Revealing Underground Infrastructure and Supporting Heritage Compliance using Advanced Geospatial Technologies

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Key words: Engineering survey, Geoinformation/GI, Ground Penetrating Radar, GIS, Heritage compliance, Asset management

1. SUMMARY

Legacy office sites present elevated operational, environmental and compliance risks due to undocumented or poorly recorded underground services. Accidental damage to critical assets or heritage structures can trigger costly repairs, environmental contamination, and non-compliance with the National Heritage Resources Act, the Occupational Health and Safety Act, and the National Water Act. Addressing these risks requires accurate, non-destructive identification and documentation of subsurface assets.

This paper demonstrates how integrated geospatial technologies enhance science-based understanding and decision-making for subsurface infrastructure in legacy and heritage environments. A combined workflow of Geographic Information System (GIS), laser scanning, Ground Penetrating Radar (GPR) and electromagnetic locating was applied to detect, map and verify underground diesel tanks, pipelines, and stormwater networks. High-frequency GPR (LMX100 series) enabled detection of metallic and non-metallic utilities in shallow, congested settings; Trimble M3 total station and Trimble R2 RTK GPS delivered centimetre-level positioning; and CAT GEN4 with Genny 4 enhanced tracing of conductive assets. Surveys were controlled in Hartebeesthoek94 Lo29, ensuring consistent, interoperable spatial records.

Results delivered precise spatial records of asset locations, depths, dimensions, and connectivity, including verified linkages between diesel tanks and generators and delineation of stormwater discharge routes toward Victoria Lake. The validated datasets reduced the risk of cross-connections between potable, stormwater and hazardous systems, strengthened SHEQ compliance, and supported heritage protection during maintenance and infrastructure upgrades. Compared with conventional investigative methods, the integrated approach produced tamper-proof records, reduced rework and project duration, and improved long-term asset management.
This study demonstrates a practical approach to improving the understanding and management of underground infrastructure within legacy and heritage campuses. The findings indicate that establishing a digital underground asset register, supported by pre-excavation geophysical scanning and consistent survey control, can meaningfully reduce uncertainty associated with buried services. When linked to existing legislative and organisational compliance frameworks,

these measures contribute to improved operational safety, more informed maintenance planning, and enhanced protection of heritage-sensitive infrastructure, while supporting more efficient long-term asset management.

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2. INTRODUCTION

Legacy office sites pose elevated operational and regulatory risks due to incomplete or outdated records of underground services. Unidentified utilities increase the likelihood of accidental damage during maintenance or, potentially resulting in service disruption, environmental contamination, and non-compliance with statutory requirements. In South Africa, these risks are particularly significant within heritage-designated sites, where infrastructure interventions must comply with the National Heritage Resources Act (RSA Government, 1999), the Occupational Health and Safety Act (RSA Government, 1993) , and the National Water Act (RSA Government, 1998).

Internationally, the identification and management of underground services form a core component of recognised risk management frameworks. Standards and guidelines such as ISO 45001 (Occupational Health and Safety Management Systems) (International Organization for Standardization (2018) ISO 45001:2018, 2018), ISO 14001 (Environmental Management Systems) (International Organization for Standardization (2015) ISO 14001:2015, 2015), and the International Labour Organization (ILO) Convention No. 155 on Occupational Safety and Health, emphasise proactive risk identification, environmental protection, and safeguarding culturally sensitive assets. Ground Penetrating Radar (GPR) was utilised due to its demonstrated suitability as a non-destructive method for locating buried infrastructure and subsurface objects, as documented in previous studies (E. Pasolli, 2009).

The NTCSA Simmerpan Office Park exemplifies these challenges. The site holds dual designation as a National Key Point and a National Heritage Site, imposing significant regulatory and operational requirements (RSA Government, 1999) (RSA Government, 1980). As a National Key Point, the site is subject to stringent security protocols aimed at safeguarding critical infrastructure against potential threats, requiring controlled access, surveillance systems, and compliance with national security legislation. Simultaneously, its status as a National Heritage Site mandates adherence to heritage conservation laws that preserve the architectural integrity and historical value of the buildings and surrounding areas. These combined obligations mean that any renovation, restoration, or maintenance activities must conform to both security and heritage standards, often necessitating specialised materials, approved methodologies, and oversight by regulatory authorities (RSA Government, 1980) (RSA Government, 1999).

