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Systematic Literature Review of Condition Assessment of Buried Infrastructure: Techniques and Future Directions

Purpose:
The purpose of this paper is to provide a systematic literature review of current techniques used in the condition assessment and maintenance of buried infrastructure, such as water and gas pipes, telecommunication cables, and tunnels. Each of existing methods suffer from certain pitfalls. For example, acoustic methods or geophysical techniques, face significant challenges like noise interface and limited penetration, which hinder accurate assessment. This shortcoming necessitates that these techniques should be used in complementary and should be selected based on certain criteria to best suit the scenario. In view of this, the study aims to address the lack of integrated analysis of these techniques, offering new insights and a foundation for future advancements in underground utility management.

Design/methodology/approach:
This study employs a systematic literature review (SLR) approach, analysing 63 papers on various techniques for mapping and assessing the condition of buried infrastructure. The research categorizes these techniques based on environmental conditions and the materials of the buried structures, highlighting their practical applications, limitations, and the potential of digital twin technology.

Findings:
The review identifies that while various methods are available for assessing buried infrastructure, each has its own advantages and limitations, often requiring a combination of techniques for effective condition assessment. The study also highlights the emerging role of digital twins and BIM in enhancing the efficiency and accuracy of underground infrastructure management.

Originality/value:
The paper's originality lies in its integrated analysis and comprehensive categorization of condition assessment techniques for buried infrastructure. It provides significant value to researchers and practitioners by highlighting the practical applications, challenges, and future directions for digital technologies in this critical area of infrastructure management.

Keywords: Underground infrastructure, Buried infrastructure, Condition assessment, Maintenance, Underground mapping, Digital Twin

1. Introduction

Beneath the streets of contemporary cities lies a complex network of subterranean utilities, encompassing gas, electricity, water, sewage, telecommunications, and other essential services (Wang and Yin, 2022). In the UK, the total length of the networks for the first four of these services exceeds 1.5 million kilometres (Prisutova et al., 2022). It is estimated that in the UK, up to 4 million holes are excavated into the road network per year to repair or install buried pipes and cables. (Stylianidis et al., 2020). In urban areas, buried utilities significantly facilitate the underground transportation of gases and liquids, such as water, petrochemicals, and natural gases (Yazdekhasti et al., 2020).

The efficient and safe conveyance of substances through buried utilities is crucial. However, several factors, such as the materials of the pipes, environmental effects, corrosion, collision, and erosion, significantly impact the performance of subterranean utilities (Ali et al., 2022). If not properly maintained, these factors can lead to leaks, cracks, and other defects in underground utilities. Ensuring the reliability and integrity of these buried networks is increasingly important for various reasons, including the high costs of repairs and the potential loss of materials due to system failures (Meribout, 2021). Early detection of these defects is necessary to prevent catastrophic failures that could result in habitat loss, property loss, and other severe consequences (Durai et al., 2022). Identifying the current state and expected rate of deterioration of these utilities is crucial for scheduling proactive maintenance in the most economical manner (Hao et al., 2012).

Conventional methods for accessing buried utilities for condition assessment typically involve open excavation, allowing personnel to work directly with the underground assets (Li et al., 2022). In the UK, utility companies excavate approximately 4 million holes annually, each posing a risk to other buried services (Costello et al., 2007). These excavations lead to various undesirable side effects in urban areas, including road closures, pollution from spoil and material heaps, noise, and permanent damage to surface structures (Aitken et al., 2021).

Several non-invasive methods are available for the condition assessment of buried utilities, such as laser surveys, sonar surveys, and closed-circuit television (CCTV). Each technique has its limitations. For instance, sonar, while capable of functioning in both air and water, cannot operate in both simultaneously (Hao et al., 2012). CCTV imagery and laser-based technology, on the other hand, are only effective above the waterline (Costello et al., 2007). Consequently, several multi-sensor systems are currently being developed to overcome these limitations.

A holistic review of the body of knowledge indicates that some studies are available on current and emerging technologies and infrastructure projects. Several review articles focus on condition assessment and underground projects. For example, Zeng et al. (2023) reviewed progress in drainage pipeline condition assessment and deterioration prediction models (Zeng et al., 2023); Hao et al. (2012) and Costello et al. (2007) examined some condition assessment technologies for pipeline system (Costello et al., 2007; Hao et al., 2012); Wang and Yin. (2022) discussed the construction and maintenance of urban underground infrastructure using digital technologies (Wang and Yin, 2022); and Hou et al. (2022) reviewed GPR activities in civil infrastructure (Hou et al., 2022).

However, despite these studies, there is a lack of a comprehensive review that integrates and analyses the various condition assessment techniques for buried infrastructure. While there have been recent applications of different techniques in buried infrastructure projects, a thorough analysis and review of these methods and tools are still missing in the relevant literature. In view of this, this study aims to conduct a comprehensive review of condition assessment techniques for buried infrastructure, analysing their effectiveness, advantages, and limitations. It seeks to develop analytical frameworks to evaluate these methods and explore future trends and digital technologies to enhance the assessment of buried infrastructure.

The structure of the study is as follows: the review methodology is explained, the main contents of the analysis of the sensing technologies applied to buried infrastructure are presented, and a comprehensive explanation of buried infrastructure and digital technologies is provided. The study concludes with a summary of the original findings and a discussion of future works.

2. Methodology

The study utilises a Systematic Literature Review (SLR) approach to explore the condition assessment and mapping techniques of buried infrastructure, analysing their advantages and limitations. It aims to address the lack of integrated analysis of these techniques, offering new insights and a foundation for future advancements in underground utility management. There are four steps in this review, as presented in Figure I: 1) identify databases and academic journals; 2) compile a list of potential keywords and query them; 3) save and filter identified articles, and 4) analyse information. The primary results were filtered in two phases. The accessibility of articles was investigated in the first step, which collected a total of 423 publications. The relevance of the articles was considered in the second phase, resulting in a total of 60 publications. Many articles were removed using these steps. These papers are the basis for the discussions and conclusions highlighted in the following sections. The fourth phase involved applying the cross-referencing technique, resulting in 63 articles that were ultimately selected for the state-of-the-art and content analysis.

