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Application of Ground Penetrating Radar (GPR) and 3D Modelling in Pipeline Detection for Seismic-Resilient Urban Infrastructure

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Taiwan is located at the boundary between the Eurasian Plate and the Philippine Sea Plate, resulting in frequent seismic activity and increasing risks to aging underground infrastructure, particularly in liquefaction-prone areas. To address these challenges, Taipei City has mandated Ground Penetrating Radar (GPR) inspections for construction projects to assess subsurface conditions and underground utilities. This study aims to enhance the reliability of GPR in urban subsurface investigations through a combination of literature review, sandbox experiments, and field validation. Controlled indoor sandbox tests and LIDA case data were used to evaluate the accuracy of pipeline detection and material identification. Key parameters of buried pipelines and surrounding soils were analyzed using digital signal processing techniques. Furthermore, GPR data were integrated with 3D modeling to reconstruct spatial distributions of underground utilities. The results demonstrate that the proposed approach improves detection accuracy and provides a practical framework for mapping urban subsurface infrastructure. This study contributes to reducing risks associated with aging underground facilities and supports the development of earthquake-resilient urban infrastructure management.

Keywords: Ground Penetrating Radar, Underground Pipeline Detection, Sandbox Experiment, Signal Processing, 3D Reconstruction

1 Introduction

Taiwan is located at the boundary between the Eurasian Plate and the Philippine Sea Plate, making it one of the most seismically active regions worldwide. In addition to frequent earthquakes, extreme weather events such as typhoons and heavy rainfall further exacerbate the vulnerability of underground infrastructure systems. Aging buried pipelines, particularly in urban and liquefaction-prone areas, pose significant risks to public safety, infrastructure stability, and emergency response efficiency. Consequently, accurate and reliable detection of underground utilities has become an essential task for modern urban management and disaster prevention.

Ground-penetrating radar (GPR) has been widely adopted as a non-destructive testing (NDT) technique for subsurface investigation due to its rapid detection capability and minimal disturbance to the ground (Jol, 2009; Utsi, 2017). However, the performance of GPR is strongly influenced by subsurface conditions, including soil type, moisture content, and heterogeneity (Hassan et al., 2023). Signal attenuation, clutter noise, and interpretation uncertainty often reduce detection accuracy, especially in complex urban environments (Siow and Hashim, 2013). Previous studies have applied GPR for underground utility detection and road condition assessment (Alsharahi et al., 2021; Amelia et al., 2022). In addition, recent advancements have incorporated machine learning and 3D reconstruction techniques to improve detection accuracy and interpretation efficiency (Lei et al., 2024; Zhou et al., 2024). Nevertheless, many studies focus either on laboratory simulations or field applications, lacking integrated validation.

To address these limitations, this study aims to develop an integrated framework for improving underground pipeline detection using GPR. By combining controlled sandbox experiments, advanced signal processing techniques, and field validation through excavation, this research systematically evaluates GPR performance under both idealized and realistic conditions. In addition, three-dimensional (3D) reconstruction is employed to enhance spatial interpretation. The proposed methodology not only improves detection accuracy but also provides a practical reference for infrastructure inspection and urban underground management. This study also aligns with the emerging trend of integrating digital technologies into smart infrastructure management.

2 Methodology

2.1 *GPR System and Data Processing*

The GPR system adopted in this study consists of a MALÅ ProEx control unit equipped with 500 MHz and 800 MHz shielded antennas. The selection of dual-frequency antennas allows a comprehensive comparison between

penetration depth and resolution. Specifically, the 500 MHz antenna is capable of detecting deeper subsurface targets, whereas the 800 MHz antenna provides higher resolution for shallow objects.

Raw GPR data are typically affected by noise and background interference; therefore, signal processing is essential to enhance data interpretability (Maruddani and Sandi, 2019). In this study, ReflexW software was employed to perform a series of data processing procedures (see **Fig. 1**), including:
(1) Dewow filtering, which removes low-frequency components caused by system drift;
(2) Background removal, which eliminates consistent horizontal noise;
(3) Gain adjustment, which enhances weak reflections at deeper depths; and
(4) Static correction, which aligns reflection signals for accurate depth estimation.

These processing techniques significantly improve signal clarity and facilitate the identification of hyperbolic reflections associated with buried pipelines.

