International IAHR Meeting on Transient Flows
25-26 November 2025
Vitória, Brazil
in conjunction with the
XXVI Brazilian Symposium on Water Resources
23-28 November 2025

EVALUATION OF PRESSURE WAVE SPEED IN PVC PIPES

Daniela B. SODEK[1], André L.S. S. MARTIM[2], José Gilberto DALFRÉ FILHO[3], Edevar LUVIZOTTO Junior[4]

[1,2,3,4] FECFAU – Unicamp, Brazil
email: danibonazzi@hotmail.com
email: asmartim@unicamp.br
email: dalfre@unicamp.br
email: edevar@unicamp.br

ABSTRACT

This study investigates the speed of pressure wave propagation in PVC pipelines, with a particular focus on analyzing the influence of each variable involved in wave speed calculation within an elastic model, as compared to a rigid model. The research determined experimentally the values for the elastic modulus. To ensure accurate material characterization, laboratory tensile tests were conducted to determine the actual elastic properties of the PVC pipes used in the analysis. Additionally, the study considers the influence of other parameters, including the water bulk modulus, density, and pipe diameter, which also contribute to the determination of wave speed, though to a lesser extent. The results demonstrate that variations in the elastic modulus of the pipe material have the most substantial impact on wave speed folowed by pipe anchoring coeficient, surpassing the effects of temperature and other geometric factors.

Keywords: elasticity module, wave speed.

1. Introduction

Water distribution systems, as any pressurized systems carrying a fluid, are subject to transient patterns due to events such as valve operation and pump starts and stop maneuvering (Britton and Willey, 2024). In the transient analysis of water pipes, there are essentially two main modeling approaches: rigid water collum and the water hammer (elastic) model. The rigid water collum, also known as surge model, is appropriate for simulating relatively slow transients where the fluid and pipe compresebility can be considered negletable. This model is based on ordinary differential equations, making it simpler to apply and computationally less intensive. In the other hand, the water hammer, or elastic model is used to simulate rapid transient events, where sudden changes in pressure and velocity occur, and both fluid and pipe compressibility must be considered. This approach requires the determination of pressure wave propagation (celerity) and involves solving partial differential equations (Tullis, 1989; Larock *et al.* , 2000).

The propagation of pressure waves, also known as celerity is a critical parameter in the dynamic behavior of water distribution systems (Karney and McInnis, 1990). The pressure wave propagation is a key parameter in the context of hydraulic transients and the water hammer phenomenon (Mushumbusi *et al.*, 2025) as the calculation of pressure variation is directly proportional to it as shown on Eq. (1) (Tullis, 1989). Therefore, accurate knowledge of wave speed is essential for the proper sizing of protection devices, relief valves, and for the reliable simulation of transient events (Larock *et al.*, 2000).

$$\Delta H = -a \frac{\Delta V}{g} \quad (1)$$

where, ΔH is the pressure variation, a is the wave speed (or celerity), ΔV is the velocity variation and g acceleration of gravity.

In some cases, for simplification, pipes with very small elasticity modules are considered rigid this model can be called elastic model with rigid pipe. The elastic model with rigid pipe assumes that the pipe walls are perfectly rigid and the fluid is compressible. In this case, the wave speed is determined solely by the compressibility of the fluid and is significantly higher. This aproach tends to overestimate the pressure surge because it neglects the energy absorption provided by the pipe wall deformation. In contrast, the elastic model with elastic pipe accounts for both fluid compressibility and pipe wall elasticity, resulting in a lower wave speed and a more realistic prediction of transient pressures, especially during rapid events where elastic effects play a significant role (Larson and Jönsson, 1991). On the elastic model with rigid pipes, wave speed is determined as per Eq (2). On the other hand, for the elastic model of thin wall pipes, wave speed is determined taking into consideration the pipe material and caracteristics as per Eq (3) (Tullis, 1989).

$$a = \sqrt{\frac{K}{\rho}} \tag{2}$$

where *a* is wave speed (celerity) in *m/s*, *K* (*Pa*) is the bulk modul of fluid and ρ (kg/m^3) is the fluid density.

$$a = \sqrt{\frac{\frac{K}{\rho}}{\left(1+\frac{KD}{E.e}.\Psi\right)}} \tag{3}$$

where *a* is wave speed (celerity) in *m/s*, *K* (*Pa*) is the bulk modul of fluid and ρ (kg/m^3) is the fluid density, *D* is the pipe diameter (*mm*), *e* is the pipe wall thickness (*mm*), *E* is the elasticity module of the pipe material (*Pa*) and ψ is the admensional pipe restraint coefficient.