This study applied an integrated geospatial workflow combining engineering survey techniques, Geographic Information Systems (GIS), laser scanning, and Ground Penetrating Radar (GPR) to investigate and document the underground infrastructure. This included mapping the connections between diesel tanks and generators across various designated zones on the site and incorporated a detailed survey of the stormwater reticulation network to delineate pipeline alignments and identify connection nodes across the system.

GPR is a non-destructive testing (NDT) technique that employ electromagnetic (EM) wave pulses to image the subsurface infrastructure and objects. The GPR scan the surface through sending EM radiation, typically within the microwave band of the radio spectrum, into the subsurface (Iftimie, 2021). The EM waves enable the GPR systems to detect signals reflected from different materials or interfaces below the surface. The produced scans/signals contain information about the sub-surface objects (Ishfaq Aziz, 2025).

Owing to its capability to image subsurface features in a manner analogous to X-ray inspection, GPR has been utilised across multiple disciplines for the detection and localisation of underground targets, such as in archaeology (Solla, et al., 2011), civil engineering (Demirci, et al., 2012), military applications (Xavier, et al., 2014), etc. The system operates through transducers that couple electromagnetic energy within the near field using evanescent and propagating waves (Smith & Petersson, 2000).

3. STUDY AREA

Eskom NTCSA Simmerpan, located in Germiston, is designated as a National Key Point and forms part of the country's critical infrastructure. As part of its energy mix, the Simmerpan site utilises generators powered by underground diesel storage tanks. It also consists of an integrated pipeline network designed to transport stormwater, greywater, and toxic wastewater to their respective discharge points. The study implemented an integrated workflow designed to address complex subsurface challenges through a systematic and technology-driven approach. This complexity necessitated an integrated, non-destructive geospatial workflow, as described in the following section.

4. METHODOLOGY

This study employed an integrated methodology combining engineering survey techniques and GPR to achieve the high-accuracy detection and mapping of underground infrastructure. The employed technology enables the detection of both metallic and non-metallic infrastructure under challenging conditions such as hard pavements, compacted soils, waterlogged areas, and dense building environments. Accurate geomatic positioning was essential to achieve precise spatial mapping and mitigate the risk of utility strikes. This was achieved through rigorous engineering survey control and continuous validation throughout the data acquisition process (Smith, 2023).

A single, consistent geodetic reference framework was applied across all datasets to ensure spatial integrity and interoperability. Survey control was established using existing benchmarks from previous topographical and GPR surveys conducted on-site. These benchmarks were verified and re-used to maintain consistency between historical and newly acquired data. Instrument calibration was performed prior to fieldwork to minimise systematic errors and ensure alignment with established control points.

All positional data were referenced to the South African Hartebeeshoek94 coordinate system (Lo29), based on the WGS84 ellipsoid and Transverse Mercator projection, which is appropriate for regional scale mapping. Elevation data and depth measurements were referenced to the Land Levelling Datum (LLD), commonly known as Mean Sea Level (MSL), ensuring compatibility with national geodetic standards. By consolidating all spatial information within a single reference system, the study avoided redundancy and ensured seamless integration of survey, GPR, and GIS outputs.

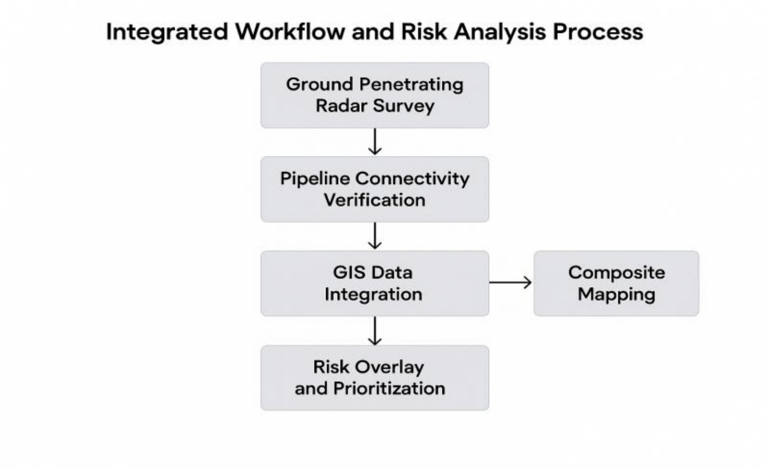

Figure 1: Integrated workflow
Figure 1: Integrated workflow diagram represent simplified the methodology into a linear process with one branching element (Composite Mapping), making it easier to understand the flow from data collection to risk assessment.