The first step is to identify databases and academic journals that might have relevant content for this review. Several databases, such as Scopus, Web of Science, and Google Scholar, are used in this study to find relevant literature, with Scopus being the main source. The buried infrastructure, which includes underground cables, sewage networks, gas pipes, and other systems, frames the research's scope.

The second phase involved searching for and locating relevant literature. All possible keyword combinations for this topic were considered, as many nomenclatures may cover the same subject. The subjects were divided into subtopics that cover the terms "condition assessed" and "built infrastructure." The keywords for searching the related literature are: (“Underground structures” OR “buried structure” OR “underground services” OR “buried service” OR “shallow foundation” OR “deep foundation” OR “embedded retaining wall” OR “buried concrete box frame” OR “buried concrete portal frame” OR “corrugated steel buried structure” OR “buried abutments of integral bridges” OR “channel tunnel” OR “swear” OR “drainage” OR “duct” OR “Utilities” OR “pipe” OR “gas pipe” OR “electric cables” OR “optical cables” OR “buried pipe” OR “buried gas pipe” OR “Buried electric cables” OR “buried optical cables”) AND (“BIM” OR “building information modelling” OR “digital twin” OR “identification” OR “condition assessment” OR “modelling” OR “simulation” OR “maintenance” OR “Diagnosis” OR “Repair” OR “Detection” OR “prediction”)).The main themes extracted from these papers focused on the techniques' effectiveness, limitations, and future research directions.

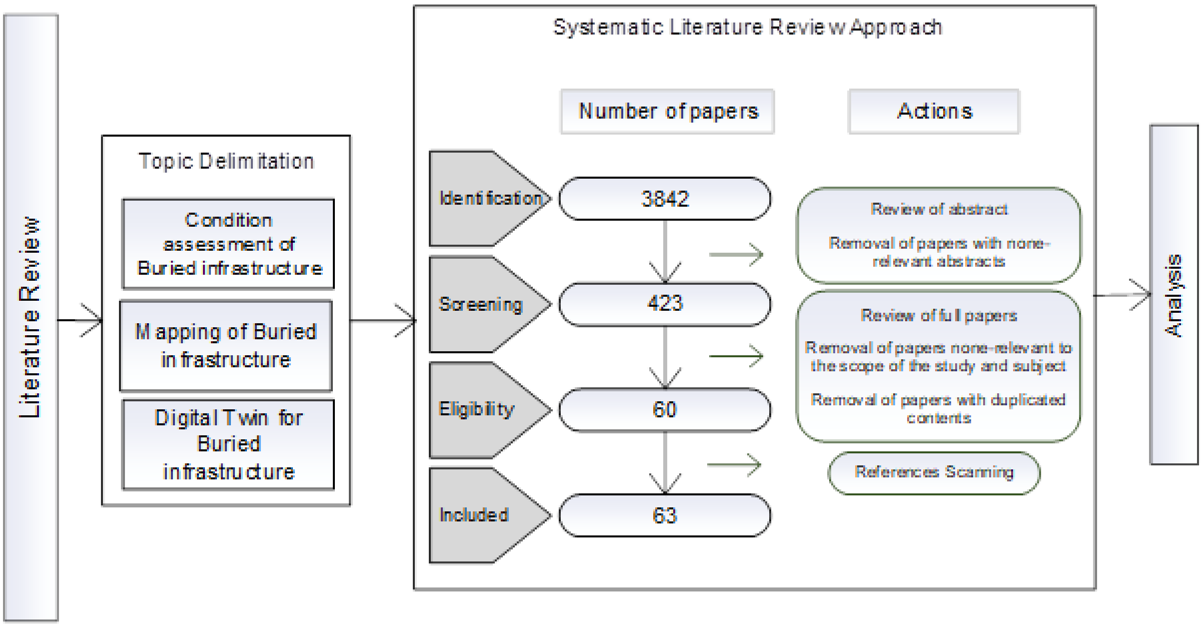

Figure I: Review methodology

In-depth analysis employed content analysis to address the research aim and evaluate the articles extracted from the screening phase. These methods align with a common objective of SLR, which involves examining the development of a specific research area. Content analysis was used to synthesise the progression and intricacies of the condition assessment and mapping of buried infrastructure research domain.

3. Challenges and Considerations in the Condition Assessment and Maintenance techniques of Buried Infrastructure

Buried infrastructure includes pipes (e.g., water and gas), cables (e.g., telecommunication and electric), and tunnels (e.g., transportation and utility) (Hao et al., 2012). Pipeline leaks present significant challenges, with the mean leakage rate in European drinking water distribution networks at approximately 25%, leading to considerable water wastage and financial, social, and environmental repercussions (EurEau, 2017). Consequently, the EU has mandated monitoring and reducing pipeline defects, highlighting the need for accurate and reliable detection methods (Scarpetta et al., 2023). Additionally, tunnels play a crucial role in urban transportation networks, often receiving higher maintenance priority due to their importance in civil engineering projects (Harseno et al., 2022; Wang et al., 2022).

In the UK, open-cut excavation techniques, such as trenching, have been predominantly used for the past 200 years to place underground facilities, leading to various implications and challenges (Hunt et al., 2014). These challenges include road closures, permanent damage to above-ground utilities, pollution from spoil heaps and materials, noise pollution, and the risk of striking existing buried infrastructure, which can result in fires, explosions, and bursting water pipes. It is estimated that 4.25 million holes are excavated annually in UK streets for the condition assessment of buried infrastructure (Stylianidis et al., 2020). Accidental strikes on underground pipes and cables in the UK may cost up to £1.2 billion annually (Wang and Yin, 2022).

