

EXPLORING UNCERTAINTIES IN THE PROPAGATION OF LEAK NOISE WAVE IN BURIED WATER PIPES

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Resumo. A escassez de água é uma preocupação global crescente, sendo os vazamentos em tubulações de distribuição uma das principais causas de perdas hídricas. Métodos acústicos de detecção de vazamentos, como os correlacionadores, dependem do comportamento da propagação de ondas — especialmente da onda transportada pelo fluido com modo $s=1$. Este estudo apresenta uma nova análise estocástica das incertezas no número de onda da onda $s=1$, utilizando simulação de Monte Carlo, abordagem ainda não aplicada nesse contexto. As simulações numéricas são realizadas considerando a geometria da tubulação, as propriedades do material e os parâmetros do solo como variáveis estocásticas dentro de modelos analíticos de propagação de ondas. São investigados cenários de tubulações tanto expostas ao ar quanto enterradas. O método permite estimar limites superiores e inferiores para a velocidade da onda e sua atenuação, oferecendo uma compreensão valiosa sobre a variabilidade dos sinais acústicos induzidos por vazamentos. A validação realizada em dois locais de teste (Reino Unido e Brasil) demonstra forte concordância entre os intervalos de número de onda previstos e os medidos. Os resultados destacam a importância de se considerar a variabilidade das rigidezes dinâmicas da tubulação e do solo, e demonstram o potencial do método em aprimorar a precisão na localização de vazamentos.

Palavras chave: Propagação de Onda por Vazamento, Tubulações Enterradas, Modelagem Estocástica, Sistemas de Distribuição de Água

Abstract. Water shortages are an increasing global concern, with leaks in distribution pipelines contributing significantly to water loss. Acoustic leak detection methods, such as correlators, rely on wave propagation behaviour — particularly of the fluid-borne $s=1$ wave. This study presents a novel stochastic analysis of $s=1$ wave wavenumber uncertainties using Monte Carlo simulation, an approach not previously applied in this context. Numerical simulations are performed by treating pipe geometry, material properties, and soil parameters as stochastic variables within analytical wave propagation models. Both in-air and buried pipe scenarios are investigated. The method enables the estimation of upper and lower bounds for wave speed and wave attenuation, offering valuable insight into the variability of leak-induced acoustic signals. Validation at two test sites (UK and Brazil) shows strong agreement between predicted and measured wavenumber ranges. The results emphasize the importance of accounting for pipe and soil dynamical stiffnesses variability and demonstrate the method's potential to improve leak localization accuracy.

Keywords: Leak Noise Wave Propagation, Buried Pipes, Stochastic Modelling, Water Distribution Systems

1. 1. INTRODUCTION

Water scarcity is an escalating global concern, intensified by population growth, unsustainable economic practices — particularly excessive water use in agriculture — and rapid urbanization, all of which place increasing pressure on finite water resources (Hu *et al.*, 2021; Biswas *et al.*, 2025). A significant contributor to water loss is leakage within aging and deteriorating water distribution networks. Timely detection and localization of these leaks are essential for reducing losses, conserving water, and improving the efficiency and sustainability of water management systems (Waqar *et al.*, 2025).

Among the various techniques available, vibro-acoustic methods have emerged as reliable and non-invasive tools for leak detection, with acoustic correlators being widely used in practice (Gao *et al.*, 2018; Liu *et al.*, 2025). These systems rely on time delay estimation between sensor signals, which is directly influenced by the propagation characteristics of leak-induced noise (Brennan *et al.*, 2018). A central aspect of these characteristics is the behaviour of the fluid-borne $s=1$ wave, whose propagation is governed by complex interactions among the fluid, the pipe wall, and the surrounding soil

(Scussel *et al.*, 2024). Accurately modelling these wave dynamics is critical for effective leak localization, particularly in buried pipelines where soil-pipe interactions introduce additional complexities.

Traditional deterministic wave propagation models often assume fixed material and environmental properties, thereby neglecting the inherent uncertainties in pipe geometry, material properties, and soil conditions. These simplifications can lead to significant discrepancies between predicted and actual leak signal behaviours.

Building upon the foundational work of Scussel *et al.* (2021), who introduced a basic stochastic framework focused solely on the real part of the wavenumber (i.e., wave speed), the present study advances the field by incorporating both the real and imaginary components — capturing not only wave speed but also wave attenuation. This is achieved through the application of Monte Carlo simulation, a robust probabilistic technique not previously employed in this context. By treating key parameters as stochastic variables within analytical wave propagation models, the proposed method offers a comprehensive characterization of uncertainty in leak noise propagation, applicable to both in-air and buried pipeline scenarios.

This work is organized as follows. Following this introduction, in Section 2, an overview of vibro-acoustic correlators is given along with the stochastic wavenumber of the leak noise wave. Section 3 presents some preliminary results and analysis. Some conclusions are then given in Section 4.

