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ADVANCES IN STRUCTURAL HEALTH MONITORING OF BURIED PIPELINES USING GROUND VIBRATION MEASUREMENTS

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Abstract. *Locating buried pipelines is crucial for ensuring efficient maintenance, minimizing excavation disruptions, and reducing environmental risks associated with leaks or damage. Ground-vibration measurement techniques provide a promising and non-intrusive approach to identifying pipeline locations, with significant advantages, particularly in the detection of plastic pipelines. This paper presents a comprehensive review of ground-vibration localization methods for buried pipelines, focusing primarily on water pipelines while also addressing key techniques relevant to gas pipelines. It explores foundational principles, recent advances in signal processing and the effectiveness of various localization strategies under different field conditions. Model-based and data-driven approaches are compared in terms of accuracy, sensitivity, and reliability, considering factors such as pipe material, geometry, burial depth, soil composition, and environmental noise. The review highlights recent innovations over the past five years in excitation methods and seismic waves, beamforming techniques, and both amplitude-based and phase-based methods that enhance pipeline localization, particularly in challenging underground environments. By synthesizing current knowledge and identifying areas for improvement, this review highlights the relevance of vibration-based pipeline localization methods, particularly in challenging underground environments.*

Keywords: Structural Health Monitoring, Buried Pipelines, Wave Propagation, Ground-surface Vibration, Signal Processing.

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1 INTRODUCTION

Over the past century, various technologies and methods have been developed for mapping and locating buried pipelines. Nearly a hundred years ago, Babbit [1] documented challenges in detecting leaks of underground pipelines, highlighting problems such as flooded streets, and abnormal vegetation growth, and the use of tools like iron bars, aquaphones (or waterphones), and stethoscope-like devices. Interestingly, many of these techniques remain relevant in contemporary water leak detection practices.

Several review papers focus on the field of leakage modelling and management of oil/gas/water pipelines. Recent papers in the past five years include [2,3]. These papers highlight the evolution of leak detection technologies, leading to the advanced approaches in use today. These modern technologies include [4]:

- Leak noise loggers: They are placed in utility holes without trenching or drilling and can be used for permanent monitoring. They use advanced algorithms to distinguish leak sounds from normal operations. While they have low maintenance costs, real-time monitoring is expensive and requires correlators for precise leak location.

- Tracer gas: Uses nontoxic gases like helium, which escape through leaks and are detected by handheld sensors. Highly sensitive and non-invasive, but it requires trained operators and can be affected by environmental factors. It is best for pipelines 75mm–1000mm but is costly for larger systems.

- Ground penetrating radar (GPR): Uses electromagnetic waves (125–370 MHz) to image underground leaks in pipes of any material, down to 5m depth. It is portable and versatile but requires road access, skilled operators, and has high costs. Accuracy improves with advanced algorithms.

- Robots and smart balls: Several robotic devices have been developed for pipe inspection and leak detection in sewers. These devices can operate wirelessly or be cord-connected, with some also capable of performing leak repair tasks [5]. Another example of a robot is the smart ball, a free-swimming technology designed to detect leaks in live large water pipelines.

- Other technologies: Thermal cameras on drones detect leaks via infrared imaging. Leak-sniffing dogs trained to detect chlorine additives have shown mixed results but have potential [6].

An emerging approach that has received significant attention is the use of ground-surface vibration measurements, which is the focus of this paper. These include listening sticks, geophones, and hydrophones used to listen to buried water pipelines from the surface. While these devices are highly dependent on the operator's ability, they are often prone to inaccuracies from external noise. Improvements are being made by integrating advanced signal analysis, filtering, and automation to reduce human error. Important developments have been achieved by the project "Mapping the Underworld" (MTU) [7], which was a UK-based research initiative launched in 2005, focused on improving the detection and mapping of buried utility assets using a multi-sensor platform [8]. It integrated technologies like ground-penetrating radar, vibro-acoustics, and electromagnetic fields to accurately locate underground pipes and cables without excavation. It was a collaborative effort involving universities and industry partners. The techniques developed have shown to be successful in detecting plastic as well as metal pipes [9].