Various methods are available for locating and detecting leaks in underground utilities. Traditional leak detection surveys, such as using soap bubbles and listening for leaks, are typically conducted manually and are often ineffective (Liang et al., 2023). Recently, rapid advancements in leakage detection techniques have been made, including acoustic, optical fibre, and visual techniques (Ostapkowicz and Bratek, 2021). Each of these techniques has its own advantages and disadvantages in terms of cost, installation, detection accuracy, and efficiency (Liang et al., 2023).

There are limited studies on 3D modelling that include modern, as-built data of existing buried utilities. Examples include monitoring and modelling the structural safety of buried sewage facilities (Perminov and Mangushev, 2022), the implementation of BIM for underground structures (Chapman et al., 2020) and developing secondary Revit software to create a 3D modelling system for underground pipelines (Chen et al., 2020). One limitation is that 3D modelling of infrastructure lacks the established standards and procedures of building 3D modelling, and obtaining accurate information about buried structures is more difficult than for above-ground infrastructure (Wang et al., 2022).

The greatest challenge is modelling the condition of underground utilities due to the inaccessibility or inaccuracy of data. Integrating condition information with infrastructure component models remains a significant hurdle (Wang et al., 2022). Advanced sensing technologies and inspection outcomes can provide current condition data. In terms of modelling defect data, existing data standards like IFC and CityGML can be expanded, or new data models can be created to represent defects (Wang et al., 2019). Consequently, a digital twin can update and visualise semantic information and as-is conditions, greatly facilitating infrastructure maintenance (Wang and Yin, 2022). A digital twin of buried utilities is envisaged to allow most activities during the Operation and Monitoring (O&M) phase to be performed more efficiently, providing real-time information for structural health monitoring (Lu, 2019).

Ultimately, it is highly desirable to utilise cutting-edge geophysical and sensing technologies to evaluate the state of surface infrastructures and underground utilities (Wang and Yin, 2022). The following sections cover both locating and condition assessment technologies. This paper examines the main groups of condition assessment techniques for buried infrastructure, such as acoustic and visual techniques, identified from 63 papers. A comparative analysis has been conducted to evaluate the effectiveness and limitations of the techniques within each group.

3.1. Acoustic techniques

Acoustic techniques are widely used for detecting leaks in water pipes by capturing vibrations and noise signals produced by leaks. These signals, detected using accelerometers, digital microphones, or hydrophones, vary based on the pipe material (Latif et al., 2022). A common tool, the listening stick, detects underground leaks by transmitting noise signals through a stainless-steel stick to a hollow wooden earpiece. While effective and portable, this method is prone to human error and is primarily used for metallic pipes (Costello et al., 2007; Hao et al., 2012).

Correlators precisely locate leaks by detecting noise signals with acoustic sensors (hydrophones or accelerometers) placed along the suspected pipe. The time delay between signals, calculated using cross-correlation, determines the leak's location. However, the performance can be impacted by pipe material and background noise (Latif et al., 2022).

Sonar profiling uses sound waves to identify defects and submerged deformations in buried utilities. Active sonar emits acoustic signals and measures the echo, while passive sonar detects signals emitted by objects. Sonar profiling is used for maintaining and monitoring buried utilities, offering high resolution with high-frequency sonar and better penetration with low-frequency sonar (Latif et al., 2022).

Transient wave techniques generate waves by altering flow conditions to detect anomalies in buried utilities. Methods include sudden valve closures, underwater electric spark-based generators, and piezoelectric wave generators. Each technique has unique benefits and drawbacks regarding system performance and deployment (Che et al., 2021).

These acoustic techniques require significant energy and are unsuitable for long-term monitoring (>20 years). Background noise and varied acoustic wave propagation in different materials complicate leak detection. To enhance leak noise quality, amplifiers and filtering techniques are employed (Fernández-Osete et al., 2024). A key advantage of these methods is that they do not require entry into the structure's interior, reducing the risk of damaging the infrastructure. However, ensuring reliable operation necessitates high sampling frequencies and careful management to minimise false alarms (Latif et al., 2022).

3.2. Visual Inspection

Visual inspection techniques for buried infrastructure primarily include laser scanning and closed-circuit television (CCTV). CCTV inspection units consist of a camera and lighting device mounted on a carrier that can navigate through structures such as stormwater or sewage pipelines (Wang & Cheng, 2018; Yin et al., 2020). The recorded data is manually evaluated, leading to potential delays in the process. CCTV inspection is the most common technique for inspecting sewers in municipal asset management. However, skilled operators are required to detect problems, which introduces subjectivity (Myrans et al., 2019; Wang et al., 2023).

Laser scanning devices collect data on the internal profile of structures, allowing for measurements such as perimeter, diameter, and cross-sectional area. This technique offers precise data on the condition of structures, including pipe wall shape, corrosion, holes, deflection, and other defects, with an accuracy of up to 0.03% (Kim et al., 2022). Unlike CCTV, laser scanning is not subjective, but it can be hindered by air entrainment and suspended materials in the water, which may obstruct or disperse the signal. It is uncommon to run laser scans and CCTV in water-filled pipes (Prisutova et al., 2022).

