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Detecting Water Leakage Patterns Using Ground Penetrating Radar in Clay and Sandy Soils

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Abstract – Non-Revenue Water (NRW) relates to water that disappears or is unaccounted for due to water pipeline leakage. Ground Penetrating Radar (GPR) is a method that can be used to detect water leaks from water pipes. It operates by utilizing the principle of dielectric contrast detection with electromagnetic signals. This study aims to determine the spatial arrangement of subsurface water leaks in two different soil types (Clay and Sandy) from different water pipe materials (metal and HDPE pipes). A prototype model was constructed to replicate soil water loss at a depth of 0.55m. The leak simulation involved separate testing of perforated HDPE and metal pipes under different soil conditions. An analysis is conducted to investigate the alteration in the hyperbolic shape of the pipe, and the disparity in the speed of the GPR and dielectric signals is computed to verify the presence of water leaking. The study's findings indicate that the dielectric material and soil type influence the velocity. Specifically, the velocity is reduced in soil containing HDPE and stronger in soil containing iron pipes. HDPE pipes in clay soil, the velocity is measured at 0.060m/ns with a dielectric value 25. For iron pipes in clay soil, the velocity is measured at 0.100m/ns with a dielectric value of 9. The confirmation of GPR signal detection on soil exhibits a consistent pattern. GPR signal radargrams demonstrate that detecting metal pipes is more feasible with GPR than HDPE pipes, even in the presence of water losses. While the findings indicate that iron pipes disrupt the assessment of leakage water distribution patterns by GPR signals, yet nevertheless yield accurate results for leak detection.

Keywords – *Water, Leakage, Pattern, Ground Penetrating Radar, Soils*

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1.0 Introduction

Pipe leaking is one of the most serious challenges in the water sector. The primary causes are waste of natural resources and excessive water consumption (Fontana and Morais, 2016). Leakage has an impact on transportation and infrastructure in cities and suburbs alike. Non-Revenue Water (NRW) refers to water that has been lost or not accounted for. Malaysia's National Water Services Commission (SPAN) uses NRW to measure water quality and quantity. According to SPAN (2013), 20-30% of all water output is wasted or unaccounted for (Cheong, 1991; Ghazali, 2012; SPAN). The International Water Supply Association (IWSA) discovered that leaks are the leading cause of water loss (Salleh & Malek, 2012).

Several ground techniques have been used to identify water leaks, including pressure difference measurements between two valves, acoustic sounding, ground-penetrating radar, and gas injection (Rizzo, 2010; Krapez et al., 2022). However, ground methods are complex and generally insufficient for detecting leaks in water transmission mains (Mazumder et al. 2018, Krapez et al. 2022). Transmission main leaks are challenging to detect because this water transportation infrastructure has one or more characteristics: low pressure, low noise frequency, big diameter, non-metallic material, and few contact points for acoustic monitoring.

Utility mapping identifies and classifies underground pipelines and cables; this sector is concerned with underground things. Underground pipeline detection, location, identification, and classification necessitates proper technology, the most commonly used of which is GPR. This study aims to discover water leakage patterns in underground distribution networks using GPR. Pipeline leaks have an impact on Malaysia's water supply. Water supply firms in all states have sustained losses. The recent destruction in Malaysia significantly impacts water supplies and transportation.

Malaysia has 127,275 km of various water pipes. These pipes include Asbestos Cement (AC) of 44,282 km (34.80%), Mild Steel Pipe (MS) of 29,372 km (23.10%), HDPE pipe of 22,111 km (17.37%), Unplasticized Polyvinyl Chlorine (uPVC) of 18,683 km (14.70%), Ductile Iron Pipe (DI) /CI of 9,885 km (7.70%), and other types with a total length of 2942 km (2.30%) (Salleh and Malek, 2012). Since Malaysia began using pipelines ten years ago, almost half of its entire water supply has been lost, while unaccounted-for water has increased (AWWA 1987). Leakage from ancient water pipelines and degraded asbestos-cement (transmit) pipes is a significant cause of water loss due to age, weathering, and natural disasters like floods. Some water losses were undetectable because the pipelines are underground and do not interfere with services. When no immediate action is taken, water losses from these leaks can persist for a long time, resulting in enormous amounts of lost water and indirectly causing NRW in Malaysia.