In the analysis of hydraulic transients, the anchoring coefficient (ψ) plays a critical role in accurately determining the pressure wave speed within pipelines. This coefficient accounts for the degree of axial movement restriction imposed by the pipeline's support and anchoring conditions. Depending on whether the pipe is rigidly anchored, equipped with expansion joints, or simply supported at its ends, the anchoring coefficient varies to reflect the corresponding mechanical behavior of the system. When a pipeline is rigidly anchored, axial expansion is fully restricted, and the anchoring coefficient is given by $\psi = 1 - \nu^2$, where υ represents the Poisson's ratio of the pipe material. Poisson's ratio describes the relationship between longitudinal and transverse deformation in a material and typically ranges from 0.30 for metallic pipes to approximately 0.45 for plastic materials such as PVC or HDPE. In contrast, pipelines with expansion joints, which permit free axial displacement, adopt an anchoring coefficient of $\psi = 1$, indicating the absence of axial constraint. For cases involving end supports or partially restrained conditions, the anchoring coefficient is $\psi = 1.25 - \upsilon$ (Tullis, 1989). Proper selection and application of the anchoring coefficient are essential to accurately model the interaction between fluid compressibility and pipe elasticity.

The elastic modulus is one of the most critical properties influencing wave speed, making the selection of pipe material a key factor in hydraulic design (Kandil, *et al.*, 2024). The elastic modulus of pipes is affected by variables such as temperature, manufacturing processes, and material aging. For viscoelastic materials like PVC, HDPE, and PE, the elastic modulus tends to decrease over time, which leads to a slight reduction in wave speed (Tjuatja *et al.*, 2023). However, for the sake of simplicity, ta constant elastic model is often used to estimate wave speed, as it slightly overestimates wave speed.

This study aims to demonstrate the impact of each variable in determining wave speed for a elastic model with elastic pipes, under different conditions, specifically considering elastic PVC pipes as on the last decades this is one of the material that has gained popularity in water distribution systems (Tjuatja *et al.*, 2023). The elastic modulus is commonly sourced from supplier catalogs, as it is not easily measured in practice (Kandil, *et al.*, 2024). In this study, the elastic modulus of PVC was determined based on experimental values obtained through laboratory analyses, providing a more accurate assessment of the wave speed in PVC pipes.

2. Method

The elastic modulus values for materials are commonly found in reference tables, as they are not easy to determine experimentally. However, for this work a bench test as presented in Martim, (2011) was used to determine the stress-strain behavior of PVC pipes and to plot the corresponding curve for calculating the pipe's elastic modulus.

The tested pipes were brown-colored PVC 6.3, type PBA, as defined by ABNT NBR 5647-1, (2025), pressure class 15, with a maximum operating pressure of 75 mH_2O (0.75 MPa) and an integrated elastic joint (JE/JEI). This material and pressure class were selected because they are generally used in water supply networks. Four PVC specimens were prepared according to ABNT NBR 5683, (1999), including two with a 50 mm diameter and two with a 100 mm diameter. Each specimen was 1 meter long, sealed at both ends with welded PVC caps, and fitted with a pressure port for injecting the test fluid, removing air, and connecting a pressure gauge.

The specimens were instrumented with strain gauges to measure deformation in both axial and circumferential directions. The extensometers used to monitor deformations were Kyowa strain gauges, model KFG-5-120-C1-11. These are general-purpose, unidirectional gauges with a 5 mm gauge length and a strain capacity of $\pm 1500 \times 10^{-6}$. The strain gauges were bonded to the external walls of both the test specimens and the pipes on the test bench.

