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Efficacy of GPR and ERT for Cavity Detection in Conductive Near-Surface Environments: A Case Study of the Arab Formation, Saudi Arabia

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Summary

This study evaluates the effectiveness of Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) for detecting subsurface geological hazards specifically cavities, voids, and cracks within the Arab Formation north of Riyadh, Saudi Arabia. The study area, located within residential planning and massive infrastructure projects, is dominated by limestone, anhydrite, and gypsum layers. These subsurface features pose significant geotechnical risks, threatening the structural integrity and sustainability of infrastructure; therefore, a reliable, consistent subsurface investigation is essential to secure this vital growth investment. GPR surveys using 500 MHz and 250 MHz experienced severe signal attenuation and failed to penetrate effectively beyond 1 meter. This failure was attributed to the high conductivity of the subsurface materials, evidenced by very low near-surface resistivity values that ranging from ~ 4 to 75 ohm·meter at 1 meter depth, which rendered the radar survey unsuccessful in detecting a known cavity. Conversely, the ERT surveys were highly successful, producing clear, strong correlations that accurately imaged the position and depth of the subsurface cavity. ERT becomes the superior and more accurate method for the detection and mapping of geohazards features. This study confirms that a multi-method geophysical approach is crucial for reliably assessing these complex geological formations prior to development.

Introduction

Karst phenomena and subsurface cavities primarily develop in soluble lithologies such as limestone, dolomite, and anhydrite through the chemical dissolution of rock by water, which leading to significant geological hazards and structural collapses. In the context of the Late Jurassic Arab Formation, characterized by extensive underground passages, tunnels, and varied structural features, the early detection and characterization of these voids are critical for engineering safety and hazard prevention (Abd El Aal et al. 2021). Geophysical methods have proven essential for subsurface imaging. Ground-penetrating radar (GPR) has demonstrated high efficacy in imaging subsurface voids, limestone outcrops, and cracks, as seen in studies of the Dammam Dome (Mansour et al. 2023; Abdullah et al. 2019). Furthermore, the integration of GPR with geoelectrical resistivity techniques allows for the precise mapping of sedimentary layers and the confirmation of small-scale fractures within limestone structure (Nouioua et al. 2013). While GPR is effective for high-resolution imaging, Electrical Resistivity Tomography (ERT) is a well-established technique for 2-D subsurface imaging in environmental and engineering applications (Caselle et al. 2020; Mogren, 2020; Allam et al. 2025). This study, situated within a planned residential development northeast of Riyadh, aims to evaluate the comparative effectiveness of

GPR and ERT responses for detecting known cavity within limestone and anhydrite sequences. By estimating key physical properties and determining the dimensions of subsurface voids, the research seeks to develop a robust engineering framework to mitigate potential collapses in similar geological conditions.

