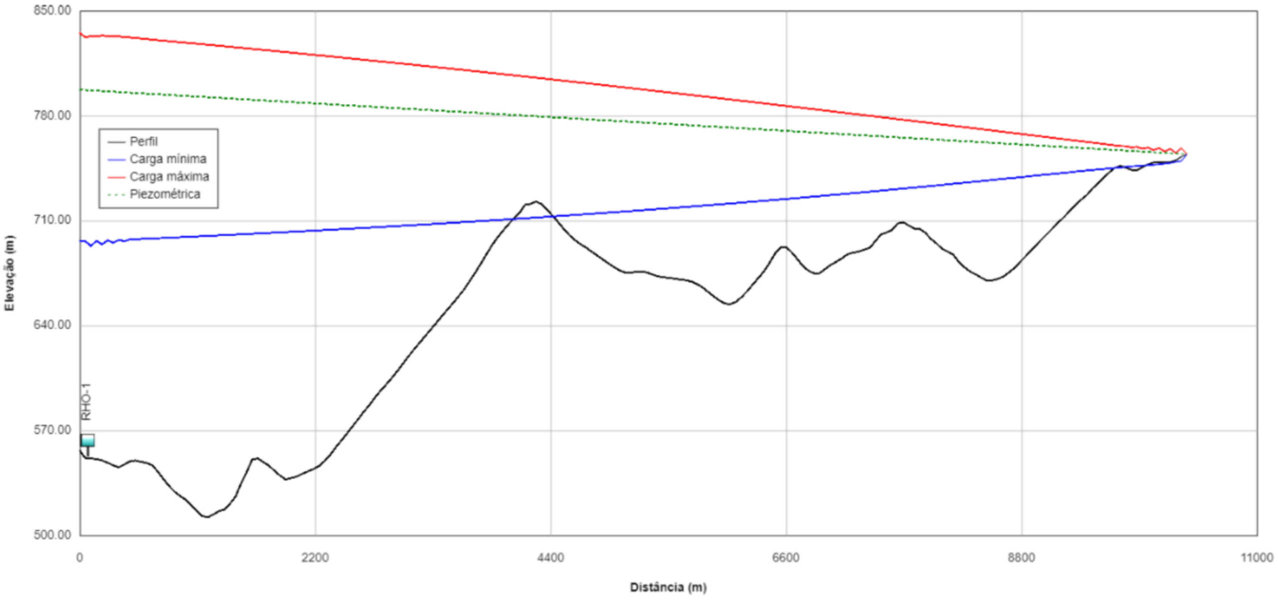

Fig. 7 Scenario 2.