The target test pressure was 7.0 MPa (700 mH_2O), approximately 9.3 times the pipe's design pressure. The hydrostatic pressure was applied using a manually operated piston pump, with a maximum capacity of 7.0 MPa. The pump draws fluid from an integrated reservoir and is operated via a manual lever. Pressure was continuously monitored using a gauge with a range up to 15 MPa. Although the target pressure was not reached during the first test, strain and pressure data were successfully recorded up to 3.92 MPa (400 mH_2O), within the material's elastic range and below its yield point.

Using the measured pressure and deformation data, the pipe's modulus of elasticity was determined through linear regression analysis. Based on these results, a detailed evaluation was conducted to assess how each variable influences wave speed in the elastic model. For this analises, Poison's ratio of 0.45 was adopted. This analysis aimed to highlight the sensitivity of wave speed to changes in parameters such as pipe stiffness, fluid properties, and internal pressure, providing valuable insights for transient flow modeling in water distribution systems.

3. Results

Two tests were performed on each specimen where internal pressure and deformation was messured as presented in Martim, (2011). With these values a linear regreation was undertaken and the elastic module determine as show in Table (1) Although four specimens were initially prepared, the fourth specimen failed during the first test and could not be used for further analysis. Overall, the first test on each specimen yielded the highest values of the PVC elastic modulus. In contrast, the second tests on each specimen resulted in a lower average accouting for the viscoelastic material behaviour.

Table 1: Elastic module determined (Martim, 2011)

Test Specimen	Test No	Determined Elastic Modulus (MPa)	Result from First Test
CP #1	1	2993.17	2993.17
	2	2348.37	
CP #2	1	2896.78	2896.78
	2	2805.76	
CP #3	1	2672.38	2672.38
	2	2396.37	

Using the elastic modulus determined from the first test, a series of additional tests were performed to evaluate the influence of other variables on wave speed. Initially, the analysis focused on a 100 mm PVC pipe, varying only the water temperature, and consequently bulk modulus and density of water, to assess its isolated effect. As presented in Fig. (1), water temperature has a neglectable impact on wave speed, while the variation in the elastic modulus of the pipe material exhibits a substantially greater. For these calculations, wave speed was determined assuming the presence of expansion joints, which allow longitudinal movement and reduce system stiffness. It is also worth noting that the typical assumption for the bulk modulus and water density corresponds to an average temperature of 20 °C, while the graph shows the variation for water at 10 °C and 30 °C.

Further simulations were carried out to explore the influence of additional geometric and structural factors, as indicated by Eq. (2), which shows that wave speed is also a function of pipe diameter, wall thickness, and the method of anchoring. Fig. (2) presents wave speed variation when applying the experimentally obtained elastic modulus to pipes of 100 mm and 50 mm in diameter, considering three distinct anchoring conditions: fully restrained, partially restrained, and with expansion joints. The results demonstrate that smaller diameter pipes tend to exhibit higher wave speed, while more flexible anchoring systems, such as those using expansion joints, significantly reduce wave speed by allowing pipe wall displacement and absorbing part of the transient energy.

4. Conclusion

In the context of transient flow in water distribution systems, wave speed plays a critical role in determining the speed at which pressure waves propagate following rapid changes in flow conditions. The comparative analysis presented in this work clearly indicates that among the variables studied, the elastic modulus and the anchoring configuration exert the greatest influence on wave speed. In contrast, temperature variations within the tested range produce comparatively minor effects. These findings emphasize the necessity of carefully selecting material properties and anchoring strategies during the design and transient analysis of water distribution systems to ensure accurate modeling and effective water hammer protection.

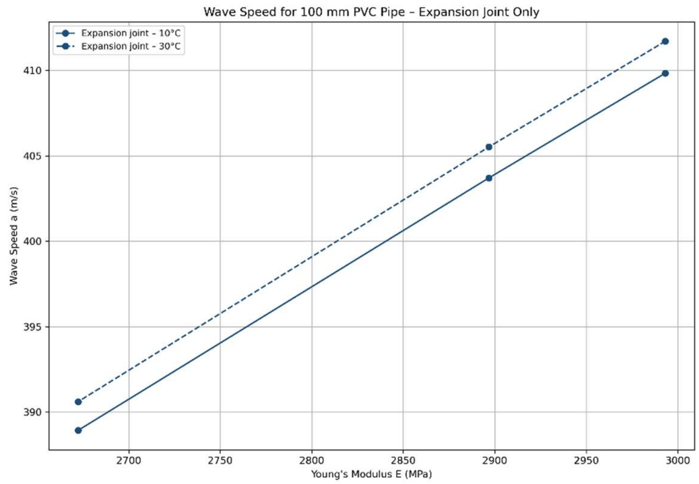

Fig. 1: Wave speed variation with elasticity module for different temperatures considering expansion joint