Universiti Teknologi Malaysia (UTM) also experienced a water pipe leak. However, UTM has modernized its infrastructure (water supply system). UTM Johor Bahru has 45 kilometres of different water pipelines. UTM has various main water pipes, including 20% Mild Steel Pipe (MS), 15% Asbestos Cement (AC), 60% Unplasticized Polyvinyl Chloride (uPVC), and 5% Galvanized Iron Pipe (GI). Infrastructure upgrades (water supply system) include replacing old AC pipes with uPVC, replacing MS-type pipes, rehabilitating the main water storage tank, installing individual meters in each block, and developing Supervisory Control and Data Acquisition (SCADA), Telemetry, and Utility Billing Systems.

This investigation aims to determine whether GPR can detect subsurface water leaking patterns. This study is planned to show that GPR can successfully detect water leakage patterns in HDPE and metal pipes in clay and sandy soils. This study also determines the validity and efficacy of GPR technology in identifying water leakage patterns, analyzing water leakage patterns from HDPE and metal pipes in two different soils, and comparing water leakage patterns from prior studies.

1.1 Underground Utility Mapping

Underground utility mapping involves identifying, classifying, and mapping underground utilities. Telecommunications, power, drainage, sewage, petroleum, and gas are the main subsurface utilities. The recently completed subsurface utility mapping has aided the development of our country. New industries are crucial since they can help smooth project development by eliminating delays. It minimizes utility damage during excavation, worker and public safety, and construction claims. Land surveyors must locate and map underground utilities to achieve the most significant results.

Underground utilities must be mapped using non-destructive procedures in order to update urban cadastral information and properly use land resources while creating new networks (Jaw and Hashim, 2014). GPR technology has the ability to detect pipelines that are planted in the subsurface and to monitor the current physical condition of the pipe (Ashraf Abd Gani, 2018). GPR has been used to detect and locate underground utilities because of its advantages, including high-resolution images that aid in appropriate interpretation. Thus, the equipment must be operated correctly to obtain superior measurement results. GPR and Electromagnetic Locator (EML) are commonly utilized in subsurface utility mapping. This study used GPR technology to identify the location of subsurface pipelines based on their reflection force, namely pipe water leakage.

1.2 Water Supply in Johor

Ranhill SAJ oversees Johor's potable water distribution (Ranhill, 2019). This integrated water corporation has a lengthy track record of accomplishment. Johor has over a million customer accounts and a pipeline of 22,000 km. Johor has a population of 3.7 million. The licensed water operator generates 1800 million litres per day (MLD). NRW has decreased from 37% to 24%, saving 250 Mld. Johor has the lowest NRW in Malaysia, measuring 20 m^3 per kilometre per day.

The Johor State New Administrative Centre (JSNAC) represents the beginning of the Nusajaya development project. The administrative core comprises the State Assembly Building, the Chief Minister Complex, and the Johor State Secretariat. Supervisory Control and Data Acquisition (SCADA) systems enable continuous monitoring and rapid issue resolution. SCADA is commonly used for long-distance pipelines. They may have multiple sites and traverse long distances (Sutton 2017). SCADA monitors pipeline flow, pressures, and temperatures while controlling pumping, compressor, and valve stations. SCADA is useful for locating pipeline leaks and fractures.

1.3 Ground Penetrating Radar

Ground Penetrating Radar (GPR) uses near-surface geophysical imaging to investigate underlying geology and engineering (Byrnes and Martinez, 2001). GPR has been extensively employed in real-world data collection to improve utility administration and maintenance. GPR can map underground utilities. New utility installations in locations with buried subterranean utilities are less likely to fail. GPR is a non-invasive technique for near-surface imaging similar to seismic but with higher resolution (Al-Shukri et al., 2014). GPR uses electromagnetic waves to analyze the depth and resolution of subsurface objects.