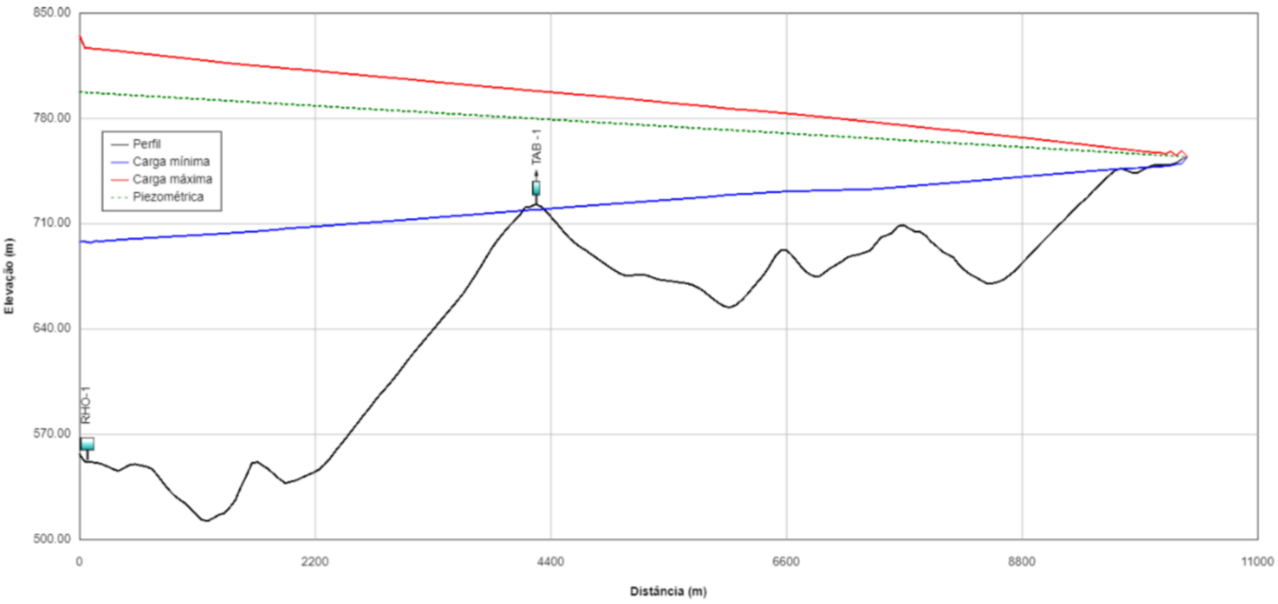

Fig. 8 Scenario 3.

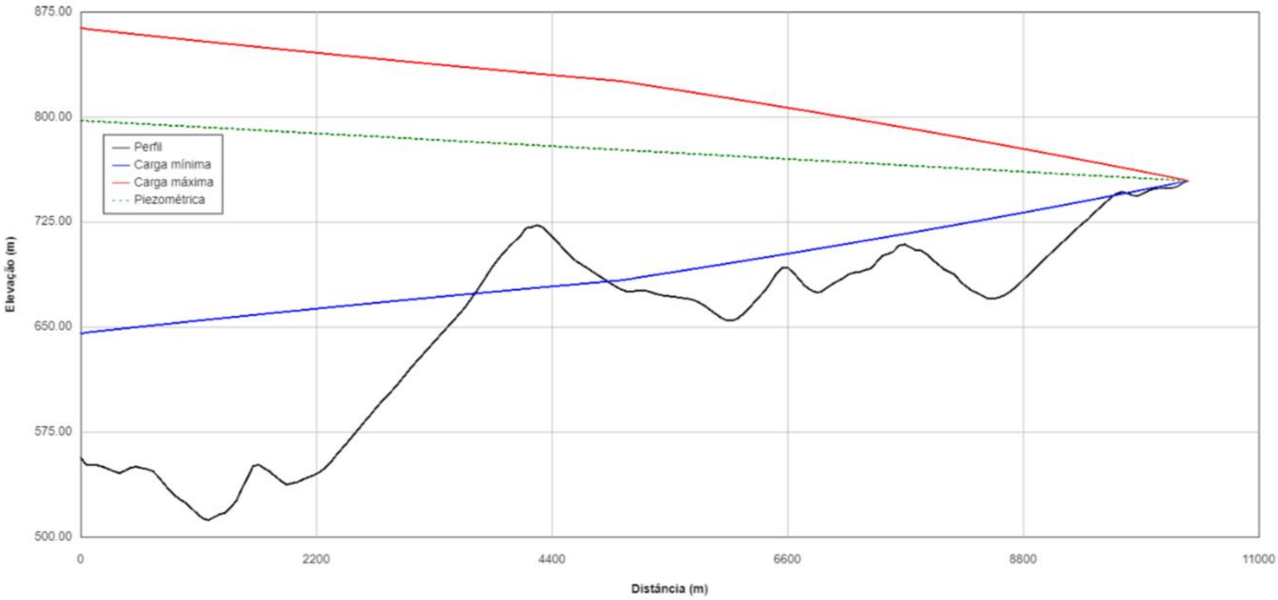

Fig. 9 Scenario 4.