Profiling or laser scanning is often utilised alongside inline CCTV inspection to provide additional details on the condition of structures. Vision-based systems using CCTV technology can identify and describe faults, while laser scanning employs a laser beam to assess structural integrity (Latif et al., 2022). Automating the detection process with image-processing techniques can address some issues, but these systems still need access to the interior of the structure. Consequently, they cannot detect voids in soil and backfill, invisible cracks, or deterioration on the outer surface (Jia et al., 2024; Munawar et al., 2021; Wu et al., 2022)

3.3. Geophysical techniques

Geophysical techniques, such as infrared thermography and ground-penetrating radar (GPR), are used to detect anomalies related to underground utilities (Ali et al., 2021; Costello et al., 2007). The maximum detection depth of GPR is typically around 3 meters under favourable conditions. However, GPR's effectiveness depends on ground properties, and it may not be suitable without strategic consideration of these factors (Cardoso et al., 2021). Additionally, GPR cannot distinguish between different types of utilities, such as gas or water pipelines and telephone or electrical cables, requiring verification by alternative techniques. Skilled operators are needed to interpret GPR data accurately (Costello et al., 2007).

Infrared thermography evaluates subsurface anomalies related to underground utilities by detecting temperature changes. An infrared scanner, which detects short- or medium-wave infrared radiation, is used to create thermographic images based on thermal properties rather than visual appearance (Costello et al., 2007; Raja et al., 2021). Similar to GPR, the effectiveness of infrared thermography is influenced by soil characteristics, particularly moisture levels. Wind speed and ground cover also impact the results. However, a significant limitation of infrared thermography is its inability to measure depth (Avdelidis, 2018).

Thermographic testing involves using an external heat source to raise the temperature of a pipe while an infrared (IR) camera monitors the subsequent cooling of the pipe. By analysing its cooling properties, it is feasible to determine whether the pipe has incurred any damage (Flores-Prado et al., 2020). This technique is relatively expensive and primarily used to inspect critical pipe infrastructure in the nuclear and petrochemical industries (Prisutova et al., 2022).

3.4. Electromagnetic technique

Electromagnetic techniques are commonly used for locating underground utilities, though they may be limited to tracing non-metallic objects. Electromagnetic line locators can assess the condition of the insulation surrounding conductors in cables (Prisutova et al., 2022). Pulsed Eddy Current (PEC) testing is particularly effective for inspecting underground tunnels and assessing the condition of metallic structures such as tunnel walls or support beams, detecting corrosion on inner surfaces, and evaluating structural integrity (Harseno et al., 2022; McDonald et al., 2022).

Eddy current testing is typically employed for inspecting small metallic pipes (Brun et al., 2023). A challenge with eddy current testing is the skin depth dimension, which varies with the frequency induced; for example, in steel pipes at 50 Hz, the skin depth is around 3 mm. To address this, the Remote Field Eddy Current technique was developed, enabling inspection through thicker materials (Hao et al., 2012).

The Magnetic Flux Leakage (MFL) is primarily used on the external surface of clean, unlined pipes and is recognised for its ability to detect minor pitting abnormalities (Feng et al., 2022). This technique is used in intelligent pigs to detect and characterise metal loss issues, such as corrosion and cracks in underground pipelines (Durai et al., 2022). However, MFL has limitations, including the need for the tool to maintain close contact with the pipe wall, which may damage internal linings. Additionally, small and shallow flaws may go undetected, and the inspection data may provide an unreliable description of corrosion defects, necessitating cautious interpretation (Feng et al., 2022; Hao et al., 2012).

3.5. Wave analysis

Ultrasonic guided waves are widely used to detect corrosion in pipes, capable of identifying defects on both the inside and outside surfaces. However, before inspection, it is important to clean the pipe thoroughly to remove wax or debris, which could interfere with the results

(Costello et al., 2007; Lyu et al., 2024). Another technique, Acoustic Pulse Reflectometry (APR) measures one-dimensional acoustic waves propagating in pipes. Any change in the pipe's cross-sectional area creates a reflection that is recorded and analysed to detect defects (Costello et al., 2007).

Ultrasonic guided waves are also effective for inspecting tunnel walls, capable of detecting cracks, voids, or other defects (Bombarda et al., 2021; Lyu et al., 2024). Guided waves can propagate over long distances, making them suitable for inspecting extended sections of tunnels without needing access to every point. Additionally, these waves can help identify defects within cables, including discontinuities, water ingress, or other structural issues (Bombarda et al., 2021).

3.6. Fiber optic technology

Fibre optic technology offers a solution to traditional methods for monitoring buried infrastructure and is capable of addressing many limitations of older techniques. traditionFiber optics are utilised in many infrastructures monitoring systems, offering significant benefits such as long-range capabilities and sensor nodes that do not require a power supply, making them a desirable option for pipeline monitoring (Bertulessi et al., 2023). However, installing fibre optics can be challenging and expensive, especially when retrofitting them into existing pipes. . Another drawback is their inability to quickly recover from failures. If a pipe is damaged or bursts, the connected fibre optic system may fail at the point of the damage, potentially disrupting the entire system(Hooper et al., 2024).

Fiber optic cables can also be used for distributed temperature sensing in tunnels. By measuring temperature along the length of the fiber, it is possible to identify variations and potential issues, such as overheating or abnormal temperature patterns (Du et al., 2020. This can be employed for monitoring activities within the tunnel, such as assessing structural vibrations or identifying potential issues. In addition, fibre optic sensors are capable of monitoring vibrations, strain, or deformation in tunnel structures. This provides valuable insights into the structural health of tunnels, allowing authorities to detect potential problems and take action before they worsen (Prisutova et al., 2022).

3.7. Radiographic Methods

Radiographic methods utilise gamma and X-ray radiation to detect and map voids or structural abnormalities within pipes. These technologies can penetrate dense materials such as soil, concrete, or metal coverings to identify internal defects without requiring excavation (Muhammad et al., 2024). However, a limitation of the X-ray method is that pipes with a diameter of 381 mm or more must be emptied before inspection (Prisutova et al., 2022). X-ray imaging can assess the integrity of cable insulation, detecting issues such as cracks, voids, or irregularities that may impact cable performance. Additionally, X-rays can reveal the condition of connectors and joints in cables, helping identify any abnormalities or defects. These methods are also applied to assess the condition of concrete structures, such as tunnel walls. Gamma rays, due to their higher penetration capability, are suited for thicker or denser materials compared to X-rays for evaluating deeply buried structures (Aliyeva-Jabbarli, 2023).

