MULTI-METHOD APPROACH FOR UNDERGROUND UTILITY ASSESSMENT: COMBINING GROUND PENETRATING RADAR AND ELECTRCIAL GEO-RESISTIVITY SURVEY

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ABSTRACT

Underground utility condition assessment is critical for ensuring the reliability and safety of water distribution systems, particularly in urban environments where excavation is challenging. This study explores the combined application of Ground Penetrating Radar (GPR) and Electrical Geo-Resistivity Tomography (ERT) as a non-destructive method to enhance underground pipeline assessment, focusing on leak detection and pipe alignment verification.

The study was conducted as part of a leak repair exploratory project, where conventional methods, such as Sahara leak detection, were initially employed but yielded inconclusive results regarding pipe alignment and leak location. To improve accuracy, GPR and ERT were introduced to map subsurface structures, identify indicative leak locations, and optimize the repair strategy.

The GPR survey utilized an 80mm frequency radar, transmitting signals into the subsurface at depths of up to 15 meters. The reflected signals provided variations indicating unique lithological or structural characteristics, enabling the detection of buried materials and subsurface discontinuities. Complementing this, the ERT survey used a pole-to-pole shifting array method, covering 180-200 meters, to generate resistivity profiles that highlighted areas of potential leakage based on moisture content variations.

The combined GPR and ERT approach proved effective in narrowing down exploration areas, significantly reducing unnecessary excavation and enhancing leak detection precision. The GPR survey identified two distinct pipe alignments at depths of 4 to 8 meters, while ERT data pinpointed high-moisture zones, confirming leakage points. Subsequent test pitting and trenching validated these findings, revealing subsurface water accumulation and pipe damages at the identified locations.

By integrating multiple non-destructive testing techniques, the study successfully optimized leak repair efforts, reduced project costs by 80%, and minimized excavation work. These findings highlight the value of advanced geophysical surveys in pipeline maintenance strategies, particularly in densely built environments where direct excavation is impractical. The methodology employed serves as a model for future underground utility condition assessments, reinforcing the importance of adopting multi-method approaches to improve water infrastructure resilience and long-term sustainability..

1. INTRODUCTION

The maintenance of water infrastructure pipelines in highly urbanized areas presents significant challenges to the continuity of water supply and can pose public health risks (Lai et al., 2016; Jaw & Hashim, 2014). In the Philippines, numerous underground pipelines, some dating back to the 1960s, lack comprehensive documentation on their exact location, structural condition, and repair history. Rapid urban development further complicates pipeline assessment, as discrepancies between outdated as-built drawings and current site conditions hinder accurate infrastructure mapping. Conventional pipeline investigation methods, such as trenching and excavation, are inherently destructive and may exacerbate safety concerns, including road subsidence and the formation of soil cavities (Zhang et al., 2024).

Pipeline condition assessment methodologies generally fall into destructive and non-destructive techniques. According to the United States Environmental Protection Agency (USEPA), non-destructive testing (NDT) methods are increasingly preferred for water pipeline evaluation due to their minimal impact on surrounding infrastructure (Thomson et al., 2009). NDT options include acoustic emission (AE), eddy currents (EC), electromagnetic methods (EM), impact-echo (IE), hammer sounding (HS), magnetic flux (MF), sonar methods (SM), ultrasonic testing (UT), pulsed induction methods (PIM), magnetic locators (ML), resistivity methods (RM), radiographic testing (RT), pipeline inspection gauges (PIGs), and ground penetrating radar (GPR). The choice of method is contingent upon pipe size and material, for example, EC and UT are most applicable to metallic pipes, while AE, IE, sonar, and visual inspection are more suited for concrete pipelines (Rizzo, 2010).

Ground penetrating radar (GPR) is a non-destructive geophysical technique that employs high-frequency electromagnetic (EM) waves to detect subsurface anomalies. The system transmits EM pulses from a surface antenna, which travel through the ground and are partially reflected upon encountering boundaries with contrasting dielectric properties. The travel time and amplitude of these reflections vary according to the composition, geometry, and moisture content of the subsurface materials, enabling detailed profiling of buried features (Turesson, 2006). GPR is particularly effective for pipeline detection in densely built urban environments, irrespective of pipe material (Zhang et al., 2024).

In addition to pipeline localization, electrical resistivity tomography (ERT) can be employed to assess subsurface conditions when pipelines have sustained damage, such as leakage. ERT is a geophysical technique that measures the ground's resistance to electrical current flow by inserting electrodes into the ground, injecting a controlled current, and recording the resulting potential differences. Electrical resistivity is influenced by factors such as moisture content, porosity, salinity, and fracture density. Water-saturated zones typically exhibit low resistivity, whereas dry, intact rock masses show higher resistivity values (Arifin et al., 2016).

ERT has proven particularly valuable in hydrogeological investigations as a non-invasive method for detecting and characterizing subsurface water-bearing zones, defining aquifer geometry, and assessing related properties. Variations in electrical conductivity can reveal groundwater presence, delineate aquifer boundaries, and differentiate between saturated and unsaturated geological layers (Turesson, 2006; André et al., 2012; Carrière et al., 2013). When combined with GPR, ERT provides complementary depth penetration and material discrimination capabilities, enhancing the accuracy of subsurface mapping (André et al., 2012; Carrière et al., 2013).

2. METHODOLOGY

This study employed non-invasive geophysical techniques, Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT), to determine the alignment, assess the subsurface condition, and detect potential leakage zones of the Pipeline. The methodological framework was adapted to site-specific constraints and is supported by established best practices in subsurface utility investigations (Arifin et al., 2016; Turesson, 2006; Carrière et al., 2013).

2.1 Preliminary Site Inspection and Documentation

2.1.1 Objectives

The site inspection aimed to:

a) Identify the probable pipeline alignment along the western easement of the Railway.
b) Document surface conditions, vegetation cover, and the presence of natural or man-made obstacles.
c) Establish survey boundaries and reference points for geophysical measurements.

2.1.2 Procedure

The initial ocular inspection involved walking the full accessible length of the suspected alignment, noting topographic variations, soil type changes, drainage features, and man-made obstructions as shown in Fig 2.1.2.1. A handheld GPS unit was used to record positional coordinates of key features such as road crossings, access points, and possible anomaly sites. This inspection stage also included selection of feasible survey lines, avoiding areas where physical constraints such as steep embankments, dense vegetation, or private structures would prevent proper equipment deployment. The findings informed the optimal antenna frequency for GPR and the array configuration for ERT based on expected burial depth, soil composition, and interference risks.

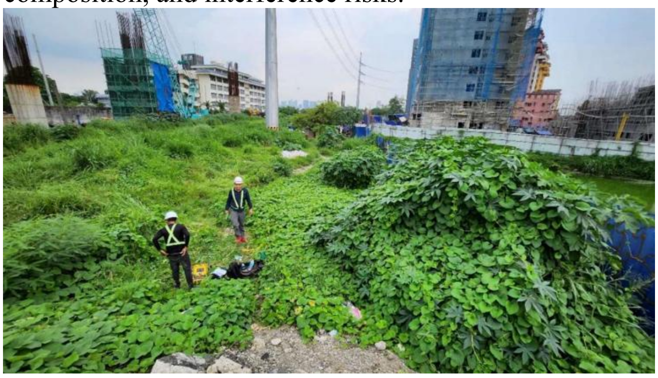

Figure 2.1.2.1 Estimated Pipeline alignment (center). Excavation site of affected property with water accumulation is visible on the right, and the Railway with transmission line on the left. Photo taken from the top of the backfill stockpile prior to removal.

Figure 2.1.2.2 Pipeline crossing the Pasig River, located approximately 80 m from the southern end of the target section.

2.2 Site Observations

The survey corridor is located along the western easement of the Railway, partially shared with an overhead transmission line. The study section extends from the northern limit at an underpass connection to the southern limit approximately 80 m from the bank of the Pasig River as shown in figures 2.2.1 and 2.2.2.

2.2.1 Survey Staging and Access Conditions

During the initial GPR calibration, the staging area at the northern segment, which also served as a parking lot, was selected for detecting the presence and possible location of the underground utility. For the subsequent ERT survey, vegetation along the proposed survey line was gradually cleared during the first day of equipment calibration. Concurrently, removal of a 3–4 m high backfill stockpile began on the second and third days of ERT operations. ERT traverse lines originated at the foot of the backfill stockpile and extended toward the Pasig River for up to 200 m.

Even after most backfill material was removed, the newly exposed surface was considered suboptimal for ERT due to insufficient compaction and high moisture content. Following completion of the ERT survey, a second GPR campaign targeted specific segments of the ERT alignment where preliminary results suggested possible leakage along the Pipeline. By this time, the base of the excavation had been compacted, and the survey area extended from the former backfill location to the vicinity of the Transmission Line Tower. Concurrently, removal of informal residential structures near the alignment was observed.

Figure 2.2.1 Northern section of the Pipeline segment under study, outlined in red.

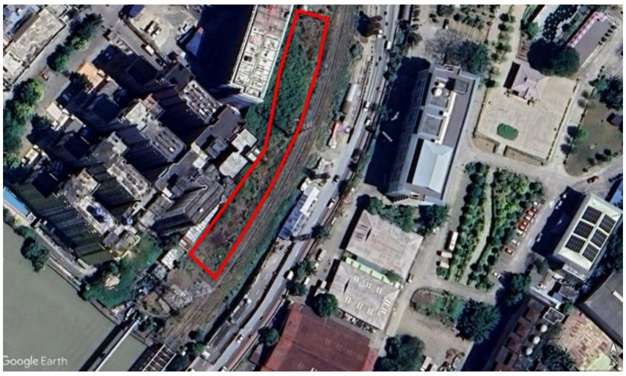

Figure 2.2.2 Southern section of the Pipeline segment under study, outlined in red.