While existing review papers [10, 11] have addressed a few ground vibration-based pipe localization and leak detection methods to some extent, significant advances have been made since their publication. The primary objective of this paper is to provide an updated review of ground vibration-based leak detection techniques, focusing on developments from 2020 to 2025. Figure 1(a) the distribution of papers by category: Analytical modelling, excitation methods, beamforming techniques, amplitude-based and phase-based methods; and Fig. 1(b) shows the number of publications per year in terms of pipeline and leak localization using ground vibration measurements over the past 5 years,

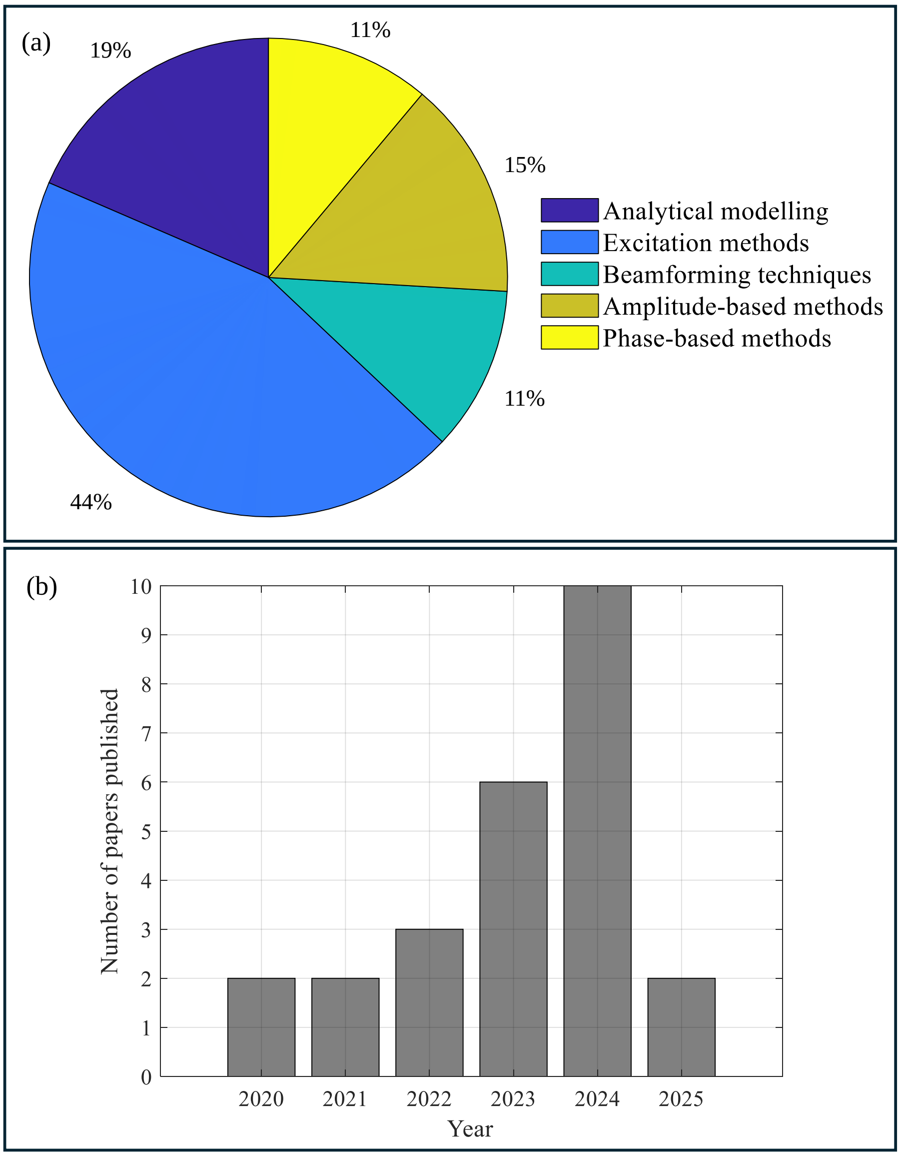

Figure 1. (a) The distribution of papers by category and (b) the number of publications since 2020.

This paper aims to highlight relevant approaches and novel technologies that have emerged over the past five years, which were not covered in previous reviews. Additionally, it examines future trends, challenges, and the potential integration of multiple detection techniques for enhanced pipeline and leak localization.