The Earth's soil covers one-third of its surface, and soil is distinguished by its changing biological, chemical, physical, and other properties (Jon and Jackie, 2015). It is a valuable resource defined by soil type, moisture content, dielectric permittivity, and other parameters. The moisture content of the soil affects its dielectric permittivity. Soil moisture is measured using oven drying, a neutron instrument, Time Domain Reflectometry (TDR), and Topp's equation (Zhang 2012).

Soil qualities are essential when employing GPR in agriculture, the environment, engineering, and construction. According to Igel et al. (2011), soil conditions influence GPR subsurface detection. The resolution and penetration depth of GPR are determined by the frequency of the antenna and the electrical characteristics of the soil. Large particles in sandy soils limit water content. Low-frequency GPR antennas can reach 50 meters deep in dry sand (Smith and Jol, 1995). Soil dielectric constant is given in equation (1):

$$\boldsymbol{\varepsilon}_r = \left(\frac{c}{v}\right)^2 \quad (1)$$

Where c is the velocity of light (ms^{-1}) and $\boldsymbol{\varepsilon}_r$ is the material dielectric permittivity.

Numerous studies have been done to assess subsurface utility data. Amalina Yusup et al. (2015) visually evaluated water leaks using GPR radargrams for compacted sand. Since the GPR signal depends on soil characteristics, structure, particle size, density, and moistness, this study emphasizes two different soil properties: clay and sand. The delayed arrival of the reflected pulse is proportional to the depth and thickness of the subsurface structure.

Next, Ahmad Fuad et al. (2019) investigated the water leak detection methods in a water distribution network, including sound, acoustic, sensor, and real-time detection. This study aims to determine the usage of GPR to detect water leakage patterns in underground distribution systems. GPR is a geophysical technique that employs radio waves to look underground (Kazunori, 2012).

2.0 Materials and Methods

The research study area is located around Block T06, Universiti Teknologi Malaysia, using dual frequency Ground Penetrating Radar (GPR) (IDS Detector Duo with 250 and 750 MHz), as shown in Figure 1.

Figure 1. Study location.

2.1 Buried Pipe Setup

This study employs a simulation process, which is the method used to create, develop, analyze, and optimize technological processes. As illustrated in Figure 2, a prototype model was initially built to simulate a pipe leak. Making two holes to allow water to seep into two different soils. This survey will be conducted using HDPE and a metal pipe. HDPE and metal pipes are tested independently by burying them in clay or sandy soil. The pipe was then injected with water. The test bed will be developed with sand and clay soil. The site dimensions employed in this investigation are 1.5 × 0.07 × 0.55 m, whereas the pipe dimensions are 1.3 × 0.05 m and 0.7 × 0.05 m. Figure 3 depicts using a 15-litre tank to run down the pipe.