2.2.2 Subsurface Conditions

The subsurface geology is part of the Guadalupe Formation, which underlies most of the gently rolling terrain of Sta. Mesa and extends eastward toward Quezon City. The formation consists of fine- to medium-grained tuffaceous sandstone, locally known as “Adobe,” visible in nearby Skyway Project excavations adjacent to the Railway and study area. This bedrock is overlain by a combination of natural soil and backfill material, the latter likely placed to provide a consistent grade for the Railway and associated utilities, including the transmission pipeline. Geomorphologically, the Sta. Mesa area is characterized by low, undulating terrain (low mesa features) extending toward San Juan and Mandaluyong, historically referred to as “Hagdang Bato” and “Mesa,” descriptive of its stepped and elevated landscape.

2.2.3 Environmental Considerations

Weather conditions during the survey period were predominantly dry, providing favorable conditions for GPR penetration and stable surface access. Isolated low-lying areas exhibited localized soil saturation, likely due to perched water or subsurface seepage, which could influence ERT resistivity measurements. Slight moisture content in some sections improved electrode contact for ERT but could cause attenuation of GPR signals in saturated zones. Dense vegetation present during the first survey limited initial accessibility and required clearing before equipment deployment. Proximity to overhead transmission lines and railway electrification infrastructure introduced potential sources of electromagnetic interference, which were mitigated through careful line placement and post-processing signal filtering.

2.3 Ground Penetrating Radar (GPR) Survey

2.3.1 Equipment and Configuration

A time-domain GPR system equipped with a 250 MHz shielded antenna was selected to provide an optimal balance between spatial resolution and penetration depth under mixed urban soil conditions. This configuration enables the detection of large-diameter utilities at depths of approximately 3.5–4.0 m, with sufficient resolution to delineate pipeline geometry and associated bedding materials.

2.3.2 Survey Layout and Ground Preparation

Survey transects were oriented perpendicular to the estimated pipeline alignment to maximize the visibility of hyperbolic reflection signatures. Line spacing was determined to ensure overlap between adjacent transects, enabling the interpolation of subsurface anomalies across the survey area. Ground preparation included clearing dense vegetation, removing loose debris, and leveling uneven terrain to improve antenna-ground coupling and reduce signal scattering.

During the first survey campaign, five GPR transects were established perpendicular to the Pipeline alignment. The GPR antenna was traversed along each line to transmit radar signals into the subsurface and record the reflected responses from buried features. Detected pipeline positions were marked in the field and later plotted on a site map shown in figures 2.3.2.2 to 2.3.2.6. Initial results indicated the presence of two distinct buried objects at depths of approximately 5–6 m. Interpolated cross-sectional profiles for all transects were organized from the northernmost to the southernmost line to correspond with their mapped positions. Field-recorded offsets in GPR profiles were subsequently corrected as shown in figure 2.3.2.1 during data processing to ensure accurate spatial alignment.

A second survey was conducted after the completion and preliminary interpretation of ERT results, with transects positioned at the hypothesized leakage location near the excavation site and NGCP tower. Four perpendicular transects were established in this campaign, confirming the presence of two buried objects at depths of approximately 5–6 m within the easement area. As in the first survey, profiles were organized sequentially from north to south, and field offsets were rectified during post-processing.

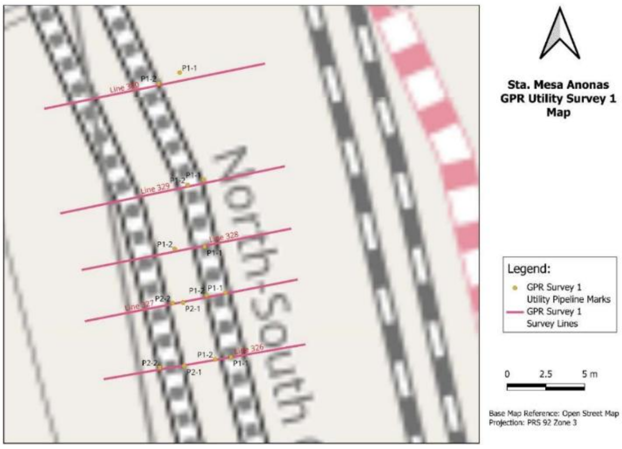

Figure 2.3.2.1 Northern section of the Pipeline segment under study, outlined in red.

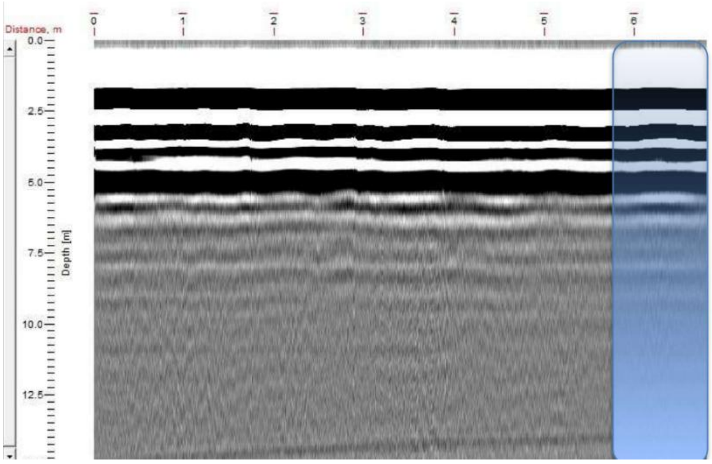

Figure 2.3.2.2 GPR Line 330 showing anomaly located 8.5 m from the Railway

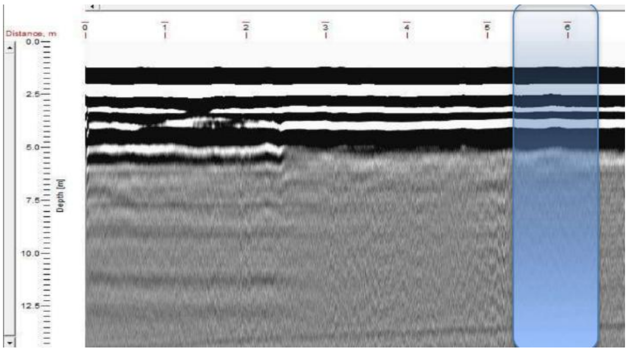

Figure 2.3.2.3 GPR Line 329 showing anomaly located 9.2 m from the Railway

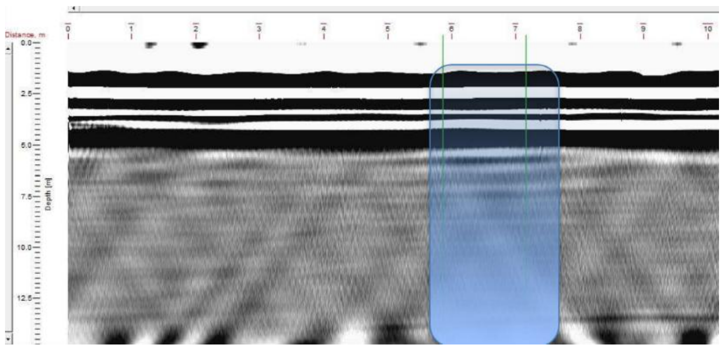

Figure 2.3.2.4 GPR Line 328 showing anomaly located 9.2 m from the Railway

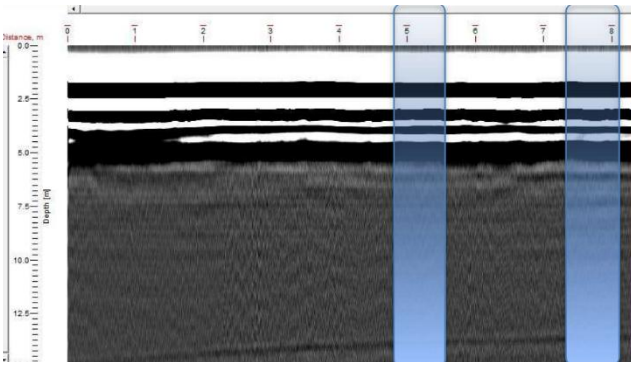

Figure 2.3.2.5 GPR Line 327 showing double anomaly located at 5.8 m and 9.2 m from the Railway

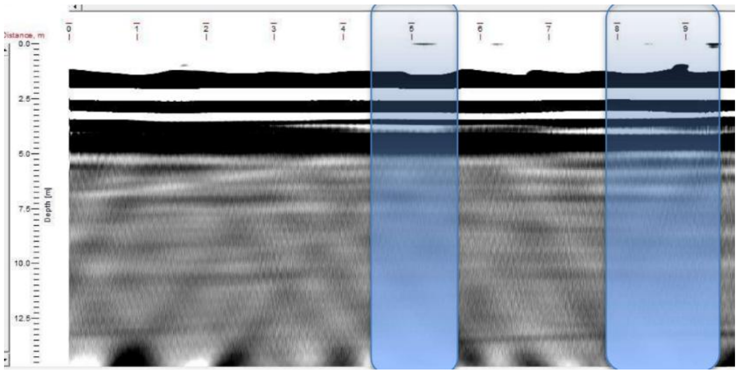

Figure 2.3.2.6 GPR Line 326 showing double anomaly located at 5.6 m and 9.6 m from the Railway

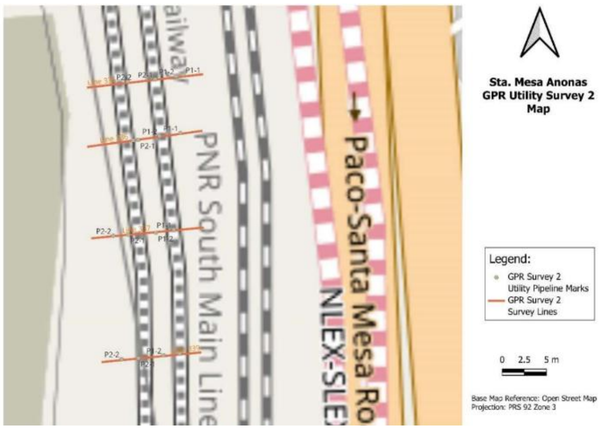

Figure 2.3.2.7 Second GPR survey lines (335, 336, 337, 339) with possible Pipeline locations marked in gray.