2 PROPAGATING WAVES IN UNDERGROUND PIPES

Ground-vibration due to sound waves propagating from leaking buried pipelines has been investigated early in the 80's by Jette and Parker [12]. The authors investigated surface displacements generated by acoustic waves inside buried pipes, demonstrating that the radiated field consists of both compressional and shear components, which interfere due to their different propagation speeds. Their theoretical predictions, validated through experimental data, highlighted the importance of axisymmetric pipe wall vibrations in generating measurable ground responses, providing a framework for non-invasive pipeline monitoring. Building on these studies, [13] analyzed low-frequency ground vibrations induced by sound waves in underground gas pipes, introducing the concept of Rayleigh wave excitation when the speed of sound inside the pipe exceeds the Rayleigh wave speed in the surrounding soil. His work revealed that this mechanism, similar to a sonic boom, could generate significant low-frequency ground vibrations, with amplitudes high enough to cause structure-borne noise.

A procedure to calculate the 3D response of a cylindrical shell of infinite length buried in a layered viscoelastic half-space and subjected to obliquely incident waves was presented by Luco and Barros [14]. This approach combined an indirect integral representation for the exterior field with a simplified Donnell shell theory for the pipeline or tunnel. The convergence of the method was verified, and extensive comparisons with previous results for a shell buried in a uniform half-space, as well as new findings for shells embedded in layered media were carried out.

Two decades later, Gao et al. [15] provided a valuable analytical approach to understanding ground vibration caused by buried water pipes. The paper presented an analytical model to predict ground surface displacements due to radiated elastic waves from a buried fluid-filled pipe, building on previous work on wave propagation and fluid-borne waves (specifically the axisymmetric $s = 1$ wave) in underground pipes. It investigated wave radiation in sandy and clay soils, predicting horizontal and vertical ground surface displacements and validating the model through experimental measurements on a dedicated pipe rig. The findings showed that interference effects in sandy soil caused phase anomalies, while only shear waves radiated in clay soil, preventing such anomalies. While the theoretical predictions aligned with experiments, discrepancies arose due to soil layering and porosity. The study contributed to pipeline detection techniques but was limited by simplified soil assumptions, neglect of Biot's theory, and frequency range constraints. Moreover, the theoretical model was developed and validated using surface measurements only above the pipe.

More recently, Zhang et al. [16] conducted a comprehensive investigation into the frequency characteristics and attenuation of leak signals from buried liquid-filled plastic and metal pipes by analyzing ground surface vibrations under controlled experimental conditions. The study explored the influence of pipe material and internal pressure on the effective frequency content of leak signals, revealing that plastic pipes predominantly exhibited low-frequency components, while cast iron pipes contained more high-frequency components. The authors employed Biot's theory to model wave propagation in partially saturated soil, allowing them to examine dispersive wave modes and attenuation mechanisms. Their findings highlighted that high-frequency leak signals attenuated more rapidly in both soil and surface wave propagation, with significant attenuation occurring within the first meter from the leak source. Additionally, they demonstrated the dominance of Rayleigh waves on the ground surface, which played a crucial role in reducing attenuation rates at greater distances. However, similar to Gao et al. [15], their analysis was limited to measurements taken directly above the pipe, without investigating variations across different lateral positions in signal propagation.

3 VIBRO-ACOUSTIC METHODS FOR LOCATING BURIED PIPES

Over the years, various technologies have been developed to detect and locate leaks in water networks. This section reviews the latest state-of-the-art techniques, highlighting their advantages and limitations. These methods are categorized into four main groups: seismic waves and excitation methods, beamforming techniques, amplitude-based methods and phase-based. methods.

3.1 Excitation methods and seismic waves

The pipe excitation method is an acoustic-based technique for locating both plastic and metal buried pipelines by transmitting an acoustic signal into the pipeline (transmitters) and detecting the resulting surface vibrations using the signal radiated from the pipe (receivers). The process can be conducted by directly injecting an acoustic signal into the pipeline or by exciting the ground surface near the pipeline using transducers such as shakers. In both cases, the radiated surface vibrations are captured using ground sensors like geophones, accelerometers, or piezoelectric sensors. Figure 2 depicts schematic diagrams illustrating the excitation methods used to localize buried pipelines.