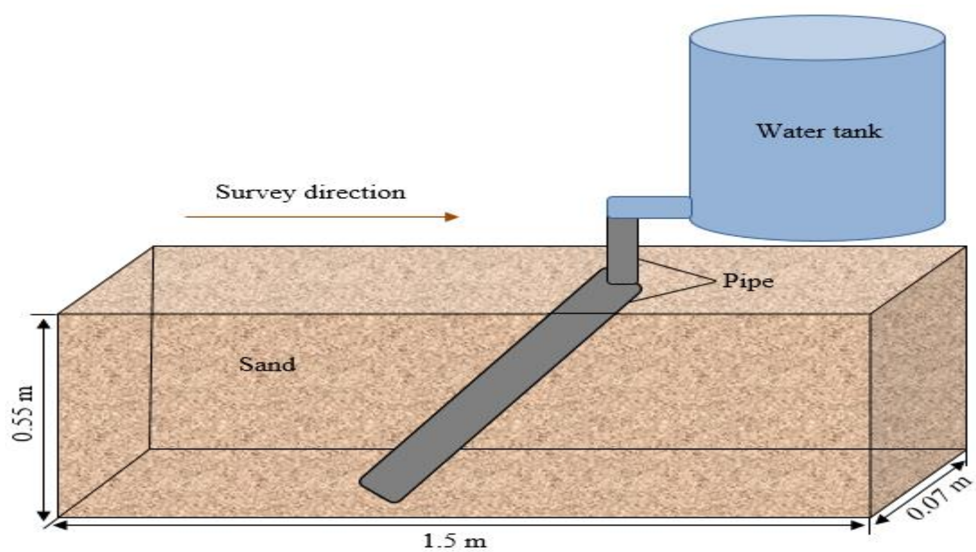


Figure 2. Prototype diagram of the test bed.

Figure 3. Pipe leakage test bed.

2.2 Calibration Phase

The equipment is relocated to the curtain distance and will automatically end. The K2 software will calibrate the device automatically and supply the proper setting. A material's relative dielectric permittivity determines the velocity and dispersion of the GPR signal in the medium. An antenna frequency appropriate for the estimated depth range is used.

2.3 Detecting Leaks Using Water Leakage Detector

A water leakage detector is an electrical gadget designed to detect the presence of water and send out a warning so that a leak can be halted in time. One typical design uses the electrical conductivity of water to reduce the resistance between two contacts, and it consists of a short wire or gadget that lies flat on the ground. When enough water bridges the contacts, the gadget sends forward signals and sounds an audio alert. These are useful in high-traffic locations near water pipes, drainpipes, vending machines, dehumidifiers, water tanks, or anything else that could leak water. Initially, this equipment was proposed to detect pipe leaks in this research. However, this instrument cannot be used because it is unavailable or presently occupied.

2.4 Data Collection

Fundamentally, data collecting is a crucial aspect of this investigation. The equipment must be in good condition and function properly during data collection. GPR data processing is currently conducted by using specific informatics tools, which allow for the elaboration, cleaning, and enhancement of raw data to produce vertical profiles and horizontal time-slices--i.e., raster images of the subsoil as layers located at different depths, where depth is calculated based on the wave travel time and wave velocity (Angeli, Serpetti, & Battistin, 2022). To achieve the study's goal of detecting water leaks using GPR, GPR tests were performed under two conditions: good pipe and leaking pipe. The inspection is carried out once the pipe has been securely installed in the ground. A suitable antenna frequency was chosen for the approximate depth range. Thus, deep things must have a wider diameter than shallow items. Data was processed using Reflex W and Reflex 3D Scan to derive picture parameters.

2.5 Data Processing

Once the data is acquired, the processing phases must be completed before the results can be received and analyzed. Reflex W and Reflex 3D Scan are utilized to process the collected data. Image filtering generally reduces noise and retrieves important information while improving visual quality. For example, Figure 4 boosts an image's brightness and contrast while adding textures, tones, and effects. Nevertheless, removing background noise is unnecessary, as it may hinder the interpretation of water leakage from GPR radargram signals.