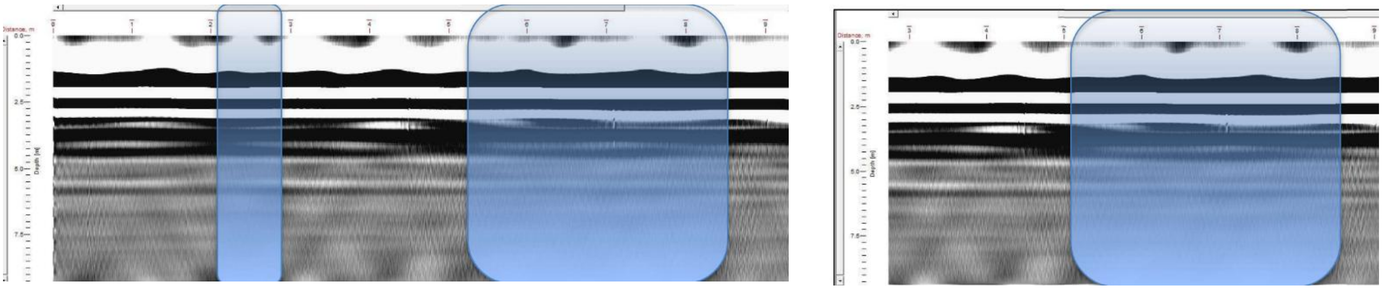

Figure 2.3.2.8 GPR Line 335 showing double anomaly at 2.0–2.8 m and 5.2–8.4 m starting 2.773 m from the Railway

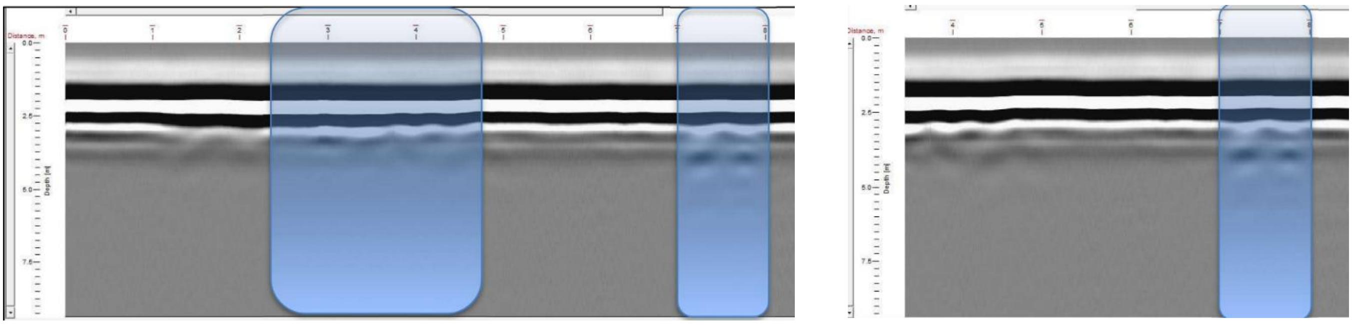

Figure 2.3.2.9 GPR Line 336 showing double anomaly at 2.4–4.8 m and 7.2–7.8 m starting 2.81 m from the Railway

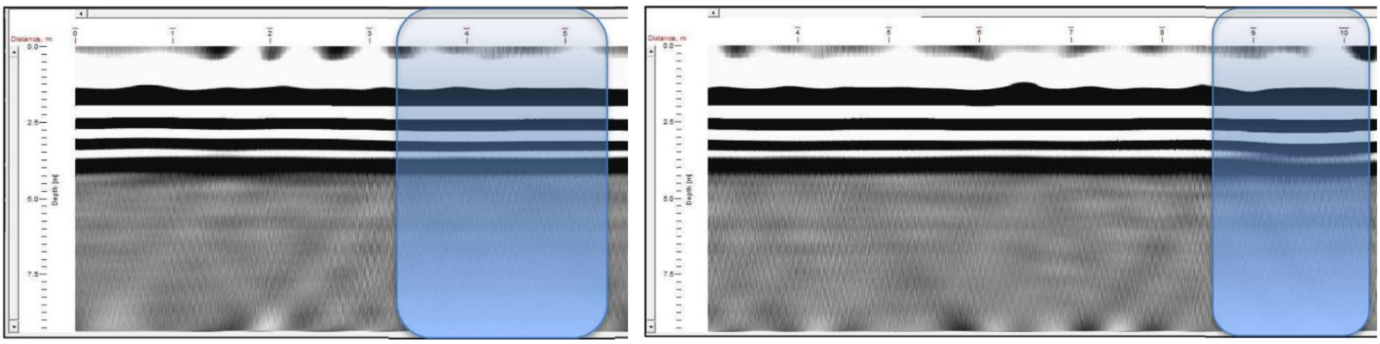

Figure 2.3.2.10 GPR Line 337 showing double anomaly at 3.2-5.2 m and 8.4-10 m starting at 15.26 m from the Railway

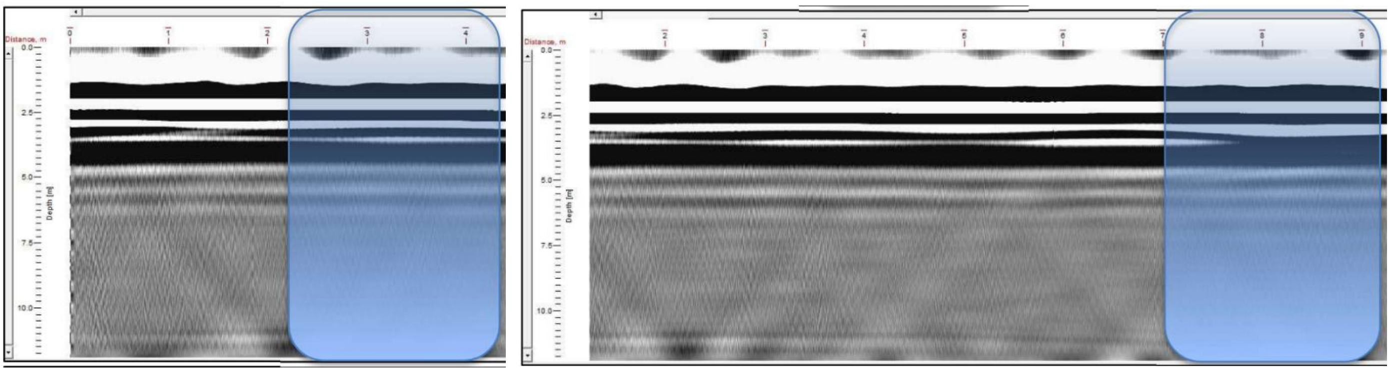

Figure 2.3.2.11 GPR Line 339 showing double anomaly at 2.2-4.2 m and 7-9 m starting at 4.95 m from the Railway

2.3.3 Data Acquisition

Data collection was conducted in single-pass mode with continuous recording along each transect. Real-time monitoring allowed field operators to identify sections with excessive noise or signal attenuation, which were re-surveyed immediately to ensure data quality. Calibration scans were carried out in open, obstruction-free areas to determine electromagnetic wave velocities, which were later used to calculate depth estimates for detected anomalies.

2.3.4 Target Depth and Interpretation

The survey targeted the 0–5 m depth range, corresponding to the expected burial depth of the 1350 mm transmission main. Indicators used to identify the pipeline included:

a) Continuous hyperbolic reflections of consistent depth and geometry.
b) High-amplitude reflections compared to surrounding soils.
c) Correlation with available engineering records where possible.

Post-processing involved time-zero correction, background removal, gain adjustments, and migration to enhance reflector clarity. Pipeline locations were confirmed when hyperbolic signatures of similar depth and form were consistently detected across multiple perpendicular transects.

2.4 Electrical Resistivity Tomography (ERT) Survey

2.4.1 Equipment and Array Configuration

ERT measurements were conducted using an AEMC Ground Tester Model with stacking capabilities to suppress noise. A Pole-Pole array was chosen for its flexibility in constrained rights-of-way and suitability for detecting elongated anomalies along a corridor.

2.4.2 Survey Line Setup

Active electrodes (C1 and P1) were positioned at 10 m intervals along the survey line, while remote electrodes (C2 and P2) were placed at distances at least 10 times greater than the maximum active electrode spacing to approximate ideal pole-pole conditions. Peg markers were installed to designate electrode positions. In compacted or rocky soils, shallow auger holes were prepared to improve contact resistance, and moisture was applied where necessary to enhance conductivity.

2.4.3 Data Acquisition and Target Depth

The ERT system was configured to achieve penetration depths of up to 30 m, with the highest resolution in the upper 10 m where leakage effects were expected. Multiple stacks were recorded at each electrode position to reduce random noise and stabilize readings.

2.4.4 Data Processing and Interpretation

Measured resistivity values were inverted using RES2DINV to produce two-dimensional resistivity profiles. Interpretation focused on:

A. Low-resistivity anomalies indicative of increased moisture or soil saturation potentially linked to pipeline leakage.
B. Resistivity gradients suggesting material changes, voids, or trench backfill boundaries.
C. Anomalies were considered significant only when their location corresponded with the suspected pipeline alignment or when corroborated by GPR results.

2.5 Integration of GPR and ERT Results

The combined use of GPR and ERT maximized interpretative reliability by leveraging the strengths of each method:

A. GPR Strengths: High-resolution imaging of shallow subsurface structures capable of resolving pipe geometry and immediate surrounding soil conditions.
B. ERT Strengths: Greater depth penetration enabling detection of leakage plumes and broader zones of altered moisture content beyond the immediate pipe zone.