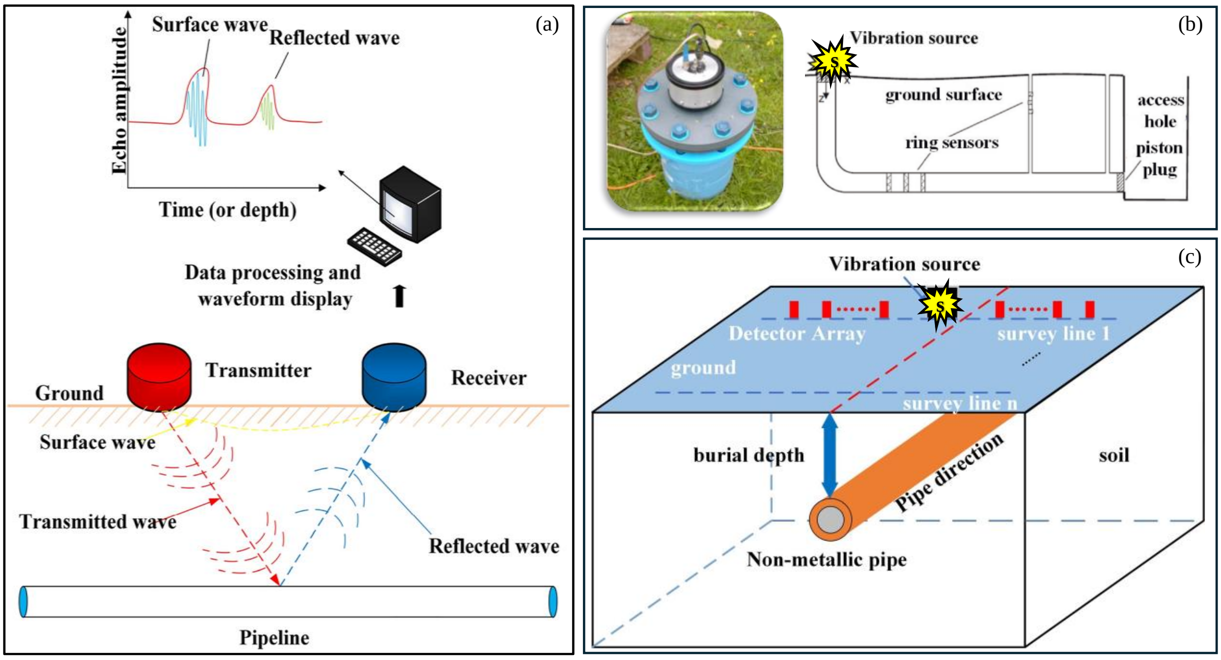

Figure 2. Schematics illustrating some excitation and seismic waves methods: (a) Ge et al. [11]; (b) Muggleton and Brennan [18]; (c) Ge et al. [27].

The pioneering work on underground pipeline detection was published in 1946 by Fisher [17], introducing the M-Scope Finder, an electronic device designed to locate pipelines and determine their depth. This system utilized a directional transmitter and receiver, along with a pair of headphones and a carrying case, to amplify leak-induced vibrations and precisely pinpoint pipeline locations.

Muggleton and Brennan [18] developed a buried pipe rig for acoustic detection as part of the UK's Mapping the Underworld program. Traditional methods relied on vibrational energy at the surface but faced limitations like crude excitation and reliance on signal magnitude. Their rig improved detection by exciting the axisymmetric fluid-dominated mode with an inertial shaker proving most effective. Later, Muggleton et al. [19] confirmed that phase information, not magnitude, best indicated pipe location, achieving 0.1–0.2 m accuracy. Muggleton and

Papandreou [20] demonstrated that shear-wave ground vibration effectively locates plastic and cast-iron pipes, with improved coherence and cross-correlation techniques enhancing detection in noisy environments.

Recent advancements in acoustic-based pipeline localization have focused on improving wave excitation, imaging techniques, and signal processing methods. One approach, proposed by Yan et al. [21], used shear wave excitation and a triaxial accelerometer array for cross-correlation imaging, effectively mapping buried pipelines while demonstrating resilience to background noise. Building on this, Cui et al. [22] introduced a superimposed imaging method that incorporated an elastic wave propagation model and a multi-point transmit/receive strategy, enhancing spatial resolution and suppressing clutter.