Compared to other non-invasive techniques, radiographic methods provide higher-resolution imaging and can directly visualise internal defects (Jasiūnienė et al., 2024). However, they require more strict safety protocols due to radiation exposure, and the equipment tends to be more expensive and less portable (Ricci et al., 2020). In contrast, techniques like ultrasonic guided waves can cover longer distances and are better suited for preliminary inspections over large areas (Clough, 2016). Despite these challenges, radiographic methods remain critical for applications requiring detailed imaging, especially for buried infrastructure and materials with complex geometries (Ricci et al., 2020).

3.8. Summary of Technologies for Locating and Assessing Buried Infrastructure

Table I provides a comparative overview of various methods used for locating and assessing the condition of buried infrastructure, detailing their benefits and limitations. Locating and assessing the condition of a diverse range of underground utilities is highly complex. Certain techniques are deemed appropriate for specific types of buried structures and materials, with factors such as material composition, diameter, depth, and soil conditions all impacting their effectiveness.

Category	Technology	Benefits	Limitations
Acoustic techniques	Sonar profiling	Accurate measurements are attained Provides high resolution	low penetration for high-frequency sonar /Low frequency sonar has low revolution scan.
	Impact echo	Overall condition assessment of the pipe/ Applied to different materials / proper in pre-stressed concrete structure/ Not limited by size	effect on test results and wave behaviour/ Frequency domain analysis is complicated/ Geophones installation against buried utility/ Access to structure
	Listening stick	common and easy analysis real-time sounds,	Background noise, such as traffic, can have an effect/ access is required
	correlator	Successful at leak detection in the underground network	Limited success when applied in large diameter pipe
Visual Inspection	CCTV	Applied to sewer and storm water pipes Used for rehabilitation most common technique	Real time assessment / inspector must detect and categorise defects in image/ Images can just be achieved above the water line/ The carrier speed is restricted to 15 cm/s

	laser scanning	Determines internal profile of the structure/ measure volume of debris in invert, pipe wall deflection, and corrosion loss/ operated in water and air/ Creates high resolution surface profiles of the structure	Can only be used in dewatered pipes/ Requires data processing/
Geophysical techniques	GPR	Determine ground conditions external/ Independent of type of material	More signal attenuation with conductive soil / reducing the depth of penetration/ Not to distinguish between type of pipe/ Needs skilled operators to interpret GPR funding
	Infrared thermography	Can be used at ground surface	Influenced by the characteristics of the surrounding ground/ ground cover and wind speed influence funding/ Unable to measure depth
Electromagnetic technique	Pulsed eddy current (PEC)	Unaffected by table water and surrounding soil/ High resolution by ultra-short duration pulses/ Potential for pipe condition assessment	Just detect metallic objects/ Pre-commercial prototype is under development/ Possible interference by other near-by metallic pipes
	Pulsed eddy current (PEC)	Used in smaller diameter cast steel and iron pipes/ can be overcome use of Remote Field Eddy Current (RFEC) method	Access to structure/ Dimension of skin depth is a challenge
	Magnetic flux leakage	suitable for cast steel and iron pipes/ Used in intelligent pigs for characterisation of longitudinal and circumferential cracks and corrosion/ detect minor defects	often limited to unlined and cleaned pipes/ Maintaining close contact with the pipe is challenging and lead to damage to the pipe's lining/ has difficulties detecting shallow and short defects/ Access to structure

wave analysis	wave analysis	Determine mapping of defect/ proper detection rates were reported for crude gas and oil pipe detecting defects/ characterise metal loss due to the corrosion	Pipe cleaning prior to inspection essential to remove wax or debris / Just proper for pipes above 5 cm in diameter and with wall thicknesses of up to 4 cm.
Fiber optic technology	Fiber optic technology	Provides long-range monitoring capabilities/ Utilises sensor nodes that do not rely on external power supplies	the need to install fibers and sensors during the production process can result in elevated costs/ Limited Recovery from Failures

Table I: Comparative overview of technologies for locating and assessing buried Infrastructure

4. Digital Technologies for Managing Underground Infrastructure

As the complexity of infrastructure and underground environments increases, ongoing maintenance becomes essential (Prego et al., 2017). Digitisation is a crucial tool for managing these complexities. While not all digital technologies are suitable for underground infrastructure, some can be particularly beneficial in overcoming challenges in various activities related to underground infrastructure projects (Huang et al., 2021). For instance, BIM and GIS are being used to model subsurface infrastructures, improving visualisation and enabling simulation at various levels. However, their applications are still in their infancy (Sharafat et al., 2021; Wang and Yin, 2022).

The Crossrail project in London demonstrates BIM's role in buried infrastructure assessment, integrating geospatial data, structural details, and as-built information. BIM enabled precise mapping of underground utilities, reducing accidental damage risks and identifying structural defects through non-invasive inspections like laser scanning and CCTV imagery in a unified 3D model (Tylor, 2018).

Numerous reviews have been conducted regarding locating technologies, condition prediction (Nasser et al., 2020), deterioration modelling (Dawood et al., 2020), condition assessment and inspection (Hao et al., 2012), and visualisation techniques (Muthalif et al., 2022). Automated vision-based techniques for condition assessment have also been explored, yet they still face challenges in terms of accuracy and reliability (Haurum and Moeslund, 2020).

A significant milestone towards a digitalised condition assessment of buried infrastructure is the generation of a Digital Twin (DT) (Chen et al., 2020). DT is widely recognised as an effective tool for the condition assessment of above-ground infrastructure, and it is expected that these benefits can be applied to underground infrastructure as well. A digital twin of underground utilities enables many activities, such as offering real-time data for monitoring the health of structures (Wang and Yin, 2022; Wang et al., 2022).