The integration process involved:
Spatial Alignment: GPR transects and ERT profiles were georeferenced to a common baseline.
Cross-Validation: Anomalies detected in one dataset were checked against the other. For example, a low-resistivity zone in ERT was confirmed by the presence of disrupted or attenuated reflections in GPR.
Anomaly Classification:
Confirmed Utility: GPR hyperbola with ERT resistivity contrast.
Potential Leakage Zone: ERT low-resistivity anomaly with adjacent GPR signal attenuation or void signature.
Non-Utility Feature: Isolated anomaly in one dataset without corresponding evidence in the other.

This integrated interpretation reduced false positives from site-specific interferences such as metallic debris in GPR or saline contamination in ERT, producing a more robust assessment of the pipeline's condition.

3. RESULTS

The integrated Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) surveys provided complementary datasets for identifying subsurface anomalies, assessing lithological conditions, and evaluating possible leakage zones along the Pipeline alignment.

3.1 GPR Findings

The first GPR survey, conducted perpendicular to the Pipeline alignment, revealed two distinct subsurface reflectors at depths of approximately 5–6 m. These anomalies were consistently detected across multiple transects, showing strong spatial correlation to the estimated pipeline alignment.

The second GPR campaign, conducted after preliminary ERT interpretation, targeted a hypothesized leakage zone near the excavation site and NGCP tower. Four perpendicular transects confirmed the presence of the same two buried features, with depth and position consistent with the initial survey. Several transects indicated localized signal attenuation, possibly related to disturbed or moisture-rich soils.

Interpretation of the GPR data indicates two utility components located beneath the easement at an average depth of 5–6 m. The subsurface profile consists of an upper backfill layer extending from the surface to approximately 5 m depth near the underpass, and 4.5–4.8 m toward the southern end of the surveyed area. Below this, deeper units exhibit textures consistent with tuffaceous sandstone or adobe, the expected bedrock material of the Guadalupe Formation.

The pipeline structures appear to be positioned between 4–5 m below the surface. Depth measurements may be influenced by the quality and composition of the backfill material. Clay-sand mixtures with high moisture retention can attenuate GPR signals, while buried debris such as concrete slabs, steel bars, or trusses can create reflection clutter or mask utility signatures if located above the pipeline.

3.2 ERT Findings

The ERT survey was conducted over a 180 to 200 m section of the Pipeline easement, beginning at the southern base of the backfill stockpile and extending toward the Pasig River. The survey line was cleared of vegetation and temporary structures before deployment of an electrical wireline with electrodes at 10 m intervals.

Electrical current was induced in four depth intervals, each equivalent to approximately 10 m, for a maximum theoretical penetration depth of 40 m. Signals were received through the wireline-electrode array, with values recorded both manually and automatically. Two survey lines were completed, with Vertical Electrical Sounding (VES) stations spaced at 10 m intervals.

Data were processed into apparent resistivity values and modeled using RES2DINV software to produce 2D resistivity profiles at 5 m intervals. Standardized logarithmic contour intervals were applied to enable direct lithological comparison. Saturated soils and rock produced low resistivity values, whereas higher resistivity suggested drier or denser materials.

3.2.1 Survey Line 1

Resistivity values were generally low, reflecting varying degrees of saturation. The upper profile is interpreted as backfill material composed of clay, silt, and sand. Minor anomalies occurred between 0–20 m, 30–80 m, and 110–180 m along the traverse as shown in figures 3.2.1.1 to 3.2.1.4. The deeper profiles correspond to tuffaceous sandstone, with a significant anomaly between 50–70 m and elevated resistivity between 50–90 m. The inverse model indicates a continuous layer of clay and unconsolidated river deposits more than 10 m thick, with isolated clay and silt pockets at approximately 40 m, 50 m, and 120 m. A high-resistivity anomaly between 80–130 m at 9 m depth may represent a buried pipeline, vaulted structure, or lithological variation, with potential leakage suggested by overlying horizontal resistivity changes.

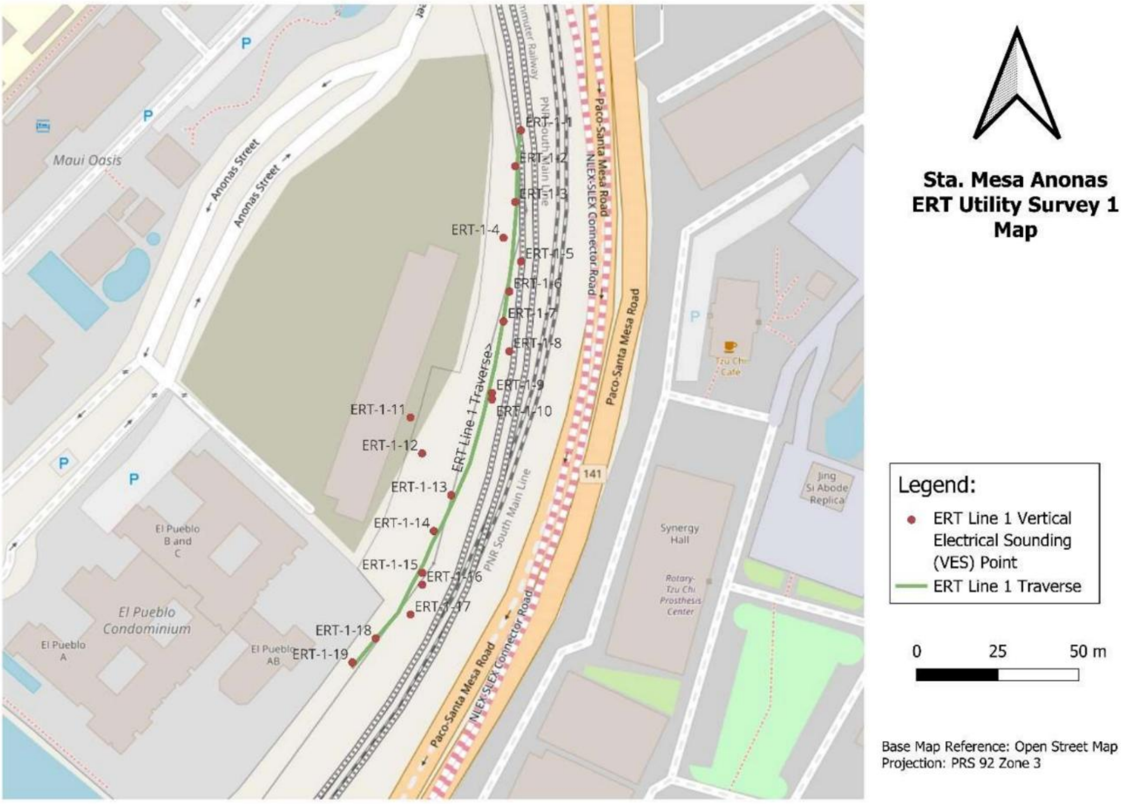

Figure 3.2.1.1 ERT Survey Line 1 Layout and corresponding Vertical Electrical Sounding (VES) Points.

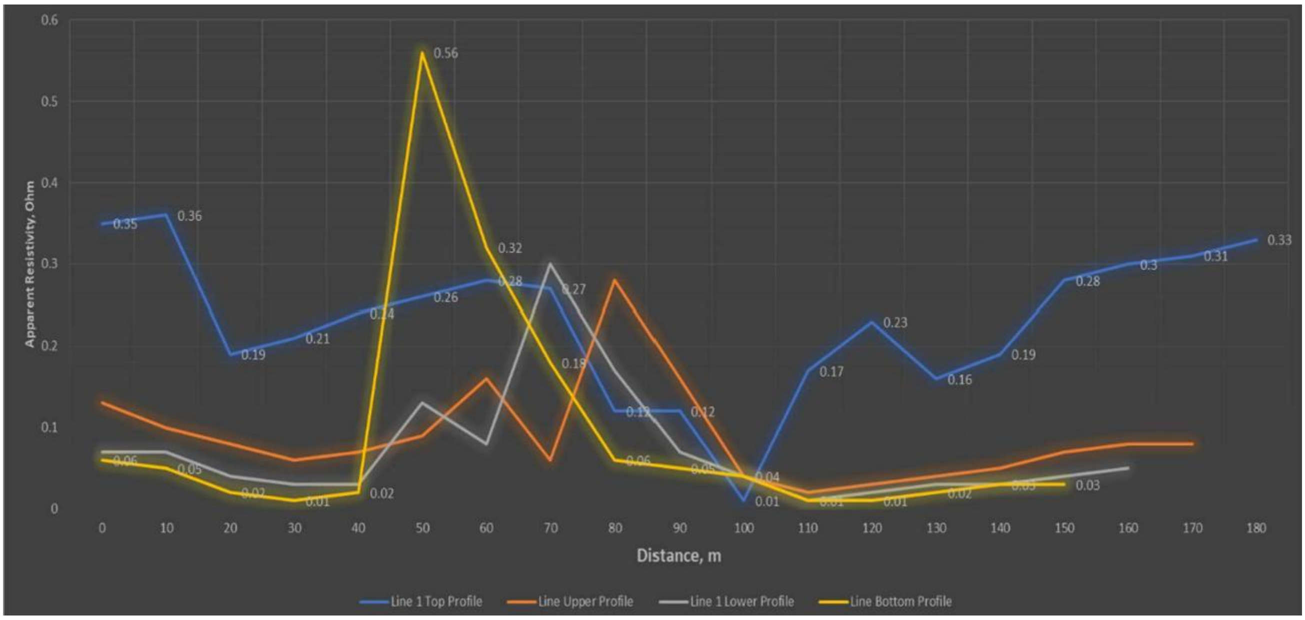

Figure 3.2.1.2 Apparent Resistance values in Ohm across the Survey Line 1 for four profiles beneath the surface, presented in line graph form.