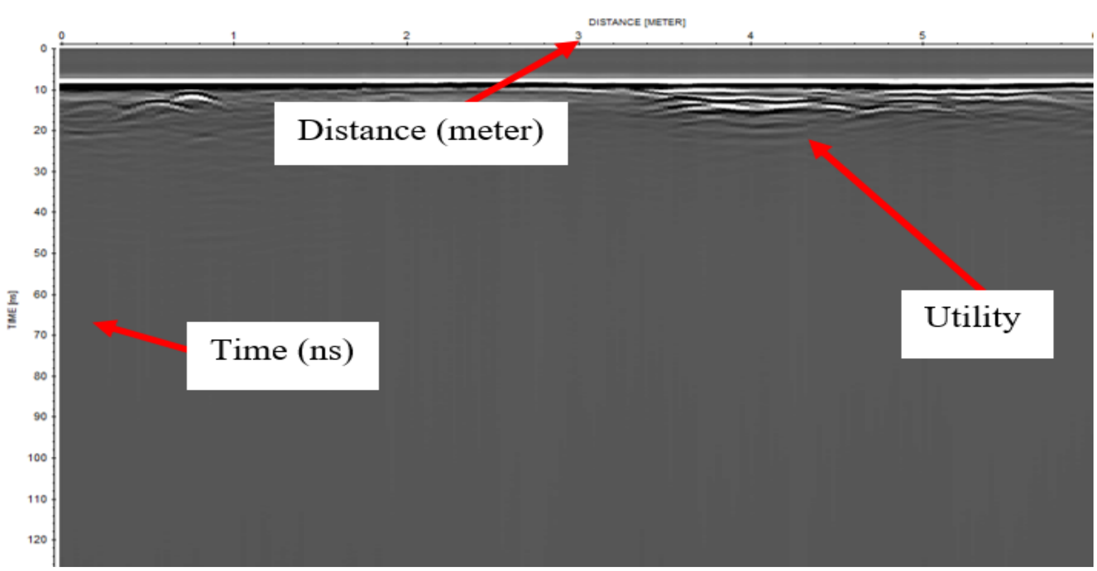


Figure 4. Radargram image.

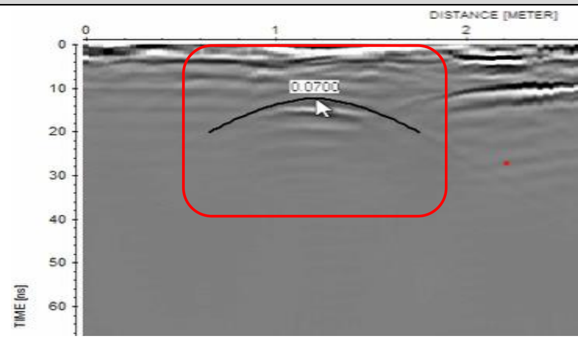
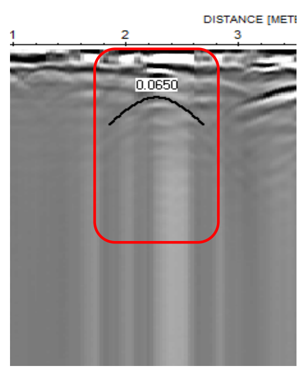
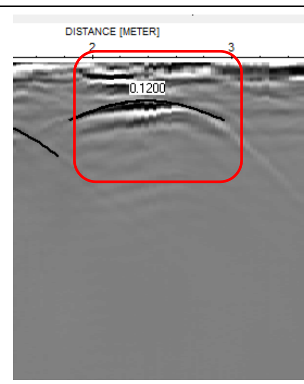
3.0 Results and Discussion

This part shows the results and analysis for improving the image pattern quality. Image filtering was used to aid in interpreting radargrams to minimize noise and retrieve valuable information while increasing visual quality.

3.1 Pipe Leakage Simulation

As previously stated, two tests were undertaken to detect water pipe leaks. Table 1 shows the test results.

Table 1. Image hyperbolic pattern for normal pipe (without water leakage).

Types of pipe	Condition	Image radiation
HDPE pipe	Buried in clay soil	
	Buried in sandy soil	
Metal pipe	Buried in clay soil	

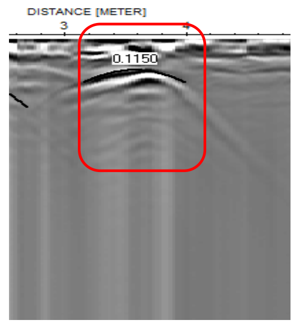
Buried in sandy soil	

Table 1 shows the output of an image pattern for a regular pipe state. The red rectangle in the table represents the detection of hyperbolas in radargrams. The hyperbola in Table 1 represents the rate of data gathering in minutes per nanosecond. Table 2 shows the parameters collected from the radargram under normal pipe conditions. These parameters allow us to calculate the dielectric constant.

Table 2. Parameters extracted from radargram for normal pipe.