2.2 Sandbox Experiment

To systematically investigate the response characteristics of GPR signals, controlled sandbox experiments were conducted. A rectangular sandbox was prepared and filled with dry, homogeneous sand to minimize external variability. PVC pipes with different diameters and burial depths were embedded within the sandbox to simulate underground pipeline conditions. Various configurations, including single-pipe and multi-pipe arrangements, were tested to evaluate signal interference and detection capability.

GPR surveys were performed along predefined linear paths above the embedded pipes. The controlled environment of the sandbox allows precise evaluation of the relationship between radar signal patterns and physical parameters such as depth, diameter, and spacing. In particular, the characteristic hyperbolic reflection patterns were analyzed to establish interpretation criteria. The sandbox results serve as a calibration reference for subsequent field investigations.

2.3 Field Investigation and Validation

Field investigations were conducted in a real urban environment to validate the applicability of the proposed methodology. Survey lines were arranged based on site accessibility and expected pipeline distribution. GPR measurements were performed using the same equipment and parameters as those used in the sandbox experiments to ensure consistency.

To verify the accuracy of GPR interpretation, selected locations were excavated after the survey. The actual positions, depths, and orientations of pipelines were recorded and compared with the GPR results. This validation process provides a direct assessment of detection accuracy.

Furthermore, multiple radar profiles were integrated to reconstruct three-dimensional (3D) models of the underground pipelines. The 3D visualization enhances the understanding of spatial relationships and improves interpretation efficiency, particularly in complex subsurface environments.

3 Results and Discussion

3.1 Sandbox Test Results

The sandbox experiment results clearly demonstrate that buried pipelines produce distinct hyperbolic reflections in GPR profiles. These reflections are consistent with theoretical expectations (Jol, 2009). After applying signal processing techniques, the clarity and continuity of the hyperbolic patterns are significantly improved.

A comparison between different antenna frequencies shows that the 800 MHz antenna provides superior resolution, enabling more accurate identification of shallow and small-diameter pipes. In contrast, the 500 MHz antenna exhibits better penetration capability, making it more suitable for detecting deeper targets. These findings highlight the importance of selecting appropriate antenna frequencies based on detection requirements.

3.2 3D Reconstruction

By integrating multiple two-dimensional radar profiles, a three-dimensional reconstruction of the underground pipeline system was successfully achieved. The resulting 3D models provide a more intuitive representation of pipeline geometry, orientation, and spatial relationships.

In this study, the 3D reconstruction integrates radar data obtained from both 500 MHz (Zone A: L1–L6 line) and 800 MHz (Zone A: L7–L12 line) antennas, allowing deeper subsurface features detected by the 500 MHz antenna and high-resolution shallow features identified by the 800 MHz antenna to be visualized simultaneously, thereby providing a more comprehensive representation of subsurface conditions. First, the processed radar profiles were stacked to generate a three-dimensional visualization using ReflexW (**Fig. 2**), enabling the identification of continuous subsurface anomalies across different survey lines. Subsequently, a conceptual 3D model was developed using SketchUp (**Fig. 3**) to further illustrate the spatial distribution of underground pipelines and the box culvert.

The reconstructed results clearly reveal the interface between the asphalt layer and the base course, the location of the box culvert, and a deeper pipeline interpreted as a high-voltage conduit. In particular, the 800 MHz data exhibit superior capability in delineating pipeline geometry, as the hyperbolic diffraction patterns are more distinct compared to those obtained from the 500 MHz data, which are more affected by heterogeneous soil conditions.

This approach effectively enhances interpretation efficiency and reduces the uncertainty associated with traditional 2D analysis. Furthermore, 3D visualization facilitates clearer communication of results to engineers and decision-makers. The findings are consistent with recent developments in 3D GPR analysis and automated subsurface interpretation (Zhou et al., 2024; Liu et al., 2024). This demonstrates the effectiveness of integrating multi-frequency GPR data with 3D reconstruction techniques.