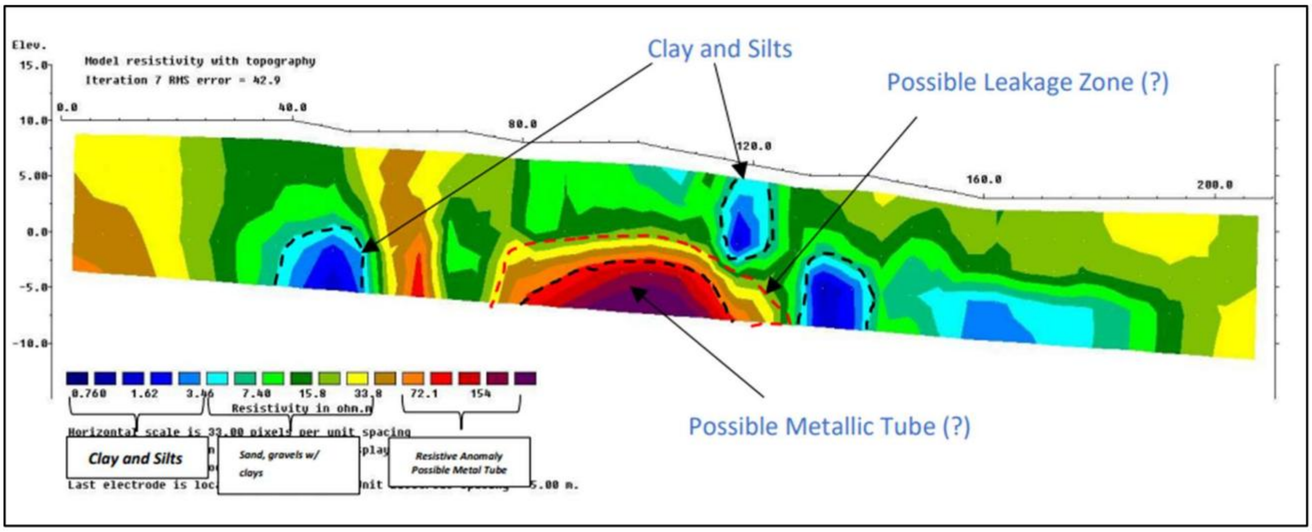

Figure 3.2.1.3 ERT Line 1 Generated Inverse Model based on Res2D inverse software reprocessed field data

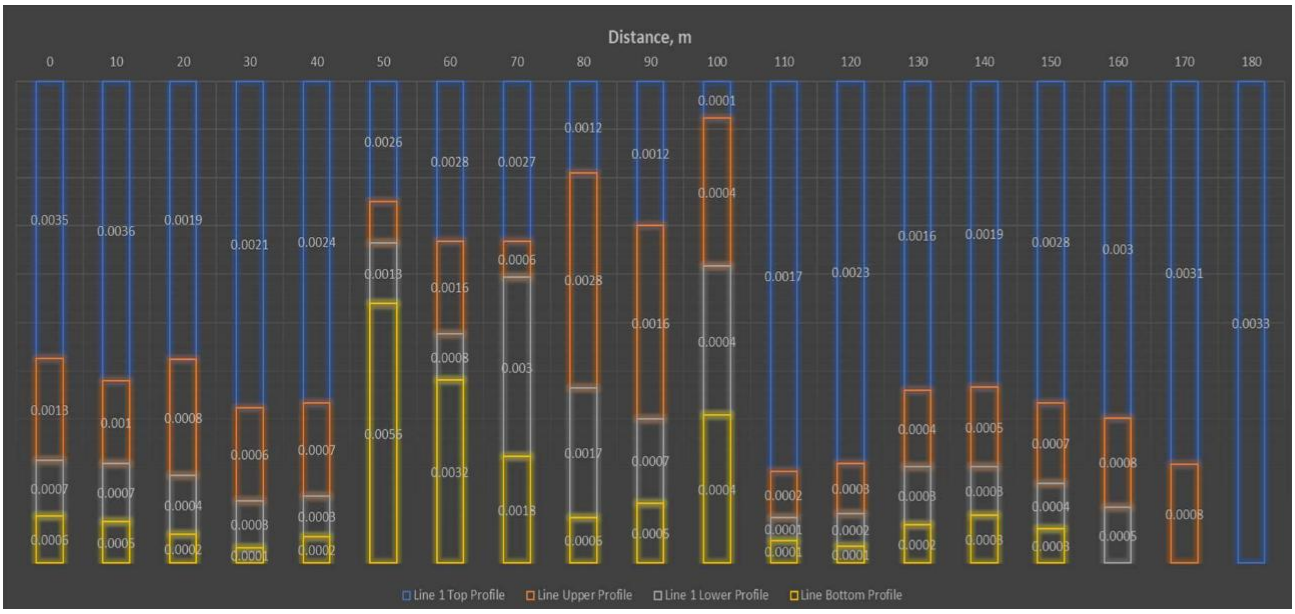

Figure 3.2.1.4 Apparent Resistance values in Ohm across the Survey Line 1 for four profiles beneath the surface, presented in stacked graph form subsurface.

3.2.2. Survey Line 2

Similar to Survey Line 1, low resistivity values were recorded across most profiles, indicating saturated backfill. Minor anomalies occurred between 0–20 m, 30–70 m, and 100–120 m. The lower profiles correspond to tuffaceous sandstone overlain by thinner alluvial deposits. The anomalies observed in Survey Line 1 were also present, with high-resistivity spikes at 70–90 m, 90–120 m, and 120–170 m toward the Pasig River. The inverse model revealed an alluvial deposit up to 10 m thick, underlain by clay and silt layers at depths of 4–7 m in multiple locations. A high-resistivity anomaly between 90–140 m at 8 m depth matched the feature detected in Survey Line 1 and is interpreted as either a buried pipeline or vaulted structure.

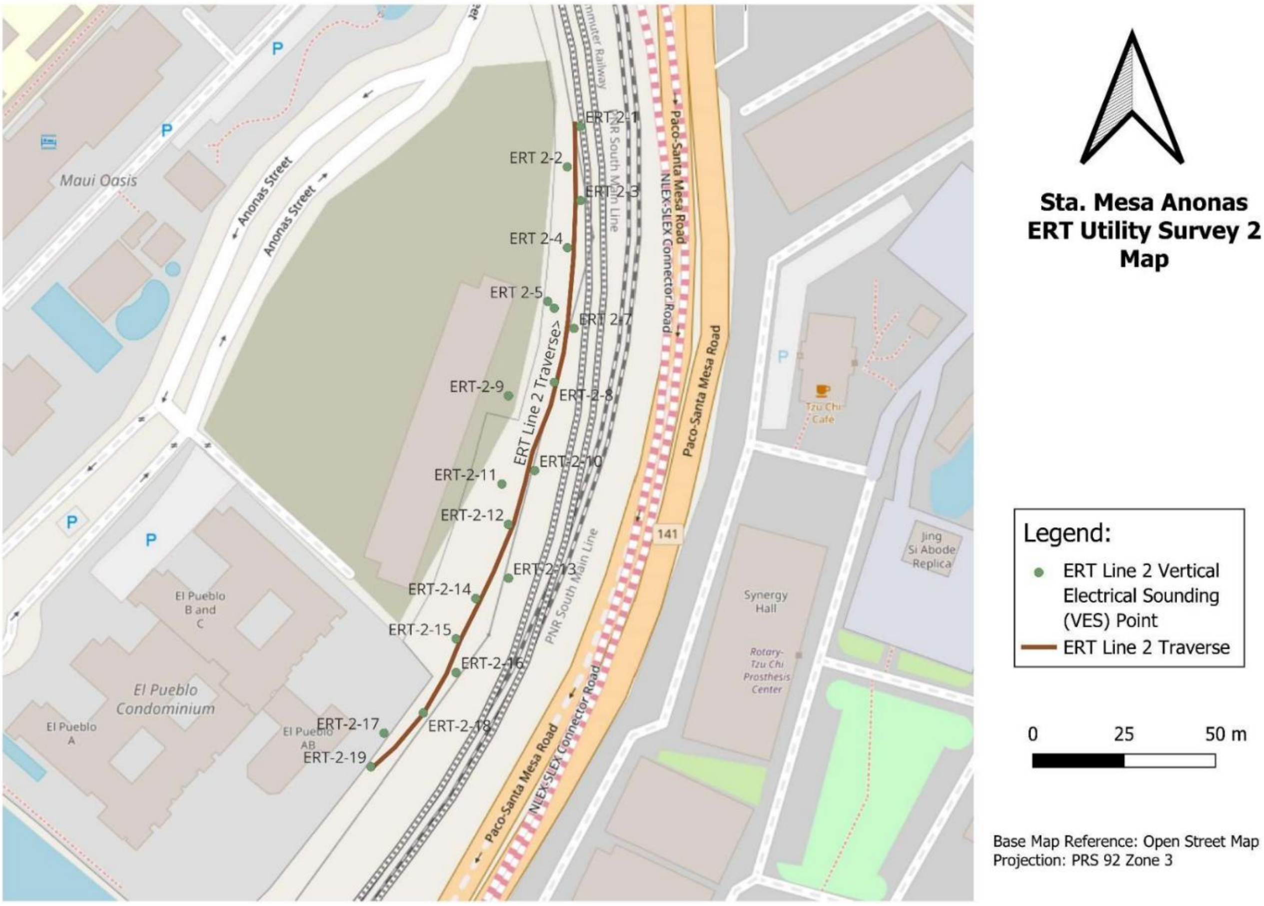

Figure 3.2.2.1 ERT Survey Line 2 Layout and corresponding Vertical Electrical Sounding (VES) Points.