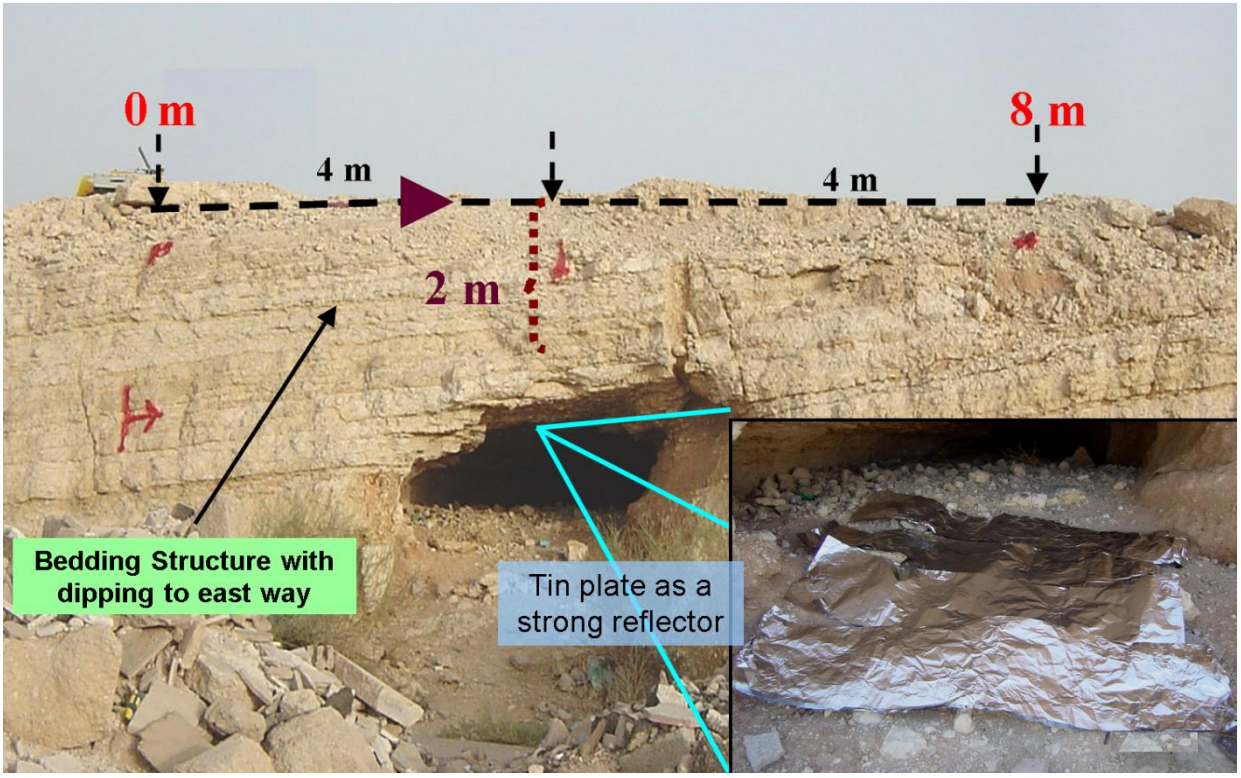


Figure 1. Survey configuration and cave geometry. The natural cave extends 20 m horizontally at a depth of 2 m, with a width narrowing from 3 m at the entrance to 1 m at the end. The GPR (8 m) and ERT (23 m) profiles are centered over the cave body, positioned 3.5 m from the road-cut margin. A tin plate was placed inside the cave during GPR scanning to serve as a high-contrast target for GPR reflection.

Geophysical Methods

- ### Ground Penetrating Radar (GPR)

Ground penetrating radar (GPR) is a non-destructive geophysical technique employing ultra-wideband high-frequency electromagnetic (EM) energy (10 MHz to 2.6 GHz) to non-invasively map the shallow subsurface with high spatial resolution (Boldrin et al., 2024; Famiglietti et al., 2024). A GPR system radiates short EM pulses into the ground; while propagation velocity is controlled by relative dielectric permittivity (ϵr), electrical conductivity (σ) primarily dictates signal attenuation. Reflections occur when waves encounter material interfaces with sufficient electromagnetic contrast, which are then detected by a receiver antenna. Processing the two-way travel time and reflection amplitudes creates high-resolution, cross-sectional images of subsurface discontinuities (Lai et al., 2018). In this study, the GPR (8 m) profiles are centered over the cave body, positioned 3.5 m from the road-cut margin as shown in Figure 1.

- **Electrical Resistivity Tomography**

Electrical resistivity tomography (ERT) is a well-established, non-invasive technique used to generate 2-D cross-sectional images by injecting controlled currents into the subsurface and measuring the resultant potential difference (Ramirez and Daily, 2001; Kemna et al., 2002; Daily et al., 2004). In this study, a multi-electrode SYSCALR1 system utilized dipole-dipole and Wenner-Schlumberger arrays along 23 m profile with 1 m electrode spacing. The target, a visible subsurface cavity, was centered at 10 m of the profile, roughly 5 m from the hill margin, (Figure 1). Data were stacked three times per point, and the measured apparent resistivity was processed using Res2Dinv software (version 4.10.3). This software applies an iterative smoothness-constrained least-squares inversion algorithm (Loke and Barker, 1996) to generate the final subsurface resistivity model.