Further refining these techniques, Qi et al. [23] combined elastic wave reflection imaging with the back projection algorithm (BPA) to generate cross-sectional images of buried PE pipelines. Recognizing the need for improved resolution, a follow-up study [24] implemented time-domain stacking to enhance wave reflection clarity. To further optimize pipeline detection, Qi et al. [25] explored deep learning applications, training an LSTM neural network on acoustic reflections to classify pipelines with high accuracy.

Expanding on wave reflection techniques, Yan et al. [26] examined frequency-dependent attenuation in PE gas pipelines, showing how signal decay impacts detection reliability. Spectral analysis using FFT helped refine pipeline positioning by identifying peak amplitudes. Complementing this, Ge et al. [27] developed an acoustic method to extract reflection time delays, achieving notable localization accuracy but highlighting challenges in deeper pipeline detection. Zhang et al. [28] proposed an active acoustic positioning method to locate buried polyethylene (PE) pipelines by analyzing acoustic wave attenuation. Since traditional magnetic or conductive-based methods fail for PE pipelines, this study derived a wave equation in non-ideal media and used finite element simulations to assess signal attenuation. The horizontal position was identified from maximum amplitude measurements, while depth was estimated using resonance and nonlinear curve fitting. On-site experiments confirmed the method's accuracy, with positioning errors under 8% for both horizontal and depth estimations. Despite its effectiveness, challenges remain due to soil variability, requiring further research for practical applications.

3.2 Beamforming techniques

Wang et al. [29] presented a method for locating leaks in buried gas pipes using dual-wave velocity pairing and multi-array fusion localization. By estimating P1 and S wave velocities and using the Root-MUSIC algorithm, the method reduced computational complexity while improving 3D leak localization accuracy. Experiments with eight accelerometers demonstrated that fusion localization outperformed single-array methods, especially for remote leaks. GDOP analysis optimized multi-array layouts, with the equilateral-triangle configuration being most effective. The method showed strong performance under various soil conditions and signal-to-noise ratios. However, the paper acknowledged limitations related to array topology's impact on DOA estimation and spatial resolution, suggesting further optimization.

In subsequent work, Xue et al. [30] proposed a joint estimation method using a nonuniform planar array for accurately localizing buried gas pipeline leaks and estimating wave-speed. The method effectively combines small-aperture subarrays to determine the relationship between wave-speed and direction of arrival (DOA), followed by 2D spectrum estimation with large-aperture arrays to estimate both wave-speed and leak distance. The approach eliminates the need for 3D spectrum estimation and achieves high accuracy in determining 3D coordinates. Experimental results across different soil types and burial depths showed RMSE values less than 0.1 m at 15 dB SNR. The method was found to outperform the MUSIC algorithm and was effective in handling various practical challenges such as box wall reflections and wave impediments in pipe structures.

In a related study, Matos et al. [31] explored the influence of steering vector wavenumber bias on leak position estimation using beamforming techniques. The study found that the deviations in estimated leak position along the depth were significantly more affected by the wavenumber bias than those along the ground surface. Using COMSOL-simulated data, the authors demonstrated that tuning the steering vector wavenumber from 0.5 to 1.5 times the actual source wavenumber resulted in varying beamforming outputs. The results revealed that, although the wavenumber's impact on the depth estimation was considerable, the leak's surface position could still be accurately located, provided the pipe depth is known. Additionally, the study revealed that wave velocity variations significantly impacted leak location, particularly at greater depths. The paper provided valuable insights into the limitations and challenges of applying array signal processing to leak localization in buried pipes and suggested directions for developing more advanced algorithms tailored to ground vibration signals and leak detection.

3.3 Amplitude-based methods

Yan et al. [32] developed an approach to underground pipeline leakage detection by integrating vibroacoustic techniques with image fusion and graph traversal methods. The study effectively demonstrates how ground surface vibrations, induced by propagating axisymmetric waves, can be leveraged for leakage localization using an array of geophones. A key contribution of this research is the introduction of connected graph traversal to enhance the accuracy of spatial mapping, improving upon conventional magnitude contour plots. Magnitude contour images of ground surface vibration measurements were estimated at five frequencies, allowing for a detailed spectral analysis of leak noise propagation. The experimental validation on a dedicated cast iron water pipe provides strong evidence supporting the effectiveness of the proposed methodology. By focusing on low-frequency features where leak noise dominates, the study successfully fuses spectral data to generate a refined leakage map, minimizing errors associated with subjective interpretation. The results show excellent agreement with actual leakage positions, highlighting the method's potential for real-world application.