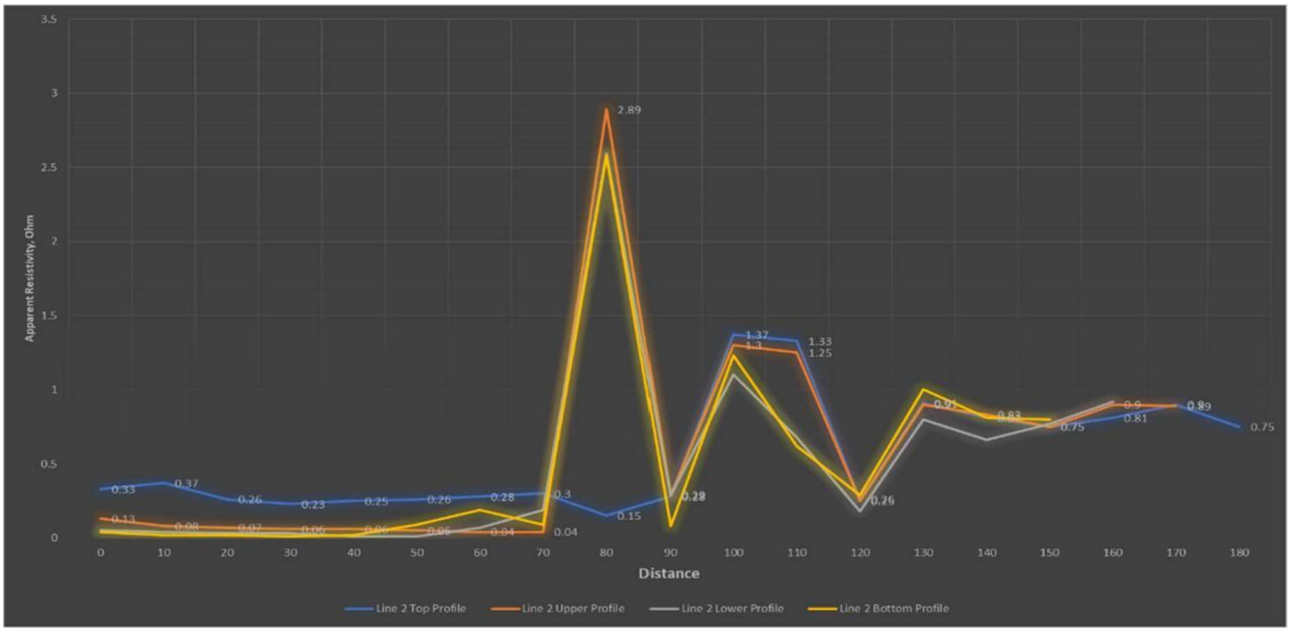

Figure 3.2.2.2 . Apparent Resistance values in Ohm across the Survey Line 2 for four profiles beneath the surface, presented in line graph form.

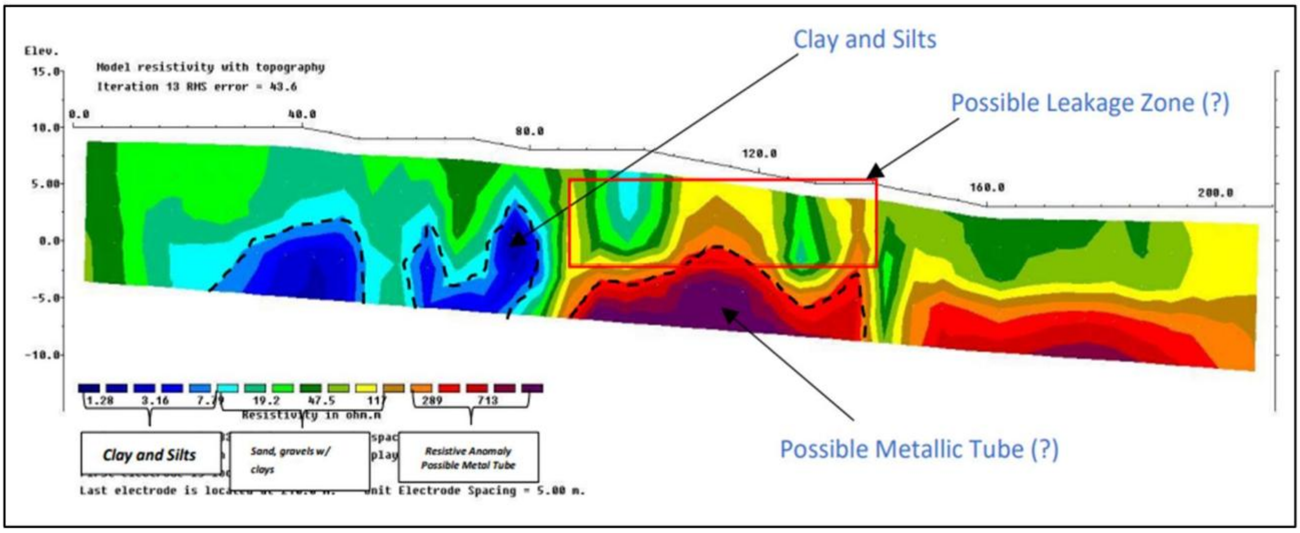

Figure 3.2.2.3. ERT Line 2 Generated Inverse Model based on Res2D inverse software reprocessed field data.

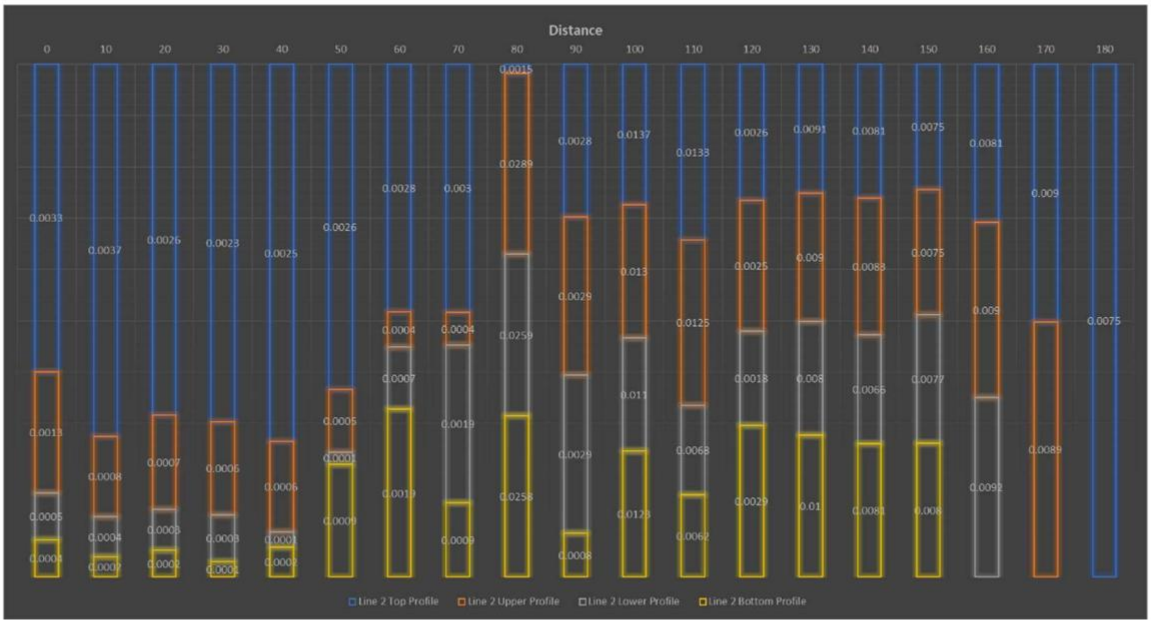

Figure 3.2.2.4. Apparent Resistance values in Ohm across the Survey Line 2 for four profiles beneath the surface, presented in stacked graph form subsurface.

3.2.3 Hydrogeological Influence

Anomalies in the upper profiles of both survey lines are likely related to backfill conditions and moisture variations. Slight increases in resistivity toward the Pasig River, particularly at the 120 m mark in Survey Line 2 and the 100 m mark in Survey Line 1, suggest inland hydrogeological influence from the river. Successive rains prior to Survey Line 2 may have affected resistivity readings in these areas.

3.3 Integrated Interpretation

Cross-validation of GPR and ERT datasets confirmed the presence of two primary anomalies along the pipeline alignment, consistently detected at depths of approximately 4–6 m. The surrounding subsurface materials correspond to an upper backfill layer overlying tuffaceous sandstone bedrock.

ERT profiles revealed continuous low-resistivity zones coinciding with GPR-detected hyperbolic reflections, particularly in the hypothesized leakage zone near the excavation site and Transmission Line tower. The overlap of low resistivity with GPR anomalies supports classification as confirmed utility features. Locations with low resistivity but no corresponding GPR signature were classified as potential leakage zones or moisture migration pathways.

The composition of the overlying backfill, particularly clay-sand mixtures with high moisture retention, likely influenced both datasets. In GPR, such materials attenuate radar signals, while buried debris can produce reflection clutter or mask targets. In ERT, conductive backfill and water saturation can exaggerate low-resistivity anomalies, complicating interpretation. These site-specific factors were incorporated into the classification process to minimize false positives and improve overall interpretation reliability.

4. ASSESSMENT

The GPR survey of the northern section of the Pipeline indicated that the backfill material covering the utility has an apparent average thickness of 5–6 m. Beneath this backfill are channel alluvium deposits up to 1 m thick, underlain by tuffaceous sandstone corresponding to the adobe units of the Guadalupe Formation. This lithological profile is projected to extend toward the southern section of the Pipeline, although confirmation will require additional GPR surveys. The GPR technique cannot directly detect moisture or water presence and therefore cannot conclusively identify leakages.

Subsurface profiling identified two buried utilities. Of these, only one is considered active and is located adjacent to the Railway track, as confirmed with trench pitting. The Pipeline has an estimated diameter of 1.2 m and lies between 5 and 6 m below the surface. Due to access constraints in the mid and southern sections of the alignment, overlap between GPR and ERT data was limited to the section between ERT 2-1 and 2-3. The second buried utility, located near the easement boundary with the adjacent private condominium property, is of similar size and depth.

Field observations indicate that the Transmission Line Tower near the adjacent private condominium property excavation site is positioned within 2 m of the main utility alignment. Reported flooding at this excavation site, suspected to originate from a leakage in the buried utility, supports the likelihood of a major leak in this section. ERT values within this zone were lower (0.019 Ohm at ERT 1-3 and 0.26 Ohm at ERT 2-3) compared to adjacent stations (0.35–0.36 Ohm at ERT 1-1 and 1-2, and 0.33–0.37 Ohm at ERT 2-1 and 2-2), suggesting increased saturation in the backfill layer with water likely sourced from deeper layers rather than surface runoff.