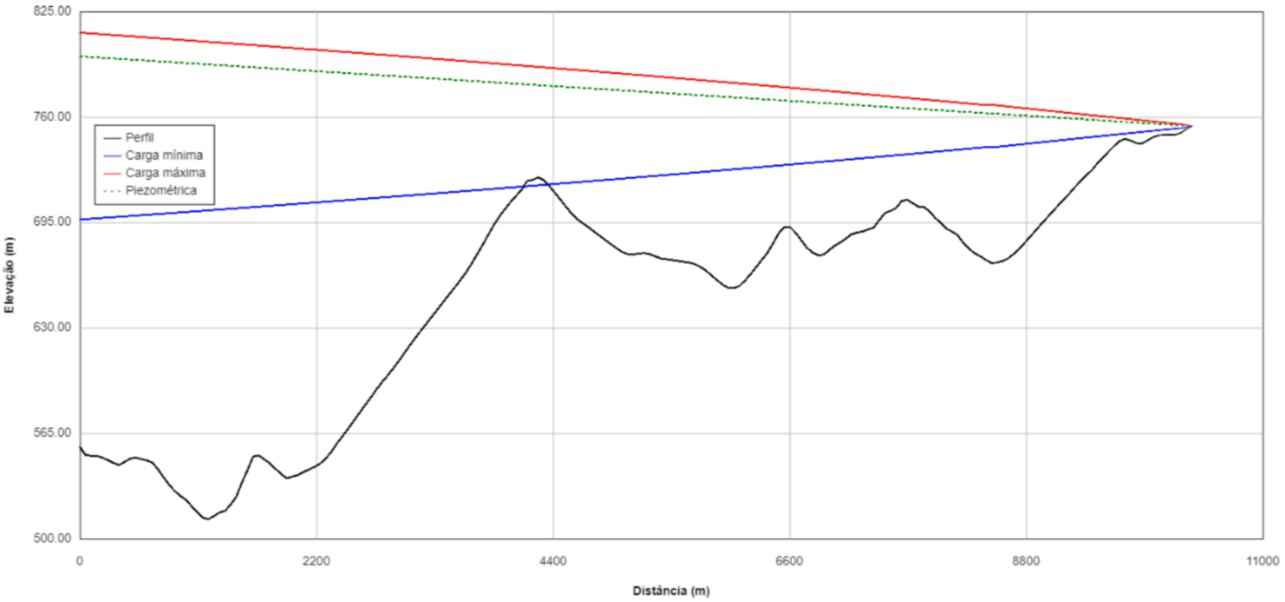

Fig. 10 Scenario 5.