Results

Utilizing 500 MHz and 250 MHz frequencies, the GPR survey showed limited capability in imaging subsurface structures (caves) due to high electrical conductivity. This caused significant signal attenuation, particularly below a depth of 1.2 meters. Although the 500 MHz and 250 MHz data were processed using different workflows, they yielded similar results. Notably, the 250 MHz survey results remained inconclusive even after a thin metal plate, a strong EM reflector, was placed inside the cave. Despite acting as a high-contrast target, the reflector was not visible in the GPR section. This suggests that the GPR energy was absorbed before reaching the target depth. This further indicates that EM energy penetration is severely limited, as illustrated in Figure 2. All GPR data at this site were acquired using different parameters and processed with various workflows; however, the radar sections consistently show good reflection data in the upper meter (less than 1 m depth). The lower parts of the sections (below 1 m depth) exhibit high noise resulting from the poor electrical characteristics specifically high conductivity and attenuation of the subsurface. Consequently, the GPR results indicate high EM attenuation below 1 m, preventing the reliable detection of the cavity. This suggests that the GPR method was unable to penetrate significantly beyond the near-surface layer with sufficient energy. Consistent with the electrical resistivity data, the high conductivity of the subsurface (with very low near-surface resistivity values of ~ 4 ohm·meter, increasing to only 75 ohm·meter at 1 m) rendered the radar survey unsuccessful in detecting this known cavity, even with the aid of an internal metal reflector. However, the Electrical Resistivity Tomography (ERT) inversion confirms an air-filled cavity, evidenced by a distinct high-resistivity anomaly at 10 m distance of the profile and 2 m depth. This aligns with the known cave location and sits within a low-resistivity background (4–30 ohm·meter) indicative of clay and silty clay sediments (Figure 3). This conductive layer likely caused the high attenuation observed in the corresponding GPR data.

Discussion and Conclusions

This study evaluates the efficacy of Ground Penetrating Radar (GPR) and Electrical Resistivity Tomography (ERT) for imaging subsurface structures and cavities within the Arab Formation. It provides key insights across a distinct geological setting dominated by conductive near-surface clay. The GPR technique showed unsuccessful for detecting structures deeper than 1 m. This limitation was attributed to significant signal attenuation caused by the high electrical conductivity of the near-surface materials. Under these high-conductivity conditions, the ERT method demonstrated superior efficiency and resolution.