A high-resistivity anomaly, detected in both ERT lines between ERT 2-10 and 2-15 at approximately 8 m depth, exhibited average resistivity values of 72.1–154 Ohm-m in Line 1 and 289–713 Ohm-m in Line 2. This feature, of variable thickness, may represent a buried structure or vault not necessarily associated with the Pipeline. Further investigation during planned excavation is recommended.

Hydrogeological influence from the Pasig River was observed in both ERT lines, with resistivity values gradually increasing toward the river. While top-profile resistivity variations may suggest possible leakages, no direct site evidence supports this interpretation. Historical accounts of possible tampering by informal settlers were confined to areas up to approximately ERT 2-15.

Reprocessed ERT results delineated three potential leakance zones based on combined geophysical data and field observations:

A. Primary Leakance Zone – Located in the overlap region of GPR Lines 336–339 and ERT section 2-1 to 2-3.
B. Secondary Leakance Zone – Bound by ERT 1-5 to 1-8, near the former settlement area of informal settlers.
C. Tertiary Leakance Zone – Bound by ERT 1-9 to 1-15, coinciding with the location of the high-resistivity anomaly. Reports from residents indicate the presence of stagnant water at the surface in this area, likely sourced from subsurface leakage rather than surface runoff from the Railway.

Site observations in certain areas were limited due to dense vegetation and remaining informal housing at the time of assessment.

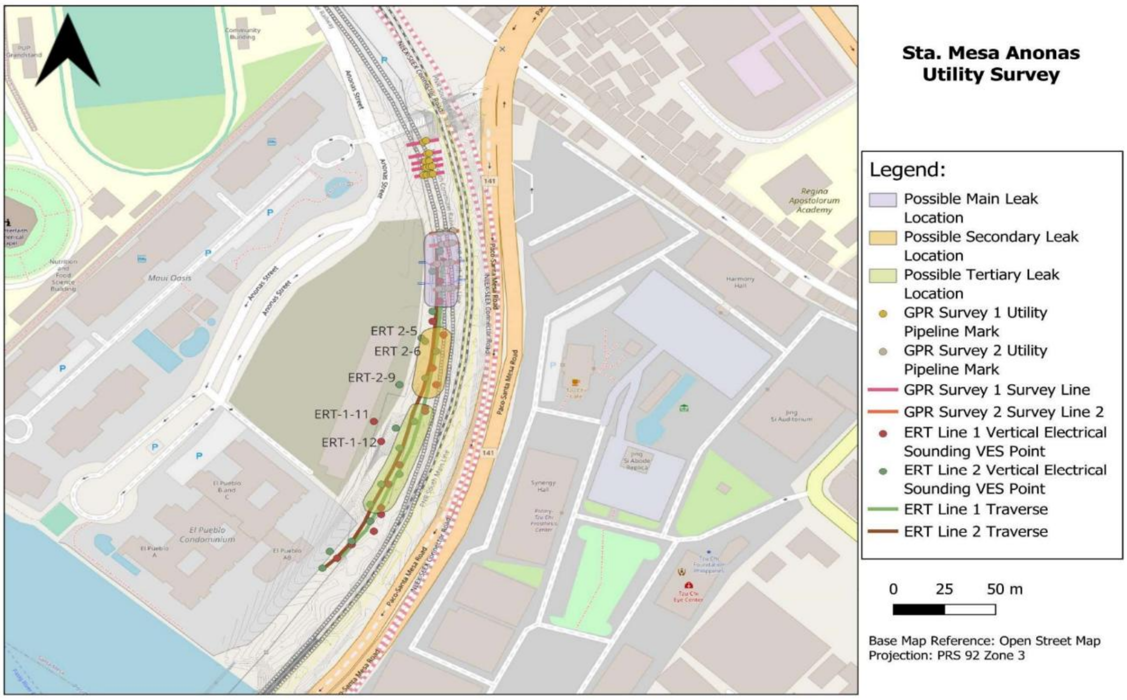

Figure 4.1. Locations of the three (3) possible leakance regions along the Pipeline survey area.

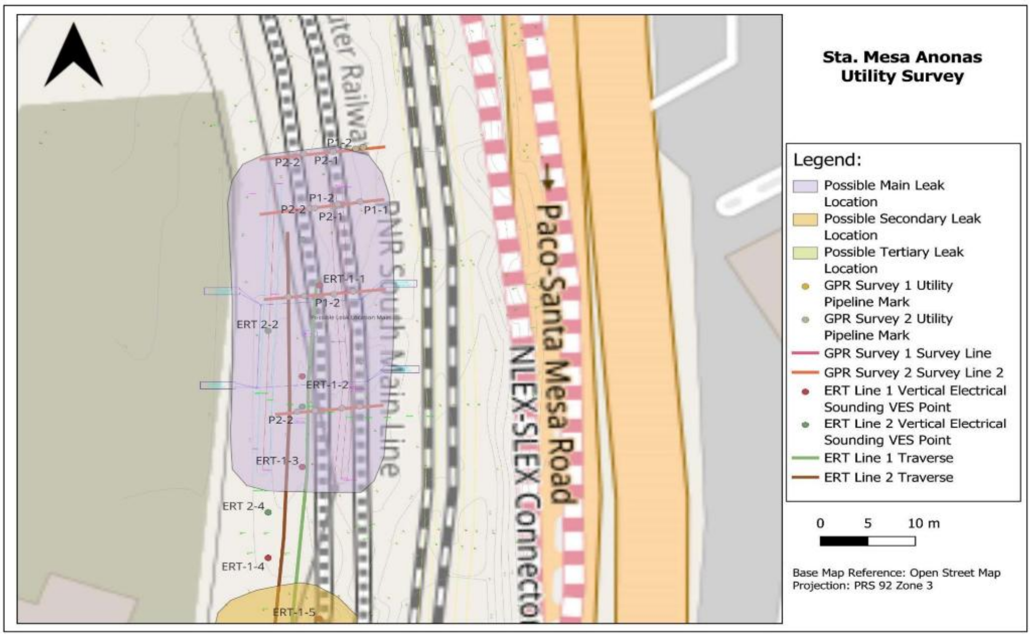

Figure 4.2. Location of the main possible leakance region at the northern segment of Pipeline survey area..

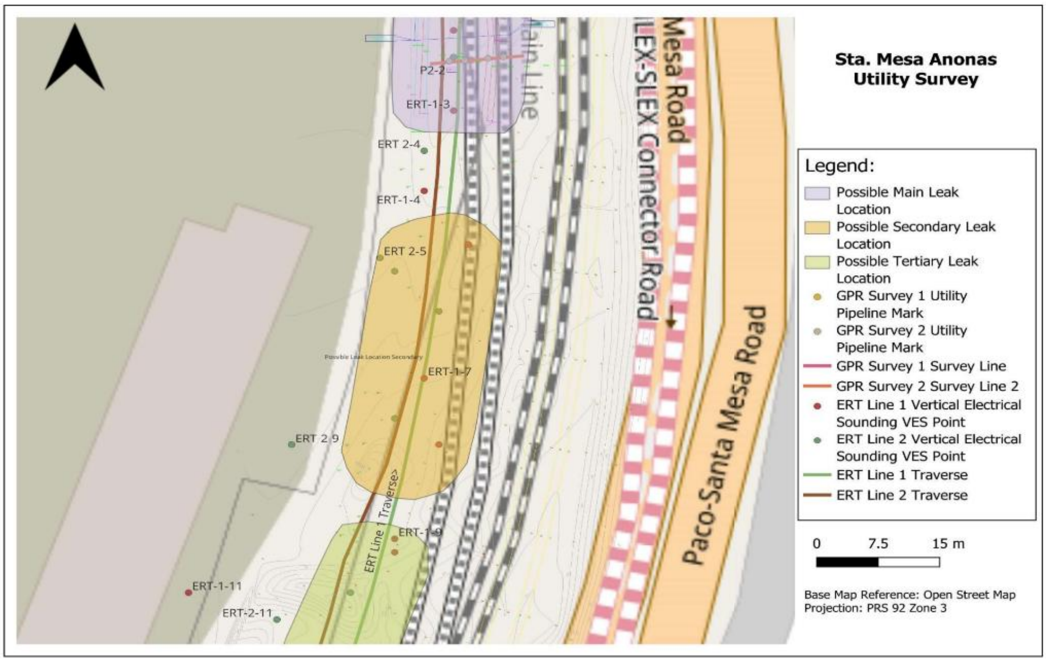

Figure 4.3. Location of the second possible leakance region at the northern middle segment of Pipeline survey area.