4.1 EQUIPMENT

To ensure accurate detection and mapping of underground utilities and infrastructure, the following instruments and technologies were used:

a) Trimble M3 3" Total Station

Utilised in areas where GPS instruments were limited due to infrastructure-related obstructions such as multi-storey buildings and dense urban features. This optical instrument provided precise angular and distance measurements for control point establishment and utility referencing.

b) Trimble R2 RTK GPS

Deployed for high-accuracy positioning of detected underground services and for establishing survey control. The RTK (Real-Time Kinematic) capability ensured centimetre-level precision in open areas with sufficient satellite visibility.

c) LMX100 Series Ground Penetrating Radar (GPR) Scanner

Used for scanning and detecting underground utilities including diesel tanks and pipeline systems. The LMX100 offers high-frequency resolution suitable for shallow subsurface investigations, making it ideal for urban utility mapping.

d) CAT GEN4 and Radio detection Genny 4 Cable Locator

These electromagnetic locators were used in conjunction to trace conductive utilities such as metallic pipelines and electrical cables. The Genny 4 transmitter enhances signal strength and tracing accuracy, especially in congested environments.

4.2 DATA ACQUISITION

- Control Setup: Benchmarks established using RTK GPS and Total Station for positional accuracy.
- GPR Survey: Conducted in a grid pattern with line spacing optimised for resolution.
- Locator Survey: CAT GEN4 and Genny 4 used to trace conductive utilities; data exported in GIS-compatible formats.

5. DATA PROCESSING

Prior to analysis, the raw dataset underwent preprocessing to guarantee accuracy and reproducibility. The workflow included depth calculation (derivation of per-sample depth values), signal processing (filtering and denoising to enhance signal-to-noise ratio), and inverse distance weighting (IDW) interpolation to generate spatially continuous surfaces from discrete observations.

a) Depth Calculation

To determine the diesel tank volume and depth the following formula was utilised:

GPR depth is derived from **two-way travel time (TWT)** using:

$$d = \frac{v \cdot t}{2}$$

Where:

d= depth

v= radar wave velocity in the medium (depends on dielectric constant)

t= travel time of the signal

b) Signal Processing

The following filtering algorithm was applied to:

- Bandpass filtering: Converts time-domain signal to frequency domain for noise removal
- Gain adjustment to enhance deeper reflections.

Band Filtering Model

These are algorithmic steps, not single formulas, but often involve Fourier transforms:

$$F(\omega) = \int_{-\infty}^{\infty} f(t)\, e^{-i\omega t} dt$$

Where :

$F(\omega)$ = frequency domain

$-\infty$ = all negative times

$+\infty$ = all positive times

$f(t)$= signal measured over time

$e^{-i\omega t}$ = a complex sinusoid.
dt = differential time

Gain Adjustment Models

The amplitude envelope is assumed to decay exponentially due to material damping. Therefore, an exponential model is applied to compensate the attenuation and improve the detection of later-time components. Geometric spreading is modelled as a power-law decay of the amplitude envelope with travel time or distance. To counteract this effect, we apply a corresponding power-law gain that compensates the reduction associated with wavefront expansion and enhances late arrivals.

Exponential Model

$\ln\ E(t) = a - \alpha t \Rightarrow g(t) = e^{\alpha t}$

where:

a is a source-related constant and

$\alpha > 0$ is the attenuation coefficient

Power-law Model

$\ln\ E(t) = c - \gamma \ln\,(t + t_0) \Rightarrow g(t) = (t + t_0)^{\beta}$ with $\beta \approx \gamma$

where:
c is source-related
t_0 avoids singularity at $t = 0$
γ governs spreading

c) Inverse Distance Weighting (IDW)

To generate continuous surface models, the study employed the IDW spatial interpolation technique. This method operates on the principle that observations located closer to the prediction point exert greater influence than those farther away, thereby producing a smoothly interpolated surface representation.

$$Z(x, y) = \frac{\sum_{i=1}^{n} \frac{z_i}{d_i^p}}{\sum_{1=1}^{n} \frac{1}{d_i^p}}$$

Where:

$Z(x, y)$: estimated value at location (x, y)

z_i: known value at point i

d_i: distance from point i

p: power parameter (commonly 2)

6. FINDINGS

a) Diesel storage and distribution

Analysis revealed two rectangular diesel tanks supplying fuel to the generators. One tank is located directly under an existing pipeline, while the other has a generator partially positioned above it. The second tank also has direct connections to adjacent buildings via buried cables and a steel fuel pipe at ±0.5 m depth. A separate refuelling manhole provides access to this tank, bypassing the generator that otherwise obstructs direct entry.