3.3 Field Verification Results

Field verification results indicate strong agreement between GPR detection and excavation observations. The identified pipeline locations and burial depths are generally consistent with actual measurements, confirming the reliability of the proposed approach. This is consistent with previous studies on GPR accuracy (Siow and Hashim, 2013). Photographic evidence obtained after excavation further supports these findings, including the measured burial depth of the pipelines (**Fig. 4(a))** and the measured horizontal distance from the survey starting point to the pipeline location (**Fig. 4(b)**). Excavation confirmed the presence of two 3-inch PVC pipes beneath Area A.

Specifically, between survey lines L4 and L5, field measurements indicate that the vertical distance from the ground surface to the top of the pipeline is approximately 68 cm, while the horizontal distance from the survey starting point is approximately 60 cm. These measurements are consistent with the previously identified anomaly highlighted by the red circle in the interpreted radargram, confirming that the feature corresponds to the detected pipeline.

In addition, during excavation between survey lines L3 and L4, a box culvert was encountered, as shown in **Figs. 5–7.** The depth of the box culvert is approximately 32 cm, and its location is consistent with the anomalies identified in the previously interpreted radargram.

However, discrepancies are observed in certain areas, particularly where soil conditions are highly heterogeneous or moisture content is elevated. In such environments, signal attenuation increases, and reflection patterns become less distinct. These results suggest that environmental conditions play a critical role in GPR performance and must be carefully considered in practical applications.

4 Conclusions

This study presents an integrated framework for improving underground pipeline detection using GPR through the combination of sandbox experiments, signal processing, and field validation. The results demonstrate that GPR is an effective tool for non-destructive subsurface investigation when appropriate processing techniques are applied.

Sandbox experiments provide a controlled environment for calibrating radar signal interpretation, while field validation confirms the applicability of the method in real-world conditions. The use of dual-frequency antennas allows a balance between resolution and penetration depth, enhancing detection capability.

Despite its effectiveness, the performance of GPR is significantly influenced by soil conditions. In highly saturated or heterogeneous soils, signal attenuation reduces detection accuracy. Therefore, GPR may not be sufficient as a standalone method in complex environments.

Future research should focus on improving detection performance under challenging conditions, including the integration of machine learning techniques (Lei et al., 2024) for automated signal interpretation and the development of real-time monitoring systems. The incorporation of digital twin technology may further enhance the applicability of GPR in smart infrastructure management. The proposed framework provides a practical reference for urban underground infrastructure management and contributes to improving seismic resilience in complex urban environments.

5 Figures and Photographs

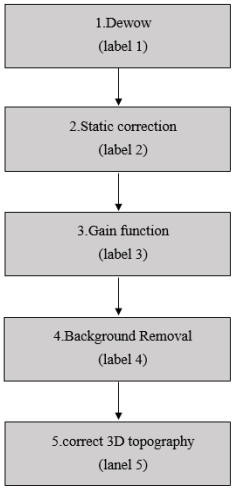


Figure 1. ReflexW post-processing workflow diagram.

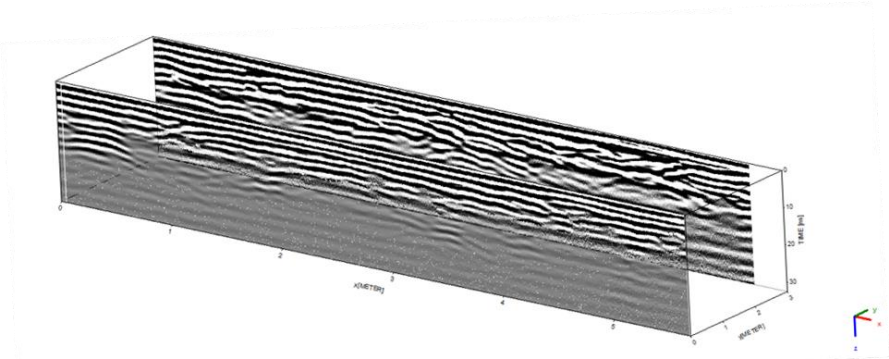
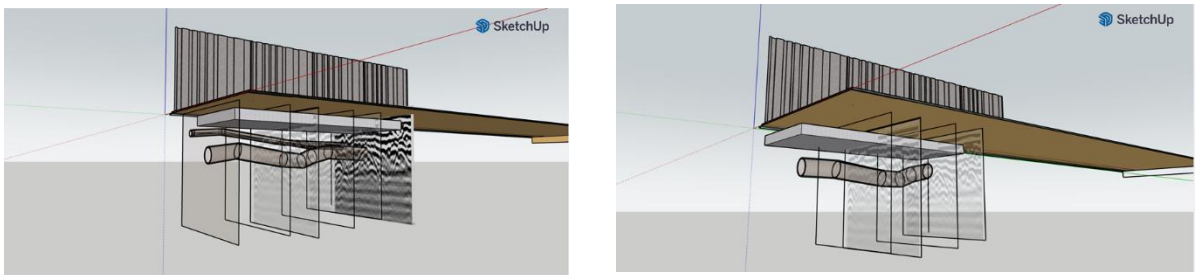