Expanding on this concept, Li et al. [33] presented a pipeline localization method based on double-tree complex wavelet cross-correlation delay analysis. The approach involved denoising signals using the double-tree complex wavelet method and determining delay times through cross-correlation to estimate pipeline locations. Experimental validation considered both symmetrical and asymmetrical sensor placements, showing that symmetrical configurations yield errors below 1%, while asymmetrical setups result in significantly higher errors. The study also highlights that localization accuracy decreases as the excitation point moves farther from the sensors. Compared to existing methods, this approach demonstrates improved accuracy, quick execution, and cost-effectiveness, making it a viable solution for locating buried PE pipelines.

Aligned with these findings, Zhang et al. [34] proposed a novel method for locating the depth of buried PE gas pipelines using acoustic signal analysis and the elliptical method. The technique combines cross-correlation time delay positioning with the elliptical equation, which forms an effective mechanism for depth determination. To enhance the accuracy of the collected signals, a dual-tree complex wavelet transform was employed for denoising. The delay times obtained through cross-correlation were used in the elliptical equation to calculate the pipeline depth. Simulations conducted in COMSOL under varying conditions and experimental results from a testing system demonstrated the feasibility of this approach, with simulation errors kept under 5% and experimental errors within 10%. The study highlighted the influence of factors like pipeline depth, sensor position, and excitation frequency on positioning accuracy. This method successfully addressed the limitations of existing pipeline localization technologies, offering a simple, low-cost solution with practical application potential. It provided valuable theoretical insights for optimizing sensor placement and improving the accuracy of future pipeline depth localization.

Qi et al. [35] presented an innovative method for locating buried polyethylene (PE) pipelines using acoustic waveguide resonance, overcoming the limitations of traditional metal pipeline detection techniques. The authors established the theoretical basis for acoustic waveguides and used finite element simulations to examine resonance characteristics in straight and T-junction pipes, considering factors like pipe diameter, pressure, and propagation distances. In the experimental section, they developed an excitation source and data acquisition system to analyze signals from PE pipes at varying depths. The research showed that the horizontal position of the pipeline could be determined by maximum signal amplitudes, while a frequency-selective algorithm effectively estimated burial depth based on soil attenuation.

3.4 Phase-based methods

Muggleton et al. [19] presented precursor work to the 'Mapping the Underworld' programme, focusing on the development of vibro-acoustic techniques for locating buried pipes. The study employed frequency response measurements, linking ground surface vibrational velocity to input excitation, to accurately identify the location of buried pipes. Through the use of unwrapped phase and magnitude contour plots, the research demonstrated that the pipe's location could be pinpointed with impressive accuracy of 0.1–0.2 meters. The authors emphasized the importance of phase information, as it encapsulated essential time delay data, making it more robust in noisy environments, while magnitude data served as a valuable supplement, aiding in the detection of pipe discontinuities like bends, material changes, or leaks. The research also examined phase gradients along the ground surface, which allowed for the identification of the specific wave-type within the pipe responsible for ground vibration, further confirming the pipe's end location. This work laid the groundwork for future advancements in the 'Mapping the Underworld' program, highlighting the efficacy of vibro-acoustic methods as a promising approach for detecting and mapping buried utilities in infrastructure monitoring and maintenance.