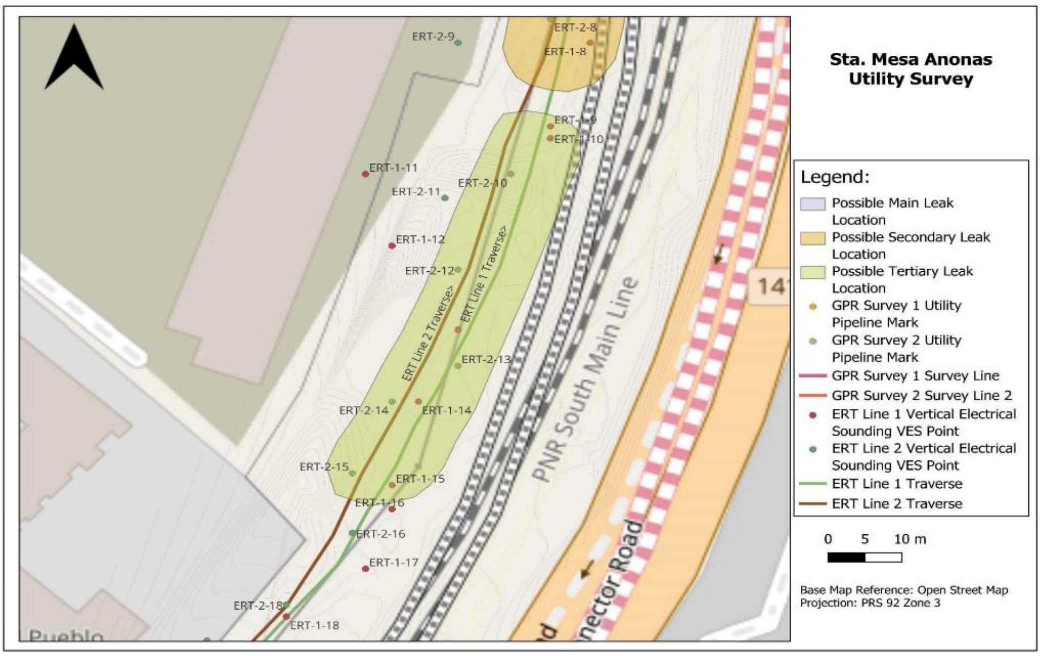

Figure 4.4. Location of the third possible leakance region at the mid to southern segment of Pipeline survey area.

5. CONCLUSION

The GPR survey profiles revealed two distinct subsurface units: an upper backfill layer approximately 5–6 m thick, and lower lithologies comprising a thin alluvium underlain by tuffaceous sandstone of the Guadalupe Formation. This stratigraphic profile is projected to extend toward the southern section of the Pipeline, although confirmation will require additional surveys.

Two buried utilities were detected within the surveyed section of the Pipeline. The primary pipeline lies at a depth of approximately 5–6 m, with localized variations. Buried debris and possible relic structures above the utility caused signal disturbances, reducing the clarity of GPR profiles and affecting depth estimation accuracy.

The ERT inverse models for both survey lines indicated that the site is overlain by river and alluvial deposits, including sand, gravel, and clay, with an average thickness exceeding 10 m. Clay and silt layers were also identified within the backfill. A high-resistivity anomaly was detected in both survey lines at approximately 8 m depth, with resistivity values ranging from 72.1 to 154 Ohm-m in Line 1 and 289 to 713 Ohm-m in Line 2. This feature may represent a large buried object or vault, potentially associated with the Pipeline, although its exact nature could not be confirmed.

Analysis of the ERT anomalies, particularly at Station ERT 1-3, indicated a distinct low-resistivity signature in the upper profile, suggesting localized water-saturated conditions beyond typical moisture content in the backfill. As the survey was conducted during relatively dry weather, the probable source of increased saturation is interpreted as upwelling from deeper profiles rather than surface runoff. This anomaly aligns closely with the Pipeline's mapped alignment using trench pitting, increasing confidence in its interpretation as a potential leakage location.

At Station ERT 2-3, located approximately 5 m north of ERT 1-3, a similar anomaly was observed, although its clarity was reduced due to rainfall the night before the second survey. This rainfall likely caused surface runoff infiltration, slightly lowering resistivity readings at nearby stations. Despite this, the anomaly was still detectable at ERT 2-3 and ERT 2-4, reinforcing the likelihood of a leakage source in the ERT 1-3 vicinity.

The study area has experienced significant historical disturbance, with built-up structures present as far back as 2001. If these structures were not completely removed prior to backfilling, residual subsurface components may have influenced the GPR results and, to a lesser extent, the ERT measurements. The presence of non-uniform materials can alter signal velocities, attenuate reflections, and obscure target features.

Three potential leakage zones were identified based on the integration of GPR and ERT results with site observations. The primary leakage zone is located in the overlap region of GPR Lines 336–339 and ERT sections 2-1 to 2-3 and 1-1 to 1-3. The secondary zone lies between ERT 1-5 and 1-8, near the former location of informal settlers. The tertiary zone is between ERT 1-9 and 1-15, coinciding with the location of the high-resistivity anomaly and supported by reports of stagnant surface water likely sourced from subsurface seepage rather than runoff from the Railway.

Flooding at the adjacent private condominium propert excavation site is likely linked to seepage from a compromised section of the Pipeline, with water migrating through the backfill and underlying lithologies. The sustained presence of water in this location suggests continuous inflow, consistent with ERT indications of saturation. However, the exact leakage points cannot be directly determined, as both geophysical methods detect only indirect indicators such as increased moisture content and structural profiling.

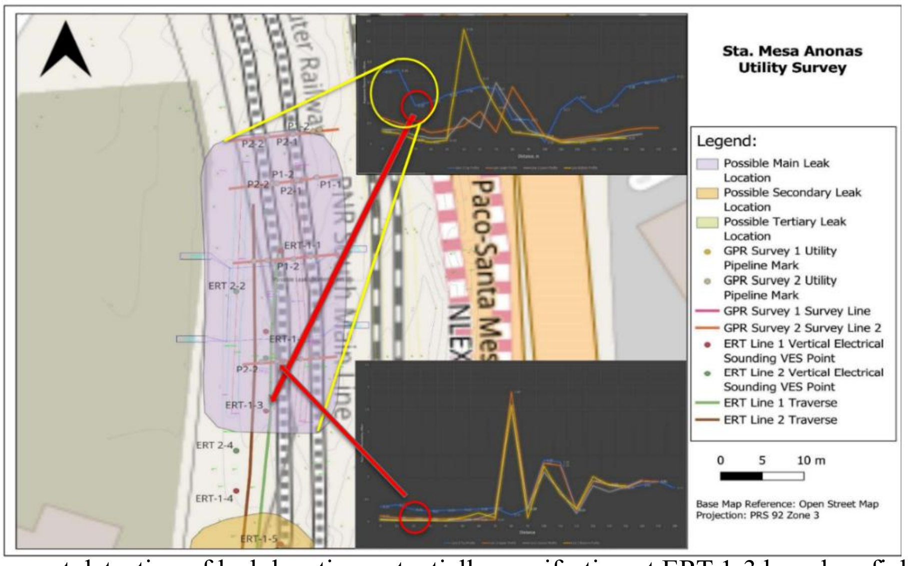

Figure 5.1. Apparent detection of leak location potentially manifesting at ERT 1-3 based on field data anomaly (inset graph), and a regional upper surface moisture plume
between ERT 1-1 to 1-3 and ERT 2-1 to 2-3.

Figure 5.2. Historical map of the Study area based on 2001 Google Earth Image. Notice the density of built-up infrastructures across the entirety of the Pipeline area. Overlain are the three probable leakance areas (main, secondary and tertiary).

6. FINAL DISCUSSION

Following the identification of potential leakage zones through GPR and ERT surveys, targeted pitting or trenching activities were undertaken perpendicular to the easement to intersect the utilities with minimal disturbance. This approach allowed for the physical verification of utility location, exposure of surrounding subsurface materials, and direct assessment of soil wetness conditions. These observations provided valuable ground truth data to support and refine geophysical interpretations.

Upon confirmation of the Pipeline's position, initial repairs were implemented to address active leakage and prevent further water loss. These immediate interventions were necessary to mitigate flooding impacts, minimize service disruption, and reduce potential structural damage to adjacent infrastructure.

However, the Pipeline, constructed in the 1960s, is approaching or has exceeded its typical service life. While short-term repairs address current leakage issues, the long-term resolution will require full replacement to ensure network reliability and operational safety. As part of this decision-making process, additional pipe wall thickness testing is recommended to evaluate the remaining structural integrity of the existing Pipeline. If testing confirms significant degradation, replacement rather than continued repair will be the more sustainable and cost-effective option.

The integration of geophysical surveys with targeted excavation proved effective in both detecting and confirming leakage sources. This combined approach allowed for rapid localization of problem areas, informed immediate remedial actions, and provided the necessary data to guide long-term asset management strategies.

7. REFERENCES

André, F., Leeuwen, C. v., Saussez, S., Durmen, R. V., Bogaert, P., Moghadas, D., . . . Lambot, S. (2012). High-resolution imaging of a vineyard in south of France using ground-penetrating radar, electromagnetic induction and electrical resistivity tomography. *Journal of Applied Geophysics*, 113–122.

Arifin, M. H., Jamaluddin, T. A., Husin, H., Ismail, A., Abbas, A. A., Nordin, M. N., . . . Sulaiman, M. A. (2016). Comparison of Geological Mapping with Electrical Resistivity and Ground Penetration Radar Methods for Rock Fractured System Study. 1346-1357.

Carrière, S. D., Chalikakis, K., Sénéchal, G., Danquigny, C., Emblanch, & Christophe. (2013). Combining Electrical Resistivity Tomography and Ground Penetrating Radar to study geological structuring of karst Unsaturated Zone. *Journal of Applied Geophysics*, 31–41.

Jaw, S. W., & Hashim, M. (2014). Urban Underground Pipelines Mapping Using Ground Penetrating Radar . *8th International Symposium of the Digital Earth (ISDE8)*.

Lai, W. W., Chang, R. K., Sham, J. F., & Pang, K. (2016). Perturbation mapping of water leak in buried water pipes via laboratory validation experiments with high-frequency ground penetrating radar (GPR). *Tunnelling and Underground Space Technology* , 157–167.

Rizzo, P. (2010). Water and Wastewater Pipe Nondestructive Evaluation and Health Monitoring: A Review. *Advances in Civil Engineering, 10*. doi:10.1155/2010/818597

Thomson, J., Wang, L., & Royer, M. (2009). *State of technology review report on condition assessment of ferrous water transmission and distribution systems. EPA United States Environmental Protection Agency.* EPA .

Turesson, A. (2006). Water content and porosity estimated from ground-penetrating radar and resistivity. *Journal of Applied Geophysics*, 99–111.

Zhang, W., Luo, J., Luo, W., & Wang, L. (2024). Leakage diagnostic method for water supply pipeline based on ground penetrating radar and image correlation algorithm . *Measurement* .