Figure 2. 3D stacked visualization generated using ReflexW.



(a) Zone A **(b) Zone B**

Figure 3. Radar profile before and after signal processing.

(a) **(b)**

Figure 4. (a) Photograph of pipeline depth measurement after excavation in Area A; **(b)** Photograph of the measured distance from the survey starting point to the pipeline location in Area A.

Figure 5. Photograph showing the box culvert identified in Area A.

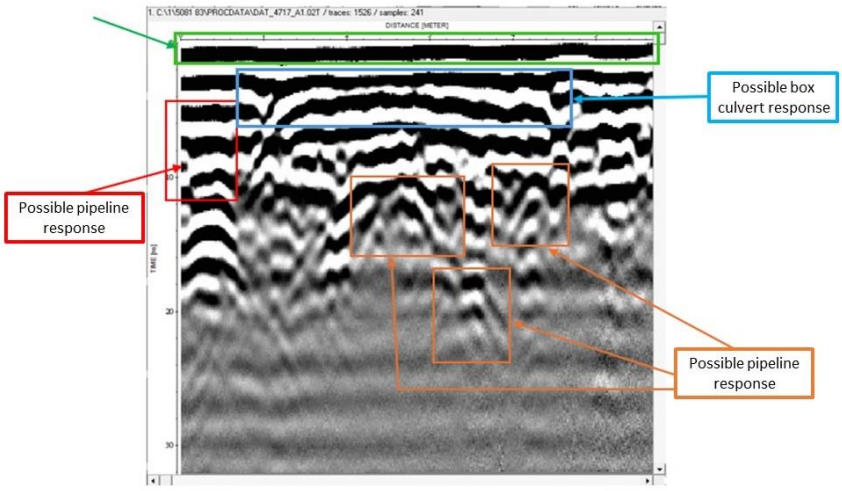


Figure 6. GPR profile along survey line L3 in Area A.

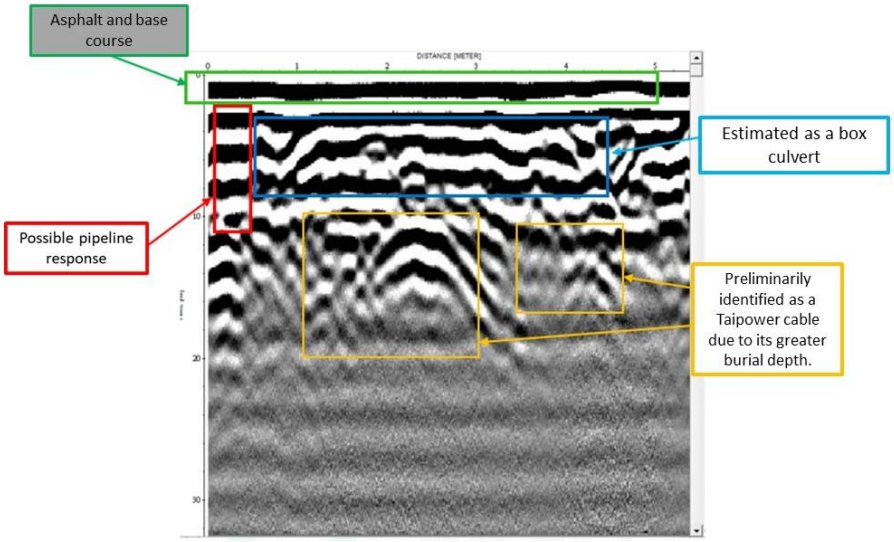


Figure 7. GPR profile along survey line L4 in Area A.

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