2. STOCHASTIC MODELLING FOR THE LEAK NOISE WAVE PROPAGATION IN BURIED PIPES

This section presents a brief overview of vibro-acoustics correlators, their applicability and role for water leak detection in buried plastic pipes, which are widely used in water distribution systems. Moreover, the stochastic modelling of leak noise wave through Monte Carlo method is then presented.

2.1. Overview of vibro-acoustic correlators

Vibro-acoustic correlation is a method used to detect pipeline leaks by analyzing the sound waves generated when fluid escapes through a leak. Sensors are strategically placed at different points along the pipeline to capture these signals. By comparing the time it takes for the acoustic waves to reach each sensor, and taking into account the wave speed, the system can accurately determine the location of the leak. This technique is especially effective for identifying leaks in buried or hard-to-reach pipelines with minimal need for excavation (Scussel *et al.*, 2023).

Typically, two sensors are positioned upstream and downstream of the suspected leak area. Specialized software then analyzes the time difference in signal arrival along with the acoustic wave velocity to accurately locate the leak, as illustrated in Fig. 1. The accuracy of this method depends on various factors including the type of pipe, surrounding soil conditions, and sensor sensitivity (Brennan *et al.*, 2018).

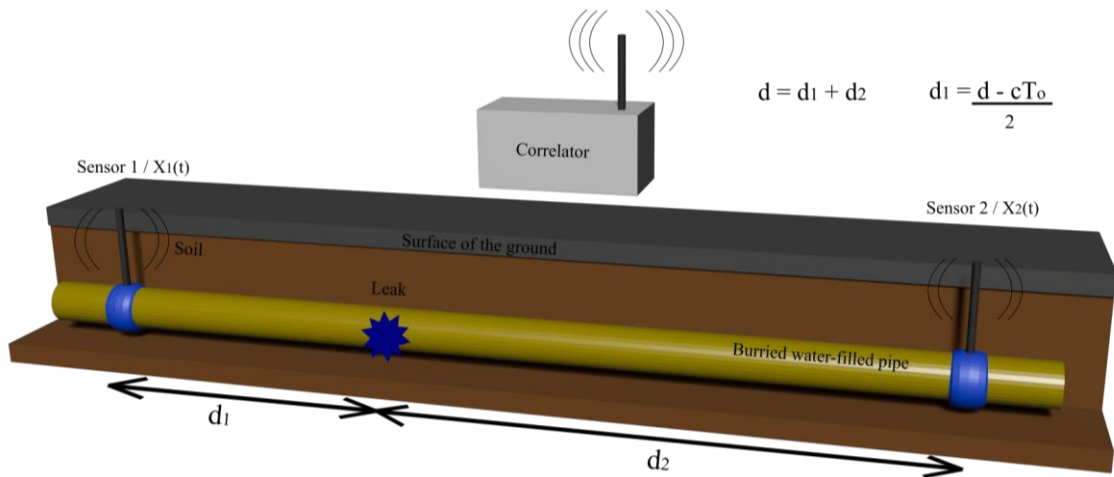


Figure 1. Schematic of the typical leak detection problem using correlators (adapted from Scussel *et al.*, 2021).

When a leak occurs, the escaping fluid creates vibrations that travel along the pipe and into the surrounding soil as acoustic waves. The most critical wave in this process is the axisymmetric ($n = 0$) predominantly fluid-borne wave ($s = 1$). This wave is significantly affected by the properties of both the pipe and the soil (Scussel *et al.*, 2024). Due to its essential role in leak detection for water distribution networks, its behaviour and characteristics have been widely studied (Cui *et al.*, 2023).

2.2. Stochastic modelling of the leak noise wave

For frequencies well below the pipe's ring frequency, the stochastic wavenumber of the axisymmetric wave can be calculated using the concept of wave dynamic stiffness (Brennan *et al.*, 2018):

$$k^2(\zeta) = k_{water}^2 \left(1 + \frac{K_{water}}{K_{pipe}(\zeta) + K_{soil}(\zeta)} \right) \quad (1)$$