More recently, in Scussel et al. [36] phase analysis of the ground-vibration was carried out using measurements above and across the pipe. The paper investigated the physical mechanisms that propagate leak noise through the pipe and the surrounding soil to the ground surface. It analyzed the relative phase between vertical ground vibration measurements at points in a rectangular grid above the pipe. The study involved experimental measurements from a site in the UK with a more realistic leak mechanism compared to previous research, a simplified analytical model to provide insight into the underlying physics, and a finite element model (FEM) to validate some of the assumptions made in the analytical model. Three primary waves were identified in propagating leak noise to the ground surface: the predominantly fluid-borne wave in the pipe and the shear and compressional waves in the soil radiating from the pipe. Their influence on ground surface vibration was examined using surface velocity measurements. The study demonstrated how shear and compressional waves combined to shape the lines of constant phase on the ground. The findings highlighted the potential of the proposed analytical and numerical models for investigating wave radiation from buried water pipes and developing pipe location strategies using phase data from surface vibration measurements. Figure 3 shows the hyperbolae on the ground surface and some results based on spatially unwrapped phase at a frequency of 55 Hz.

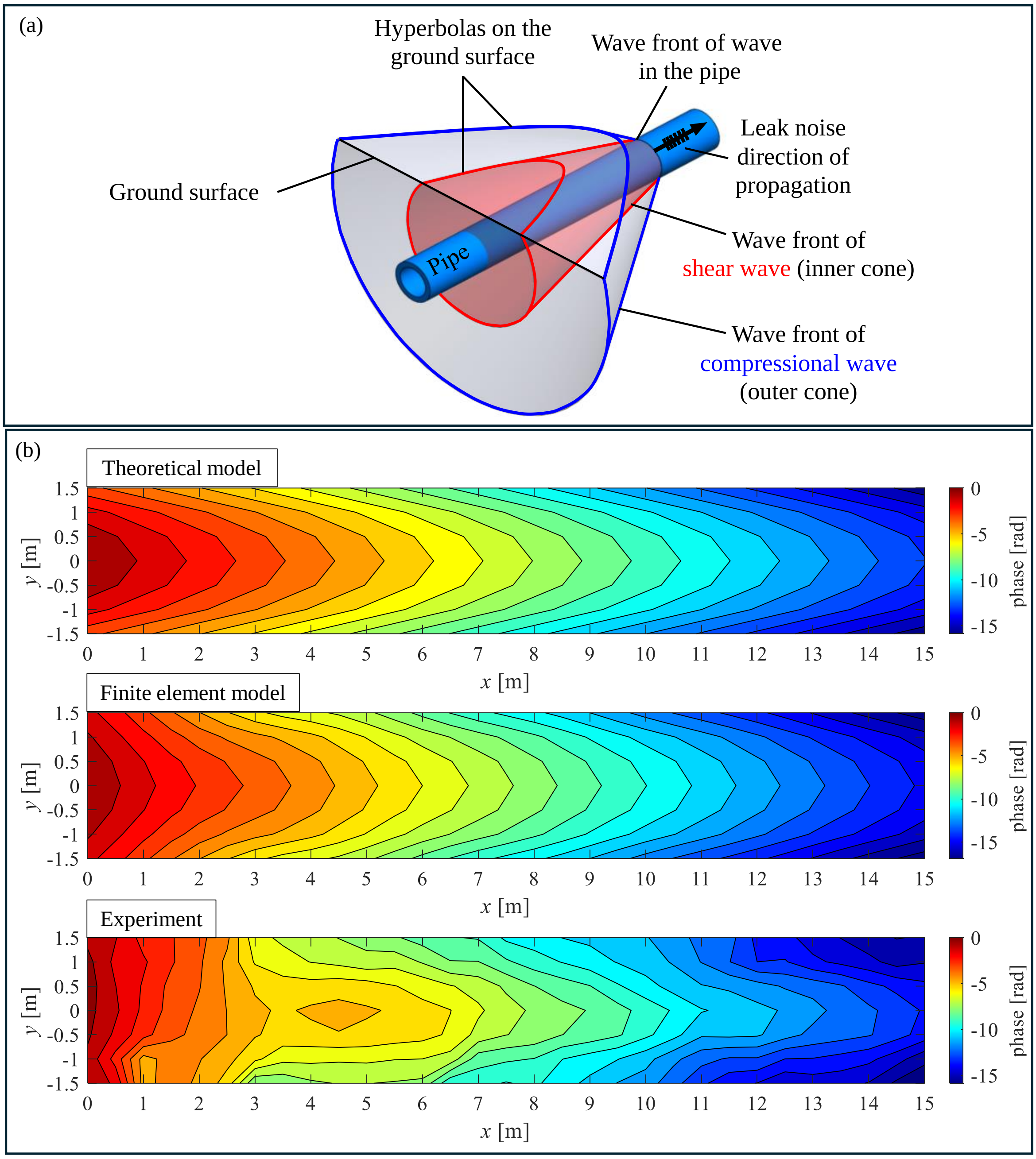

Figure 3. Phase-based method [36]: (a) Schematic diagram showing body waves propagating into the soil due to vibration caused by a leaking buried pipe; (b) Spatially unwrapped phases at 55 Hz.