The GPR survey successfully identified previously undocumented tank dimensions and volumes, providing verified measurements critical for regulatory compliance and safe refuelling operations. Tank capacities were determined as follows:

- Tank 1: 3.80 m × 2.19 m × 1.80 m → 15,000 L
- Tank 2: 3.79 m × 2.00 m × 1.79 m → 13,575 L

Tank 1, being the larger, requires a secondary containment volume of approximately 16,500 L (≥110% of tank capacity) in line with standard safety guidelines.

b) Water management

The site contains a stormwater drainage network and multiple sumps each serving specific functions for greywater, toxic water, or stormwater collection. The GPR survey revealed that water from the battery room drains into a plant greywater sump, which is manually pump and re-routed to a sewage manhole. Observations indicate that the sump stops filling at a certain level, suggesting the presence of a float-level control or hydraulic restriction that needs further investigation.

Groundwater from other sump pumps is pumped into the main stormwater system, which ultimately discharges into Victoria Lake. In contrast, the toxic water sump is isolated (no mechanical/electrical pump) and emptied manually using a honey sucker system, with disposal handled by authorised service providers in accordance with environmental regulations.

Water Pipeline Network system

The study confirmed connectivity between external pipelines and the NTCSA Simmerpan stormwater system, ensuring discharge into Victoria Lake. An external 600 mm diameter stormwater pipe from a neighbouring facility was identified connecting into the Simmerpan network. GPR and electromagnetic tracing verified that all pipelines link to their intended discharge points, preventing potential cross-connections between potable, stormwater, and hazardous systems.

Spatial mapping of the stormwater network was integrated into GIS, enabling multi-layered visualisation of pipeline routes, connections, and critical intersections. This analysis highlighted potential risks from uncontrolled external inflows, supporting risk assessment, maintenance planning, and regulatory compliance within the heritage and National Key Point context.