which is a function of the random variable vector $\zeta = [\zeta_1, \zeta_2, \zeta_3, \zeta_4, \zeta_5, \zeta_6, \zeta_7]^T$, where ζ_1 is the uncertain variable affecting the Young's modulus of the pipe with $E(\zeta_1) : \Omega_1 \rightarrow \mathbb{R}$, ζ_2 is the uncertain variable affecting the density of the pipe material with $\rho_{pipe}(\zeta_2) : \Omega_2 \rightarrow \mathbb{R}$, ζ_3 is the uncertain variable affecting the mean radius of the pipe with $r(\zeta_3) : \Omega_3 \rightarrow \mathbb{R}$ and ζ_4 is the uncertain variable influencing the thickness of the pipe-wall with $h(\zeta_4) : \Omega_4 \rightarrow \mathbb{R}$. In a similar manner, the uncertain variables ζ_5 and ζ_6 affect the bulk and shear modulus of the soil respectively, with $B_s(\zeta_5) : \Omega_5 \rightarrow \mathbb{R}$ and $G_s(\zeta_6) : \Omega_6 \rightarrow \mathbb{R}$, and $\rho_{soil}(\zeta_7) : \Omega_7 \rightarrow \mathbb{R}$ is the uncertain variable affecting the density of the soil. Here, Ω is a sample space, F is a σ -algebra on Ω , which is a non-empty collection of sets that is closed under taking complements, countable unions and intersections, and P is a probability measure on Ω , forming a probability space (Ω, F, P) (Sepahvand *et al.*, 2010). The random parameters are then modelled through normal distribution $N(\mu_{\zeta_j}, \sigma_{\zeta_j}^2)$ and probability density function given by $\frac{1}{\sqrt{2\pi\sigma_{\zeta_j}^2}} \exp(-(\zeta_j - \mu_{\zeta_j})^2 / 2\sigma_{\zeta_j}^2)$ with $j \in \{1, 2, \dots, 6\}$.

The terms μ_{ζ_j} and σ_{ζ_j} are the mean and standard deviation of the uncertain variable ζ_j , respectively. More details on how to compute the dynamical stiffnesses K_{water} , K_{pipe} and K_{soil} can be found in Scussel *et al.* (2024).

3. PRELIMINARY RESULTS AND DISCUSSION

Firstly, the deterministic wavenumber estimation was performed using the nominal parameters from Tab. 1 reflecting two test rigs located in different parts of the World, one in the UK and the other one in Brazil. These test rigs present very different pipe properties/geometry and distinct type of soil. Secondly, Monte Carlo simulations were then carried out considering 1000 simulations and standard deviation of 1% for the pipe mean radius and thickness, 5% for the Young's modulus and bulk density of the soil, and 10% for both shear and bulk modulus of the soil. All the results are shown in Figures 2.

Table 1. Properties of each experimental test rig.

Pipe-water-soil system properties	UK system	Brazilian system
Young's modulus E (N/m ²)	2×10^9	2×10^9
Density ρ_{pipe} (kg/m ³)	900	900
Loss factor η	0.06	0.06
Pipe radius a (mm)	84.5	35.8
Pipe-wall thickness h (mm)	11.0	3.40
Bulk modulus of water B_{water} (GN/m ²)	2.25	2.25
Wave speed in water c_{water} (m/s)	1500	1500
Bulk modulus of soil B_s (GN/m ²)	0.53	4.00
Shear modulus of soil G_s (GN/m ²)	0.20	0.2359
Bulk density of soil ρ_{soil} (kg/m ³)	2000	2000
Type of surrounding soil	Sand	Clay
Pipe material	HDPE	PVC

By examining Figures 2, it can be seen that the results are very different. When comparing the uncertainty levels between the test rigs, it becomes evident that attenuation in the UK setup is more sensitive than in the Brazilian setup for the considered frequency range, primarily due to the soil properties since the clay soil in Brazil is much stiffer. Meanwhile, the wave speeds show similar deviations from the mean in both cases. The predicted average wave speeds are roughly 370 m/s for the UK pipe system and 570 m/s for the Brazilian system. This difference is mainly due to the higher dynamic stiffness of clay soil compared to sandy soil. In the UK system, wave speed slightly decreases within $0 - 600 \text{ Hz}$, while it remains stable in the Brazilian system due to the inertial effect of the pipe-wall, as the PVC pipe has a thinner wall and higher density than the HDPE pipe.