Pipe	HDPE pipe		Metal pipe	
Material	Clay soil	Sandy soil	Clay soil	Sandy soil
Time (ns)	12.422	10.568	7.969	7.515
Velocity (m/ns)	0.070	0.065	0.120	0.115
Estimated depth (m)	0.373	0.317	0.239	0.225
Dielectric constant of soil	18.367	21.302	6.250	6.805

Table 3 shows the result of an image pattern for a leaky pipe condition. The red rectangle in the table represents the detection of hyperbolas in radargrams. The GPR radargram image indicates that the hyperbola pattern of the HDPE conduit has been disrupted by water leakage, particularly on sandy soil. This might be attributed to HDPE's relatively low conductance and sandy soil's high permeability. Concurrently, the GPR radargram image on clay soil remains unhindered, particularly on the iron pipes. This is probably due to the soil's smaller particle size and denser structure than sand. Table 4 shows the parameters retrieved from the radargram for the leaky pipe condition. These parameters allow us to calculate the dielectric constant. Figures 5 and 6 depict 3D representations of water-leaking pipelines in clay and sandy soil. The GPR image provided allows for assessing the water permeability in the soil by analyzing the variation in GPR signal amplitude.

Table 3. Image hyperbolic pattern for leaking pipe.

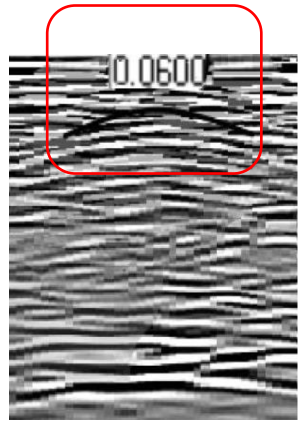
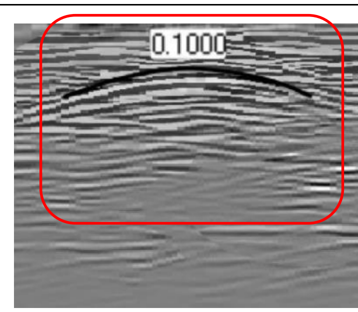
Types of pipe	Condition	Image radiation
HDPE pipe	Buried in clay soil	
	Buried in sandy soil	
Metal pipe	Buried in clay soil	
	Buried in sandy soil	

Table 4. Parameters extracted from radargram for leaking pipe.

Pipe	HDPE pipe		Metal pipe	
Material	Clay soil	Sandy soil	Clay soil	Sandy soil
Time (ns)	17.613	10.333	11.507	9.393
Velocity (m/ns)	0.060	0.060	0.100	0.110
Estimated depth (m)	0.528	0.310	0.345	0.282
Dielectric constant of soil	25.000	25.000	9.000	7.438

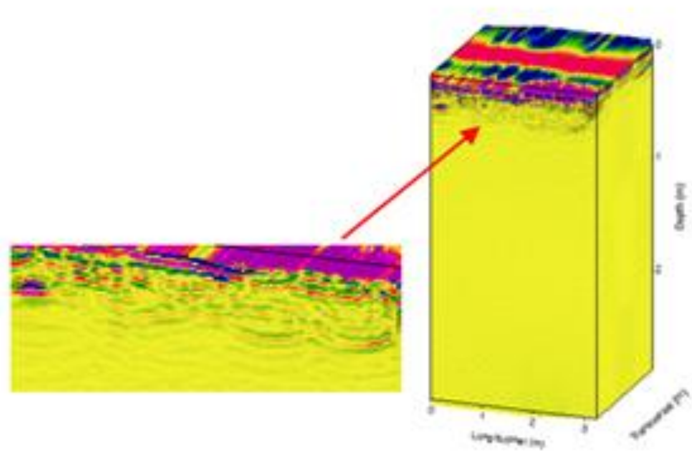


Figure 5. 3D images of water leaking pipes in clay soil.