A notable example is the implementation of DT for smart water grid operations, which integrates sensor data, geospatial mapping, and anomaly detection systems. This DT monitors underground utilities and water distribution networks in real time, improving the efficiency of maintenance planning and preventing service disruptions by offering precise predictive insights and resource allocation (Wu et al., 2023).

A DT of existing infrastructure can continuously learn and update itself from multiple data sources to represent the near-real-time status and working condition (Lu, 2019). Typical DT use cases include visualisation, drawing generation, progress monitoring, and project management. Additionally, a DT is maintained throughout the entire lifecycle and can be accessed at any time (Pires et al., 2019). This continuous updating provides infrastructure owners with early insights into potential risks induced by climatic events, heavy vehicle loads, or aging (Lu, 2019). The greatest value of using DTs lies in their potential to save significant costs for authorities and owners by automating the inspection process and enabling accurate condition assessments and timely maintenance decisions. Overall, DTs are expected to bring substantial benefits for the maintenance and operation of buried infrastructure, similar to those realised for above-ground infrastructure (Chen et al., 2020; Wang and Yin, 2022).

5. Discussion

Different techniques that are capable of monitoring or assessing the condition of buried utilities are provided in Table I. The advantages of one technique often align with the disadvantages of another technique due to their development for different practical scenarios Although there are numerous techniques available, selecting the most suitable one depends on operational conditions, materials, and the environment. This highlights the need for clear decision-making guidelines to ensure practical use in real-world projects. This comprehensive review has illustrated that no single technique is universally applicable; instead, the effectiveness of each technique is context dependent. The study successfully addressed this aim by evaluating various techniques, highlighting their practical applications and the associated challenges.

The collection of these techniques gives us the freedom to select, but in some situations, one technique does not provide appropriate inspection outcomes, and other techniques must be used in the inspection. This highlights the importance of developing analytical frameworks to assist in the selection process based on specific criteria and operational conditions. Such frameworks could guide utility managers, policymakers, and engineers in making better-informed choices. The prerequisites for applying different techniques and the associated specifications, including input, output, process, and criteria, are represented in Table II.

A variety of factors can impact the selection of techniques. The list includes environmental conditions, sounding soil properties, material, shape, size, and fault properties. Figure II shows different techniques based on criteria. These factors are critical in determining the most suitable condition assessment method, as each technique responds differently to variations in these parameters. For instance, policymakers can develop guidelines to ensure that factors like soil conditions and material types are prioritised when selecting monitoring methods, ensuring better outcomes and minimising risks.

Table II: Detailed specifications and performance criteria of various condition assessment techniques for buried infrastructure

Category	Technology	Input	Performance	Output	Criteria
Acoustic technology	Listening Stick	Acoustic Signals/ Historical Data/Environmental Data such as temperature, pressure, humidity/	placing sensors near a system and listening for the sound waves or vibrations generated when a leak occurs	leakage detection	Background noise/Shear stiffness of the surrounding soil/Pipe material/Operator Expertise
	Correlator and Transient Wave			leakage detection & exact location	
	sonar profiling				
Visual technology	Laser scanner	reflected signals from laser beams or light pulses/Environmental Condition such as temperature, humidity, and atmospheric pressure/	Laser scanners capture detailed 3D point cloud data. Software algorithms can identify irregularities or deformations in the scanned objects, which may be indicative of leaks, and cracks.	Point Cloud Data	Material and dimension/ Operator Expertise
	CCTV		CCTV cameras capture real-time video, enabling prompt leak detection. These systems include triggering immediate alarms upon detection of unusual activity.	Real-Time Video/Alarms	
Geophysical technology	infrared thermography	Material Properties/Environmental Conditions/Historical Data	Scan the area for temperature differences Capture thermal images Identify potential flaw	Mapping	Frequency type, Operator Expertise, Soil water content (SWC) or soil moisture/The nature of the leak

<table>
<tr><td></td><td>Ground Penetrating Radar (GPR)</td><td></td><td>Radar waves reflect off subsurface boundaries and features /Collected data creates a subsurface profile. /Interpretation reveals subsurface information.</td><td>Detection and mapping</td><td></td></tr>
<tr><td rowspan="3">Electromagnetic technology</td><td>MFL</td><td rowspan="2">Material Properties/Environmental Conditions</td><td rowspan="2">Coil generates a magnetic field.
Eddy currents form in the material.
Flaws disrupt eddy currents, changing coil impedance.
Data analysis identifies and visualises flaws.</td><td>Detection and mapping / Measurement of the extent and depth of defects.</td><td rowspan="3">shape of the defects/ the thickness of structure/Material Conductivity/ structure shape/ Operator Expertise/ pulse features/surrounding soil/ material/ soil moisture</td></tr>
<tr><td>ECT</td><td>Detection (corrosion, cracks, and wall thinning)/Visual representation of flaws</td></tr>
<tr><td>RFET</td><td>Material Properties/Environmental Conditions</td><td>RFET probe generates a magnetic field.
It interacts with the material's inner wall.
Anomalies create a secondary magnetic field. / RFET sensors detect this field.
Data is analysed to identify defects.</td><td>Detection and mapping of defects /Assessment of wall thickness and identification of corrosion.</td></tr>
</table>

wave analysis technology	wave analysis	Materials Information//Historical Data/Environmental Data such as temperature, pressure, humidity	send a sound wave through a fluid medium, which is then detected by a number of sensors. By observing the returned signal many of the characteristics of the material can be determined.	characteristics of the material / detect axial cracks/ defect position/ size of the defect	Pipe material/Operator Expertise/Environmental Conditions
Fiber optic technology	Fiber optic technology	Optical Signal Data/Historical Data/Environmental Data /Data Analysis Algorithms	placing sensors near a system and listening for the sound waves or vibrations generated when a leak occurs	Location/ size of flaw/ temperature variations	Pipe material/Operator Expertise
Radiographic technology	Radiographic Methods	utilise gamma and X-ray radiation	The radiation is sent and captured on either a digital camera or a photographic plate.	detection and mapping	diameter of pipe
Thermography technology	Thermography Methods	external heat source	Raise the temperature of a pipe and use an infrared (IR) camera to monitor	Detection	Cost