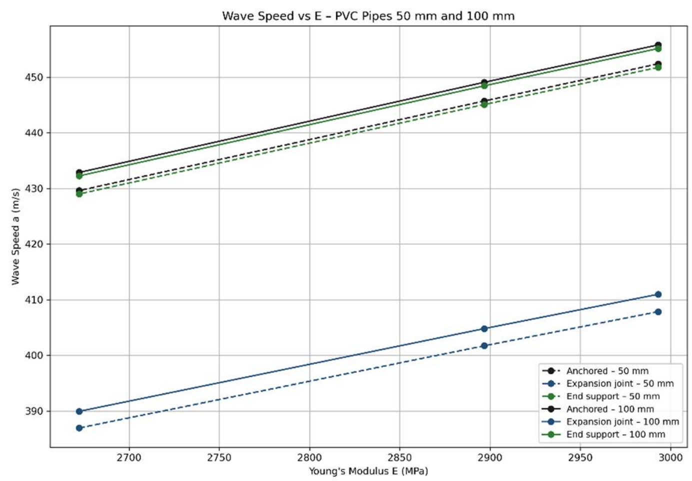

Fig. 2: Wave speed variation with elasticity module considering different diameters and anchoring coefficient.

Acknowledgements

I would like to thank the Coordination for the Improvement of Higher Education Personnel (CAPES) for sponsoring my PhD studies and the Support Fund for Education, Research, and Extension (FAEPEX) for supporting my postdoctoral researchship.

Referencies

ABNT NBR 5647-1 (2025) *Sistemas para adução e distribuição de água - TUbos e conexões de PVC-U 6,3 com junta elástica e com diâmetros nominais até DN100*.
ABNT NBR 5683 (1999) *Tubos de PVC - VErificação da resistência a pressão hidrostática interna*.
Britton, L.G. and Willey, R.J. (2024) 'Avoiding water hammer and other hydraulic transients', *Process Safety Progress*, 43(1), pp. 101–112. doi:10.1002/prs.12517.
Kandil, M., El-Sayed, T.A. and Kamal, A.M. (2024) 'Unveiling the impact of pipe materials on water hammer in pressure pipelines: an experimental and numerical study', *Scientific Reports*, 14(1), pp. 1–26. doi:10.1038/s41598-024-80853-w.
Karney, B.W. and McInnis, D. (1990) 'Transient analysis of water distribution systems', *Journal / American Water Works Association*, 82(7), pp. 62–70. doi:10.1002/j.1551-8833.1990.tb06992.x.
Larock, B.E., Jeppson, R.W. and Watters, G.Z. (2000) *Hydraulics of Pipeline Systems*.
Larson, M. and Jönsson, L. (1991) 'Elastic Properties of Pipe Materials during Hydraulic Transients', *Journal of Hydraulic Engineering*, 117(10), pp. 1317–1331. doi:10.1061/(asce)0733-9429(1991)117:10(1317).
Martim, A.L.S.S. (2011) *Análise reversa de um modelo de previsão de manutenção em redes de abastecimento de água*. UNICAMP.
Mushumbusi, P.F. *et al.* (2025) 'Modelling and analysis of hydraulic transients in water pipelines using physics-informed neural network', *Scientific African*, 28(February), p. e02637. doi:10.1016/j.sciaf.2025.e02637.
Tjuatja, V. *et al.* (2023) 'Transient flow modeling in viscoelastic pipes: A comprehensive review of literature and analysis', *Physics of Fluids*, 35(8). doi:10.1063/5.0155708.
Tullis, J.P. (1989) *Hydraulics of Pipelines: Pumps, Valves, Cavitation, Transients.* John Wiley & Sons, Inc.