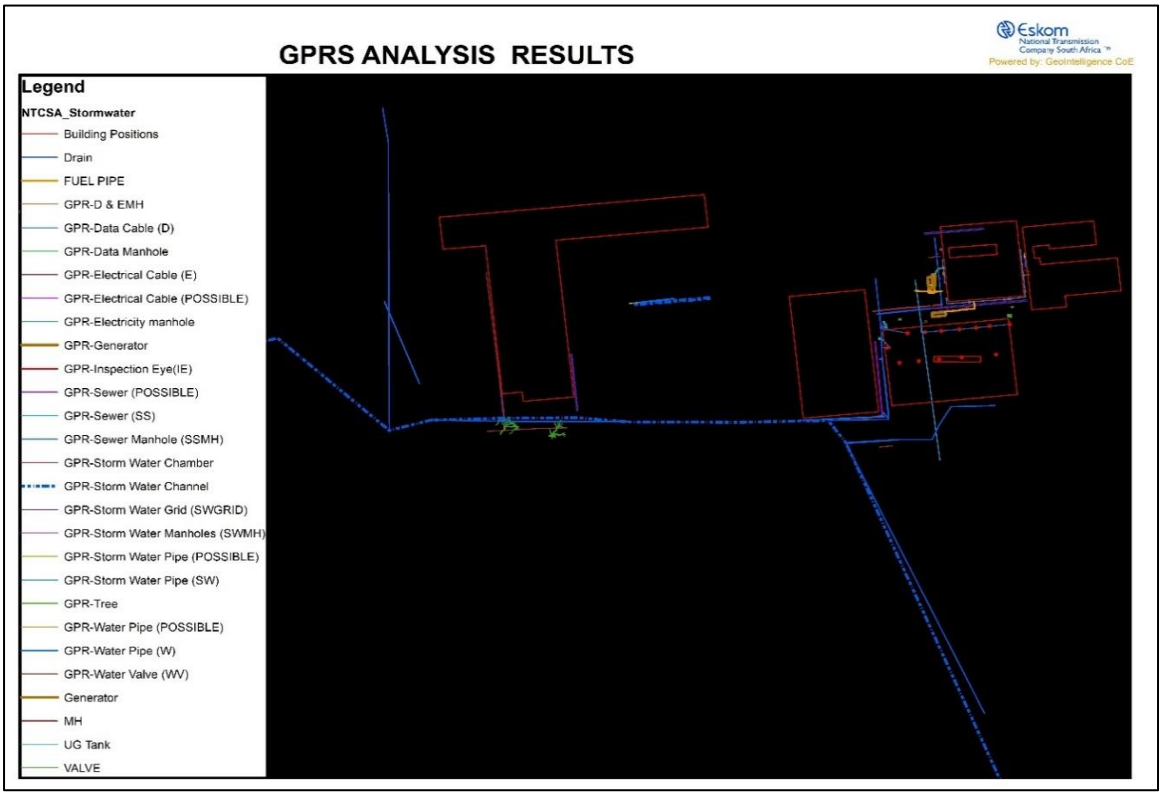

Figure 2: GPRS results

Fejl! Henvisningskilde ikke fundet., represent the scanned route with all pipe networks making up a stormwater system. The dotted line indicated the 600mm diameter pipe that originates from the factory adjacent Building.

7. RESULTS DISCUSSION

The surveys revealed detailed spatial relationships between diesel storage tanks, generator units, and stormwater networks, including confirmed discharge pathways towards Victoria Lake. These findings were essential for hazard isolation, maintenance scheduling, and safeguarding heritage-designated structures within a National Key Point site. Verification of pipeline connectivity confirmed that potable, stormwater, and hazardous systems remain segregated, reducing contamination risks and ensuring compliance with regulatory and heritage conservation requirements.

Subsurface anomalies indicative of diesel tanks and associated pipelines were detected at depths of 0.5 m to 2.5 m. Metallic pipelines and electrical cables were also mapped, allowing identification of high-risk intersections, such as stormwater conduits crossing sewage lines. This spatial intelligence enables prioritisation of potential failure points, informs contingency planning, and provides actionable guidance for operational and maintenance decisions.

The results further support improved efficiency and cost-effectiveness by identifying accurate asset positions and depths, minimising errors, and guiding long-term infrastructure management.

8. CONCLUSION

This study demonstrates the value of advanced geospatial technologies in mapping and managing underground infrastructure on heritage-sensitive, legacy sites. The integration of GPR, electromagnetic tracing, and GIS enabled accurate identification of diesel tanks, pipelines, and stormwater networks, providing a reliable foundation for operational planning, maintenance, and environmental protection.

Findings confirmed that diesel storage systems and stormwater networks are correctly segregated, mitigating cross-contamination risks, while also revealing previously undocumented subsurface features requiring attention. The spatial intelligence obtained allows prioritisation of potential hazards, supports heritage compliance, and informs long-term asset management strategies.

By focusing on actionable results rather than procedural details, the study highlights tangible benefits for safety, regulatory adherence, and cost-effective infrastructure management. This approach provides a pragmatic blueprint for legacy and heritage campuses: proactively map underground assets, verify connectivity, and use spatial data to guide operational decisions, thereby safeguarding both critical infrastructure and cultural heritage.

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BIOGRAPHICAL NOTES

Bronwyn Stolp is a senior real estate, land, and environmental management professional with over 35 years' experience in infrastructure-related property environments. She has extensive expertise in strategic and operational leadership across land acquisition, property and facilities management, environmental governance, GIS, and cadastral survey. Her experience has given her a deep working knowledge of cadastral principles, property law, statutory frameworks, and regulatory processes.

She holds a BA in Geography and Environmental Management (UNISA) and a Diploma in Advanced Property Practice, complemented by professional training in property and environmental law, land and rights management, project management, negotiation skills, ISO management systems and values, environmental management, occupational health and safety, and facilities operations.

Bronwyn's career has been primarily with Eskom, evolving from technical roles in cartography and land rights to senior advisory and management positions. She has led complex land acquisition projects, servitude and land rights management, leasing and disposal transactions, and environmental authorisations. She has overseen stakeholder engagement, resettlement processes, and compliance with legislative and governance requirements, while directing facilities maintenance and operational performance across multiple property portfolios.

From 2016 to 2023, she served as Middle Manager in Eskom Real Estate/Property Management, driving strategic planning, operational efficiency, financial oversight, risk management, and contract governance. Since February 2023, she has been Senior Manager at Transmission Real Estate, Land and Servitude Management, leading strategic land management, policy development, facilities capability building, and servitude performance improvement. Her career is marked by achievements in negotiation, stakeholder management, environmental and land governance, and the development of robust systems that support sustainable land use, operational excellence in facilities, and the performance of commercial property and land and servitude assets.

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