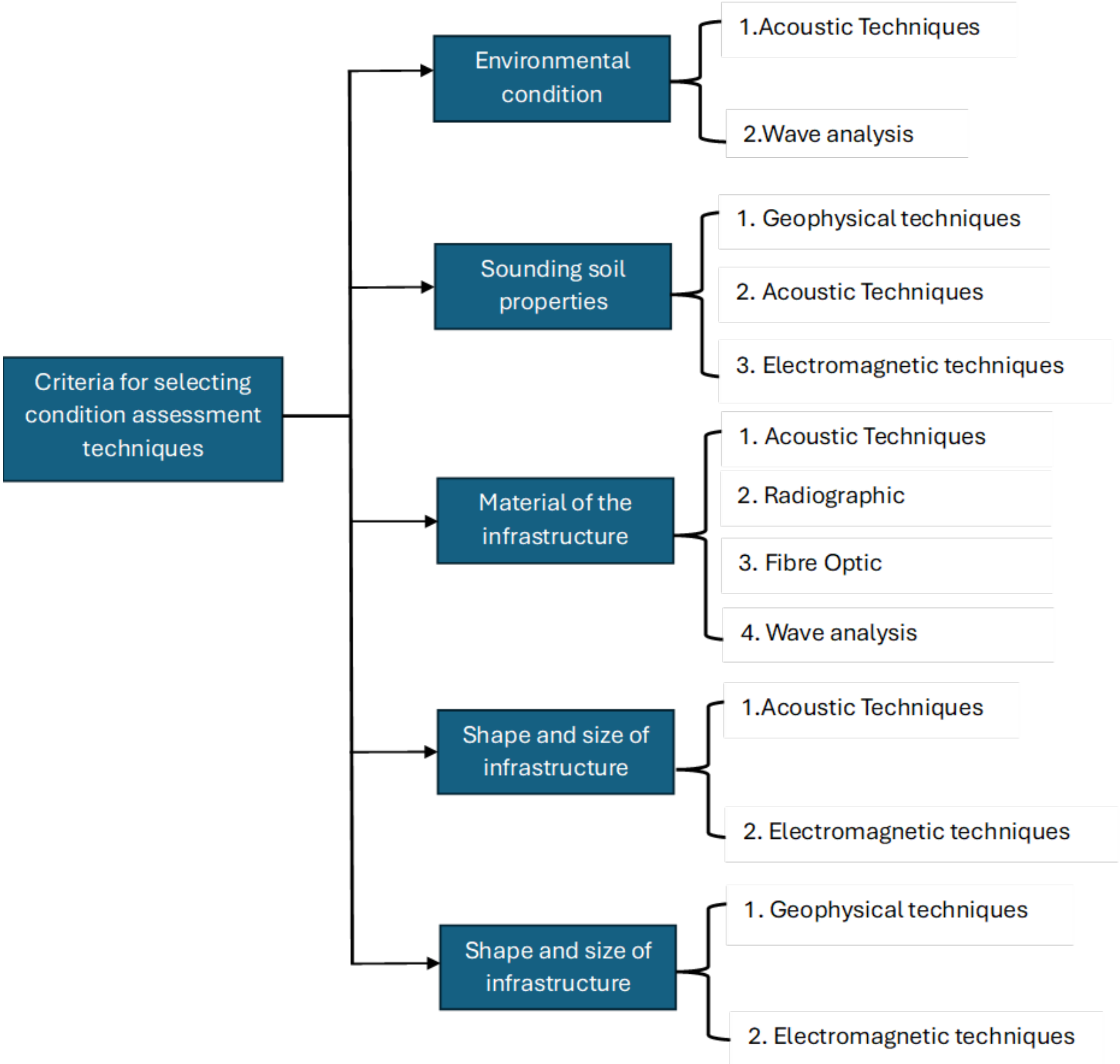

Figure II: Criteria for selecting condition assessment techniques for buried infrastructure

5.1. Challenges and Future Trends in Condition Assessment of Buried Infrastructure

The frequency of the article's keywords is listed in Figure I. Keywords that were repeated more than three times are listed. As shown, existing research heavily utilises GPR techniques and pipelines in the context of buried structures. Digital technologies like digital twins and BIM are featured in a small number of articles, indicating an opportunity for increased usage in future literature.