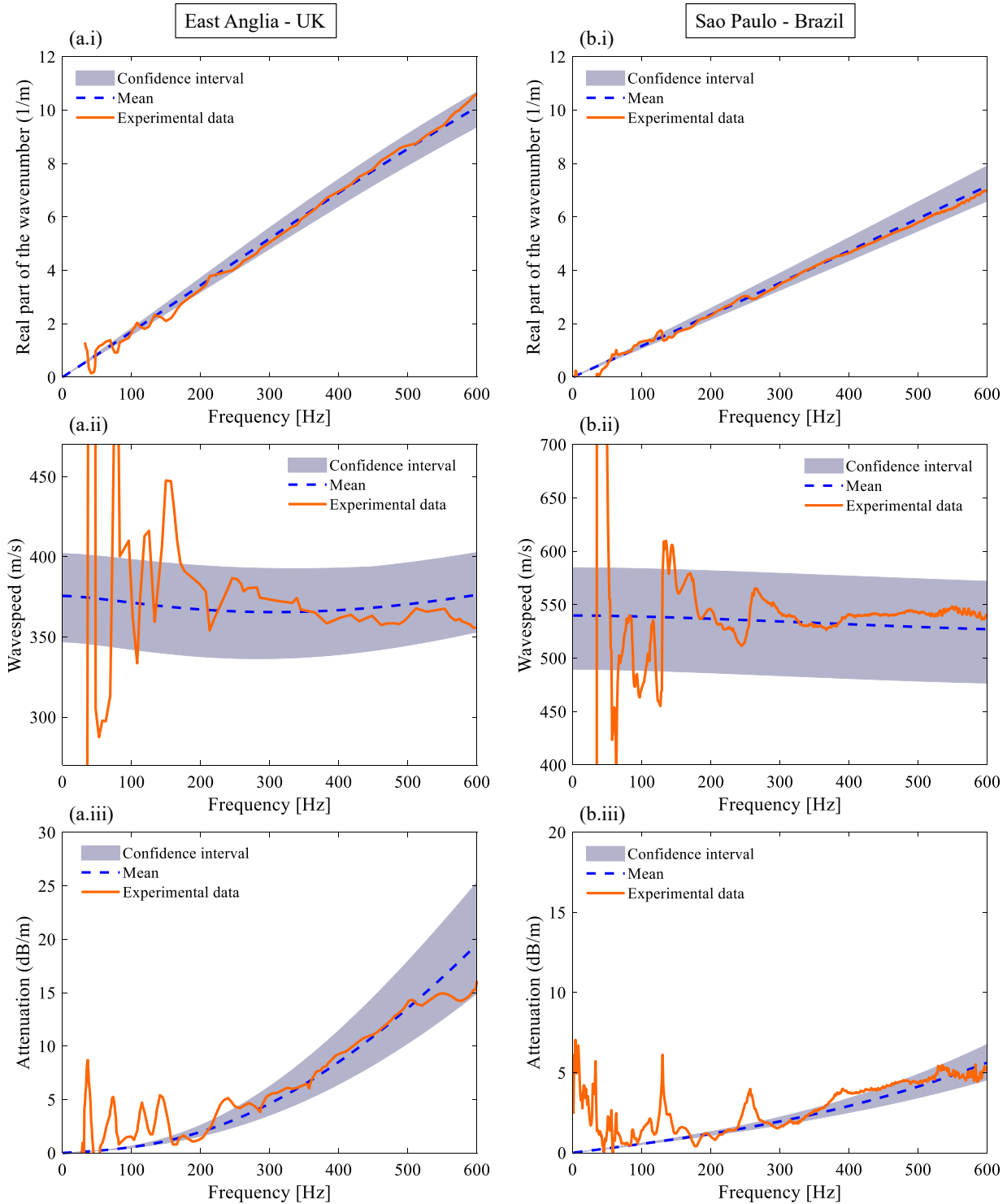


Figure 2. Experimental results: (a) UK system. (b) Brazilian system; (i) Real part of wavenumber, (ii) Wave speed, (iii) Wave attenuation.

The data used in this study were obtained from two experimental pipe systems located in Brazil and the United Kingdom, each with distinct geometric and geotechnical characteristics. The Brazilian setup consisted of a PVC pipe with a radius of 35.8 mm and a wall thickness of 3.4 mm , buried in clay-like soil and pressurized at 3.4 bar using a centrifugal pump. The fluid-dominated ($S = 1$) wave was excited by the controlled opening of a valve, and the resulting vibration signals were measured by two accelerometers positioned 7 meters apart. The UK setup, on the other hand, featured a larger HDPE pipe, radius of 84.5 mm and wall thickness of 11 mm , buried in sandy soil. In this case, the wave was excited using an underwater loudspeaker driven by a stepped sine signal ranging from 30 Hz to 1 kHz , and the dynamic pressure was measured using two hydrophones spaced 2 meters apart. Experimental measurements of wavenumber, attenuation, and wave speed were estimated from the frequency response function between sensors and used to calibrate analytical models through numerical optimization, as described in Scussel et al. (2018).

4. FINAL REMARKS

This study proposes a stochastic model for leak noise wave propagation in buried pipes commonly found in water distribution systems. The Monte Carlo method is employed to account for uncertainties associated with environmental conditions, soil types, and variations in pipe materials and geometry. This probabilistic approach demonstrates advantages over traditional deterministic models by providing a more realistic representation of real-world scenarios. Future studies will include experimental validation to assess the effectiveness of the proposed model, with the goal of enhancing current technologies, such as vibro-acoustic correlators, which typically do not account for uncertainties in leak noise wave speed and attenuation.

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5. RESPONSIBILITY FOR THE INFORMATION

The authors are solely responsible for the information included in this work.