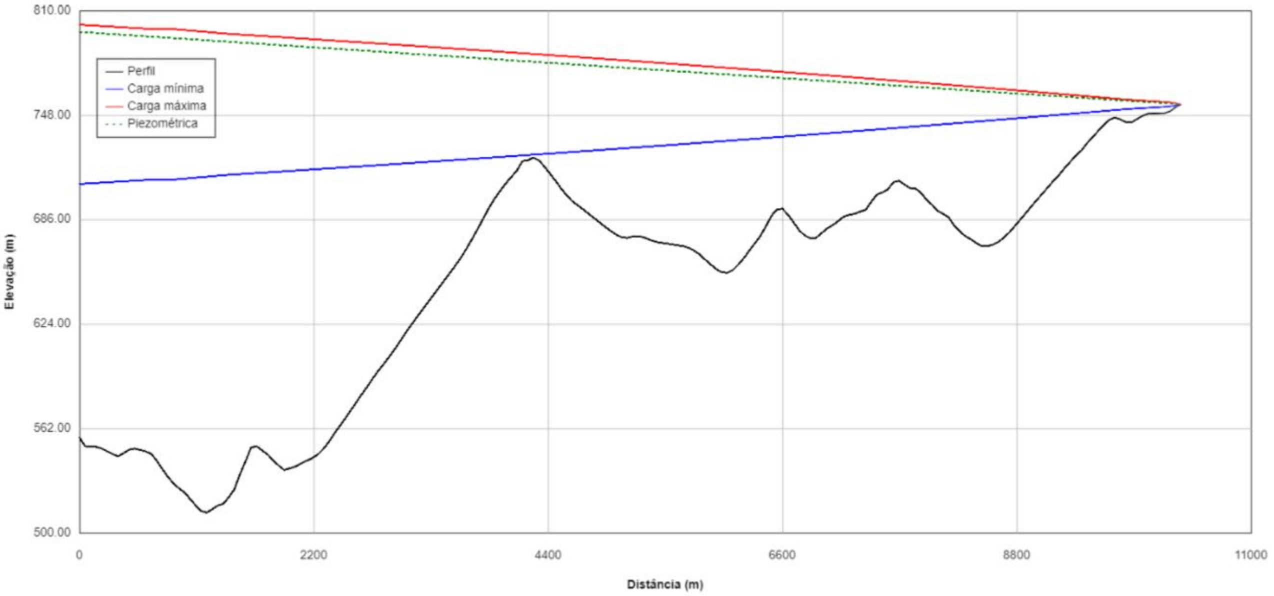

Fig. 11 Scenario 6.

The practical implementation of BESS depends on the system's ability to respond nearly instantaneously to a power grid failure. According to the manufacturer's specification, the BESS unit features a switching latency of 200 milliseconds (ms) between the detection of a main grid outage and the full activation of the battery DC bus. From a hydraulic context, this 200 ms delay is negligible when compared to the pipeline's characteristic travel time (*L/a*), which is 9.28 seconds for this study. Since the commutation occurs in a fraction of the time required for the initial pressure wave to propagate, the Variable Frequency Drive (VFD) maintains total control over the motor's torque, preventing a sharp drop in pump RPM. Consequently, the 200 ms response time ensures that the programmed 4-minute linear ramp-down is executed as a continuous, controlled maneuver, effectively safeguarding the pipeline's integrity. This controlled ramp-down is the fundamental mechanism that prevents the rapid deceleration of the liquid column and the subsequent formation of destructive subpressures observed in scenario 1.

The economic evaluation of the proposed solutions revealed distinct investment profiles for each scenario. The equipment acquisition cost for the conventional HPT and BST configuration (Scenario 3) was BRL 2,835,302.62. In comparison, the BESS (Scenarios 4, 5, and 6) presented a slightly lower acquisition cost of BRL 2,798,255.48. However, a significant difference was observed regarding implementation; the installation cost for the BESS was BRL 279,825.50, which is substantially higher than the BRL 104,000.00 required for the HPT and BST assembly. Conversely, the estimated 10-year operation and maintenance costs for the BESS were significantly lower at BRL 539,738.32, compared to BRL 1,034,046.00 for the Scenario 3 solution. Ultimately, the BESS scenarios achieved the lowest total cost of BRL 3,617,819.30, confirming its long-term financial advantage over the conventional HPT and BST total cost of BRL 3,973,348.62.

4. Conclusions

The technical analysis demonstrated that the HPT and BST combination (Scenario 3) provided a 31% reduction in overpressure and a 98% reduction in subpressure compared to the unprotected system. In contrast, the BESS with a 4-minute controlled ramp-down (Scenario 6) achieved a superior 35% overpressure reduction and the complete elimination of subpressure. From an economic perspective, the implementation of BESS resulted in a 9% reduction in total lifecycle costs compared to Scenario 3, representing a total saving of BRL 355,529.32 over the analyzed period.

Based on this comprehensive analysis, the implementation of BESS represents a technically superior and economically viable alternative for mitigating hydraulic transients in pipelines. This technology not only reduces long-term operational and maintenance costs but also significantly enhances the safety and structural reliability of water supply infrastructure.

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