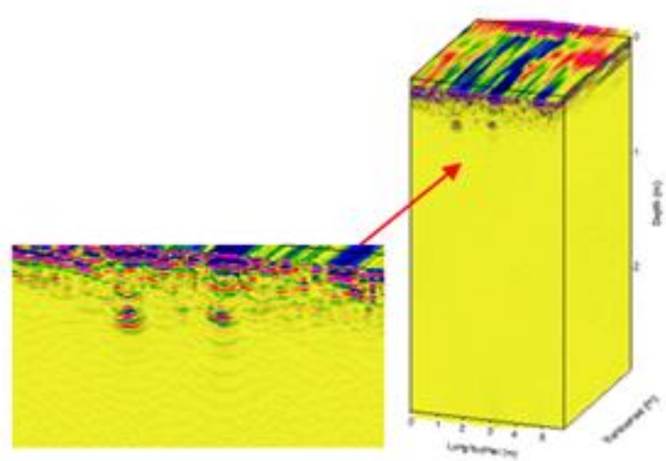


Figure 6. 3D images of water leaking pipes in sandy soil.

4.0 Conclusion and Recommendation

As previously stated, Malaysia's ground comprises several soil layers, which will produce a diverse set of scattering data after GPR penetration. To underline the finding, it is necessary to return to the study's original purpose, assessing the feasibility of using GPR to identify water leaks. The image generated by data gathering will show the changes in soil layers in a hyperbola form. The GPR image can be used to identify the presence of water leakage in the sub-soil, as the GPR image signal transitions from a normal condition without leaking water (which appears to have less noise) to a hyperbolic image pattern that is significantly more uncertain and unclear (which seems to have more noise). The fundamental idea of GPR is based on the transmission power emitted as a radar signal, which is highly effective for subsurface detection. Freshwater will be used in this simulation to mimic the circumstance of water leaking. Many materials were used in the simulation procedure. This demonstrates that GPR may be used to detect water leaks in any soil.

This project investigates whether GPR can detect water leakage patterns in underground distribution networks. As a result, the intended consequence of this investigation is that GPR efficiently detects water leakage patterns in HDPE and metal pipes in two unique soils. The first objective is to assess the validity and effectiveness of GPR technology in detecting water leakage patterns. This study demonstrates that GPR could be one of the best techniques for detecting water leaks without requiring extensive ground excavation, and the data would be displayed in real-time. During the survey, a mark might be made on the ground in real-time. In addition, GPR has a dual frequency that can be used in various applications.

The second objective was to analyze the water leakage pattern from HDPE and metal pipes in two different soils using the result radargram images created by Reflex W software. The GPR screen would serve as the design for an electromagnetic wave. The hyperbolic curves, depth, and scanning distance can be calculated using the data of this radargram image. The data will be analyzed using the Reflex W and Reflex 3D Scan applications. This software will allow us to detect pipe water leaks. Furthermore, using this software, we can describe the shape of hyperbolic peaks.

The study's ultimate goal was to compare water leakage patterns to those found in prior studies. Water leakage patterns for additional pipes and soil materials can be analyzed. Competence is required to deliver a compelling interpretation. As a result, the employment of GPR equipment for scientific and educational study should be considered, especially for advanced education.

Furthermore, it would aid the authorities in various ways, such as providing updated records and assuring the safety of the water supply system. The pipe leakage simulation design, installation, and testing are complete. GPR performance testing has demonstrated its ability to assist in utility positioning operations.

As a result, the goals of this study were achieved—the hyperbolic image pattern formed by the backscattered buried pipe in the test bed. The graphic depicts the difference between a normal and a leaking pipe. The resulting image shows that when there is a water leak, the image is crisper, and the hyperbolic pattern appears more beautiful and sharper than when there is no leak. Tables 2 and 4 show that metal pipes are more easily identified using GPR than HDPE pipes in both situations. GPR depth penetration is often limited to a few tens of meters and is mainly determined by electrical conductivity.

To ensure the reliability and accuracy of the water leakage patterns of this study, it might be beneficial to compare detection using WIRED-tested smart water sensors in the future. Determine the accuracy of GPR instruments regarding depth determination to another water leakage instrument. A study can also be carried out on the pressure effect as it might influence the result and the dimension and depth design of the buried pipe.

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