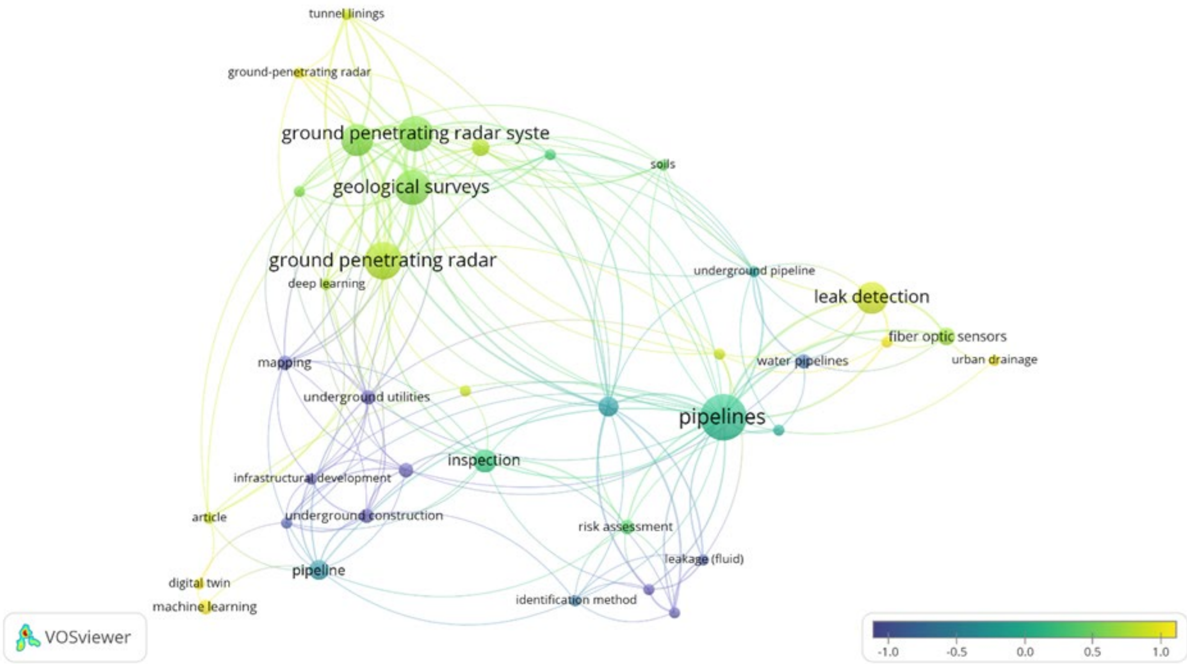

Figure II: Frequency and co occurrence of keywords in buried infrastructure research

There are several challenges in the current techniques for assessing buried infrastructure that need to be addressed in future research:

- Different factors, such as environment, material, and condition, must be considered while performing data analysis. Future research is required to examine the effects of these factors individually and the impacts of their combinations.
- In acoustic techniques, the presence of background noise and the complex mechanisms of structure failure modes make it challenging to identify leak noise signals. The similarity between leak and non-leak noise signals is a significant challenge that can result in false alarms.
- The visual monitoring system requires a moving camera inside the structure manually with wire or with a crawler. The size of the visual equipment and the geometry of the structure can also limit or restrict movement. Another main challenge is the need for large memory storage for high-quality and high-resolution imaging data.
- There are limited studies on 3D modelling with updated as-is information or as-built data of existing buried utilities.
- Existing maintenance strategies for buried utilities are reactive and typically occur after a fault has developed. This can lead to severe consequences due to the unexpected failure of utilities. With the availability of various data (e.g., environmental data, infrastructure features, inspection records), predictive maintenance can be developed to optimise maintenance planning by considering future conditions, different costs, and the consequences of failure.

Based on the reviewed literature, the following future trends are observed in the condition assessment of buried infrastructure:

- Increased focus on the integration of digital technologies such as digital twins and BIM in monitoring and maintaining buried utilities. Governments and utility companies should prioritise pilot projects that implement these technologies, leveraging them to reduce maintenance costs and improve operational efficiency. The findings indicate a lack of real-time integration of operational and environmental data. This insight has led to the recommendation for future research to focus on Digital Twins and sensor fusion technologies to address this gap.
- Continued development of advanced analytical frameworks to assist in the selection of appropriate techniques based on specific criteria and operational conditions. This is reflected in the increasing complexity and specificity of methodologies discussed in recent research. For instance, utility professionals could benefit from frameworks that standardise the selection of techniques based on factors like pipe material, soil properties, and the type of utility. For example, implementing BIM in large-scale infrastructure projects has demonstrated efficiency in risk assessment and decision-making. These findings suggest that further research into automated BIM integration could enhance predictive maintenance strategies.
- A shift towards predictive maintenance strategies leveraging big data and machine learning to proactively address potential faults and optimise maintenance schedules. The literature suggests a growing interest in moving from reactive to predictive maintenance approaches to enhance reliability and efficiency. This shift could be supported by public policies mandating predictive maintenance strategies for critical infrastructure, preventing catastrophic failures.

6. Conclusions

The technologies derived from the 63 papers analysed through the SLR approach showcase a wide variety of methods for locating and assessing the condition of buried utilities. Despite technological advancements, issues such as material dependence, noise sensitivity, and equipment limitations remain prevalent. To address these limitations, a significant finding is that no single technology can reliably assess all aspects of underground utilities, highlighting the importance of multi-sensor approaches. By classifying technologies based on their performance and environmental conditions, this review offers a practical guide for selecting and combining techniques to maximise their effectiveness. This would enable more comprehensive and accurate assessments of buried infrastructure. Furthermore, this study underscores the importance of integrating digital technologies, such as digital twins and BIM, to address current limitations, such as material dependence and noise sensitivity. Digital twins can provide real-time, dynamic models of buried utilities, enabling continuous monitoring and more accurate predictions of utility conditions. Findings from this study directly inform future research by identifying critical gaps in integrating digital solutions with traditional condition assessment methods.

The scope of this paper is limited to the existing and common techniques for condition assessment and mapping of buried infrastructure. Many emerging proactive techniques, including static systems like MISE-Pipe, as well as dynamic systems like SmartBall, are not considered in this review but could be addressed in future research. Future research should thoroughly review existing studies on this topic and explore the potential applications of real-time technologies, such as digital twins for underground infrastructure projects. These applications include real-time monitoring for immediate fault detection, predictive maintenance to optimise schedules and enhance reliability, enhanced data integration from various sources for informed decision-making, and improved design and planning through simulation. Policymakers should consider these findings to establish standardised regulations for integrating digital technologies. By overcoming these challenges and implementing digital twins, the field can achieve more accurate, efficient, and comprehensive methods for managing and maintaining buried infrastructure.

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