Expanding on this idea, Iwanaga et al. [37] developed an innovative two-sensor vibro-acoustic localization technique for detecting buried water pipes, using a leak as the source of excitation. The proposed method calculates the approximate slope for the unwrapped phase between a pair of sensors placed on the ground surface, along a line perpendicular to the pipe. By analyzing the phase slope and identifying where it approaches zero, the technique effectively locates the buried pipe. The performance of this approach was evaluated using two datasets: one derived from a numerical model (FEM) and the other from an experimental test rig. In both cases, the technique successfully identified the pipe's location, demonstrating its potential for practical applications, especially when measurements are taken at considerable distances from the leak. The study highlights the promise of this method as a cost-effective and reliable alternative to more complex excitation-based techniques, particularly in the context of water leak detection in buried pipe networks.

4 Discussion and future directions

Ground Vibration-based localization techniques for detecting and locating leaks in buried pipelines offer significant potential for non-invasive monitoring. As highlighted in this paper the choice of method depends on several practical factors, including the complexity of the environment, available data, and specific goals of the localization task.

Various methodologies for detecting and localizing underground pipes and leaks were presented, focusing on the propagation of sound waves from leaking buried pipelines and vibro-acoustic techniques. Early research demonstrated the interference between compressional and shear components of acoustic waves radiating from pipe walls, which can generate measurable ground responses. The effects of compressional and shear waves are central to the physics of wave propagation in this problem, as they directly influence the characteristics of the ground vibrations. Recent advancements in this area explore the impact of Rayleigh waves, which occur when the sound speed inside pipes exceeds the surrounding soil's Rayleigh wave speed, generating low-frequency ground vibrations.

The work also reviews modern detection techniques, categorizing them into four primary categories: excitation methods, beamforming, amplitude-based, and phase-based approaches. Excitation methods, particularly those utilizing acoustic signals and seismic waves, have improved with more refined detection systems. Beamforming techniques are being optimized for leak localization through multi-array fusion, while amplitude-based methods use spectral analysis and wavelet transforms to improve detection accuracy. Finally, phase-based methods focus on utilizing phase information, which proves to be more reliable than amplitude in noisy environments.

Key findings indicate that phase information, specifically relative phase and unwrapped phase, is crucial for determining pipeline locations with high accuracy, even under challenging conditions. Beamforming methods, which estimate wave velocities and the direction of arrival (DOA), have shown strong potential, particularly in 3D leak localization. However, challenges remain in optimizing sensor placement and addressing factors such as soil type and depth.

Recommendations for selecting the optimal approach include considering the specific application scenario (e.g., pipe material, depth, surrounding environment and surface of the ground) and combining multiple techniques for enhanced accuracy. Phase-based methods are recommended for noisy environments, while beamforming is optimal for precise 3D localization. Additionally, recent advancements in machine learning and deep learning can be integrated into these methods for improved performance.

5 Final remarks

The study of wave propagation in underground pipes for leak detection has progressed significantly, with early research providing a foundation for understanding acoustic wave interactions with soil dynamics. Over time, advances in vibro-acoustic methods, seismic wave excitation, and beamforming techniques have enhanced the accuracy and reliability of pipeline localization and leak detection. Recent innovations, including multi-array fusion localization and phase-based signal processing, have improved localization precision and addressed noise-related challenges in complex environments. However, challenges remain, particularly due to soil variability, pipe material properties, and burial depth, which impact detection system efficiency. Despite these obstacles, continued research into signal attenuation, system resolution, and real-time monitoring is essential. The integration of advanced signal processing, machine learning, and hybrid detection methods holds great promise for improving underground pipeline monitoring, ensuring the safety and sustainability of aging infrastructure and meeting the growing demand for effective pipeline detection.

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