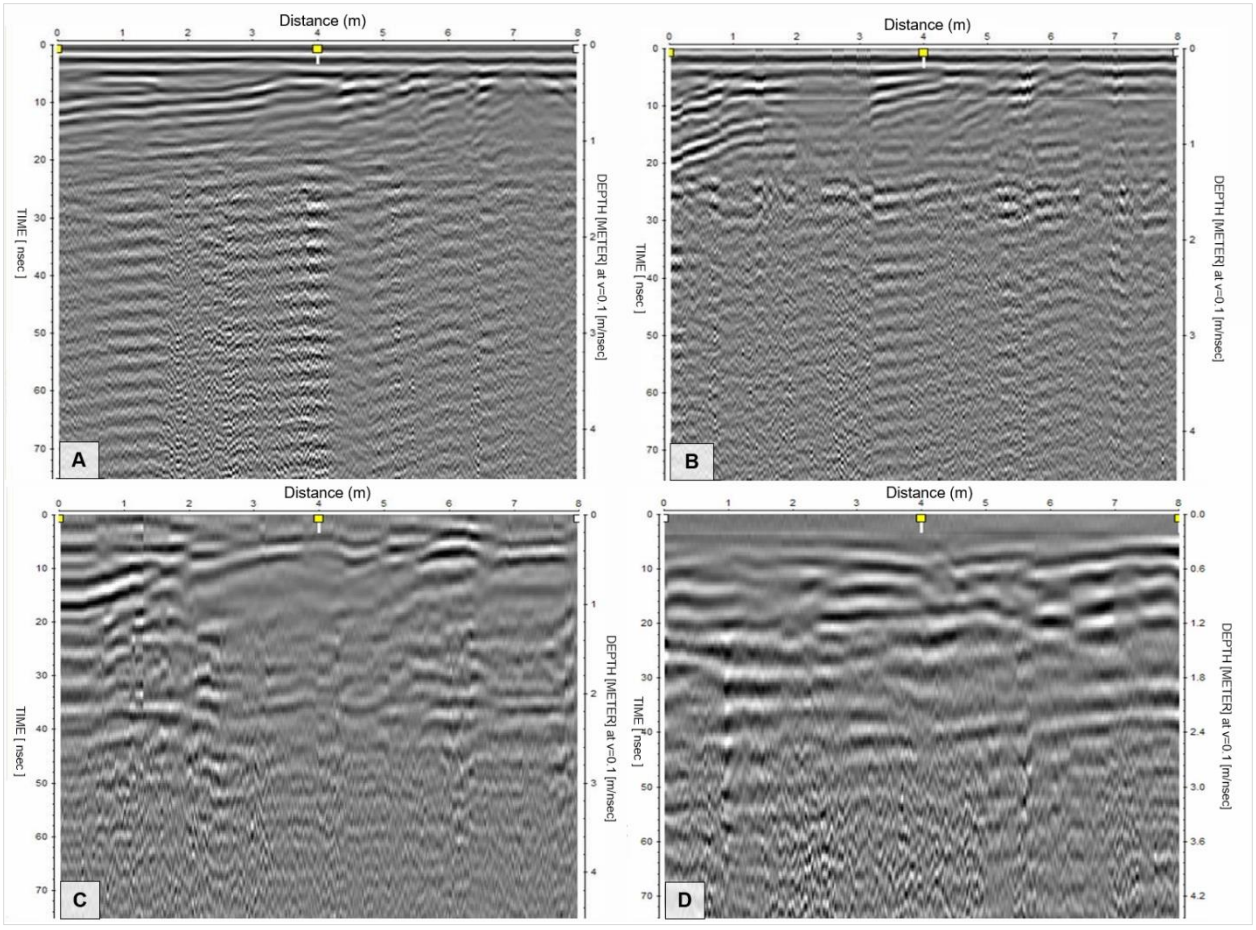


Figure 2. GPR scanning failed to detect subsurface known cavity. (A and B) represent 500MHz data that acquired in different parameters and processed by different processing flow. C) Shows 250MHz antenna result that indicates to attenuation after 1.2 m and D) shows 250MHz antenna result after putting Tin plate inside the cave, which serve as a reflector of GPR signals.

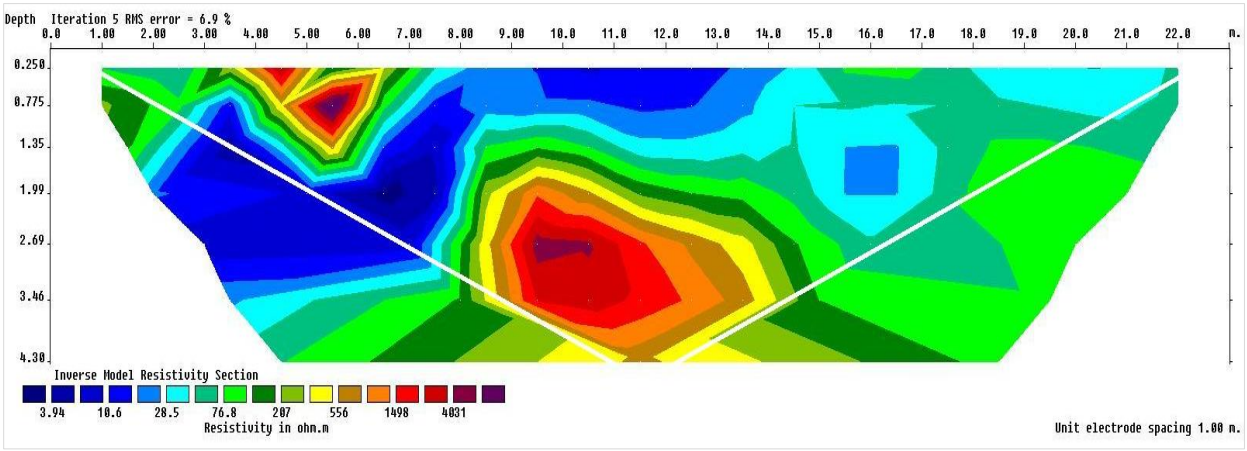


Figure 3. Electrical Resistivity Tomography profile matching the natural and visible cavity located at a distance of 10 m and a depth of 2 m.

ERT successfully located and precisely defined the position of deeper subsurface structures and cavities, making it the preferred technique for imaging deep targets at this specific site. When GPR data exhibits high attenuation, ERT serves as the primary alternative geophysical method for site evaluation. To maximize horizontal resolution when targeting narrow features like cavities, the dipole-dipole array is recommended due to its high sensitivity to localized high-resistivity targets. However, the Wenner-Schlumberger array provides a better signal-to-noise (S/N) ratio while maintaining a balanced sensitivity to both horizontal and vertical structures.

Novel/Additive Information

This research provides a critical benchmark for subsurface hazard detection in the limestone Formation by quantifying the failure points of GPR in conductive near-surface environments. Unlike theoretical models, this study uses a 'ground-truth' controlled experiment with internal reflectors (tin plates) to prove that GPR attenuation in limestone-clay sequences occurs rapidly beyond 1 meter where the resistivity values below 75 ohm.meter. Furthermore, it validates a specific ERT inversion workflow that successfully overcomes these conductive sequences, providing a proven geophysical template for the massive infrastructure expansion currently occurring in the region.

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