

Cluster analysis of 3D SRT and ERT in urban environment: cavity detection in Agrigento (Italy)

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Summary

Subsurface cavity detection in urban environments poses significant challenges due to restricted access, complex stratigraphy, and anthropogenic noise. This study presents an integrated 3D geophysical approach applied in the historical center of Agrigento (Italy), aimed at identifying potential underground voids beneath narrow streets and densely built areas. A combined acquisition of Electrical Resistivity Tomography (ERT) and Seismic Refraction Tomography (SRT) was conducted using a C-shaped sensor layout tailored for confined urban settings. Both datasets were independently inverted and subsequently integrated using a non-hierarchical k-means cluster analysis within a voxel-based domain. The clustering technique, originally developed for 2D data, was extended to 3D tomographic volumes, allowing for enhanced detection of anomalous zones based on the spatial correlation of high resistivity and low seismic velocity. The results revealed three main anomalous volumes interpreted as potential cavities, with the most prominent located at shallow depth near the intersection of Via Alletto and Vicolo Cobaitari. This methodology proved effective in overcoming typical limitations of urban surveys, providing a replicable strategy for high-resolution, non-invasive subsurface diagnostics. The findings contribute to urban geohazard assessment and offer valuable support for planning and risk mitigation in areas with known or suspected subsurface instability.

Cluster analysis of 3D SRT and ERT in urban environment: cavity detection in Agrigento (Italy)**Introduction**

Urban areas present a unique challenge for geophysical investigations due to the presence of buildings, underground utilities, and limited space for deploying equipment. In cities with historic centers, such as Agrigento, the complexity is heightened by the potential presence of ancient voids, tunnels, and anthropogenic structures, often undocumented and spatially unpredictable. These conditions require the development of tailored methodologies that are both non-invasive and adaptable to irregular survey layouts.

This study presents the results of a high-resolution geophysical investigation carried out in the constrained urban area of Agrigento (Sicily, Italy), specifically in the area of Via Cobaitari, Via Alletto, and Vicolo Cobaitari. The site selected for this study is characterized by a combination of geotechnical instability and urban constraints. It lies within the historical center of Agrigento, an area underlain by alternating calcarenite and marly formations with known susceptibility to subsurface void formation due to both natural karst processes and anthropogenic excavation. This geological setting, coupled with structural concerns related to existing buildings, necessitates an effective method for void detection.

The primary objective was the identification of potential underground cavities and the geotechnical characterization of subsurface materials in a densely built area with limited access. The methodology integrates Electrical Resistivity Tomography (ERT) and Seismic Refraction Tomography (SRT) using a C-shaped electrode/geophone geometry, optimized for narrow streets and confined spaces (Figure 1).

The interpretation was integrated through a cluster analysis applied to their respective inversion models. This integrated methodology aims to improve the resolution and reliability of subsurface cavity detection in geologically complex and physically inaccessible urban areas. Additionally, this work extends the cluster-based interpretative framework originally introduced by Carollo et al. (2020) for 2D profiles, applying it for the first time to volumetric (3D) tomographic models derived 3D inversions.



Figure 1: Map of the geophysical survey layout showing the C-shaped sensors alignment used for both ERT and SRT data acquisition. In blue dots, the position of the 48 receivers.

Method and/or Theory

A key aspect of the approach was the use of a C-shaped sensor array, which allowed the investigation to reach otherwise inaccessible portions of the subsurface beneath or adjacent to buildings. This layout was critical in adapting the survey to the urban environment's narrow streets and irregular spaces (Tejero-Andrade et al., 2015; Martorana et al., 2023) enabling continuous coverage and improving the resolution of the geophysical imaging.

The geoelectrical surveys were conducted using a mixed dipole-dipole / full range gradient array (Martorana et al., 2023) with 48 electrodes and a MAE X612-EM resistivimeter. This setup enabled fast data acquisition and preliminary in-field pseudosection visualization. Electrodes were spaced 3 meters apart, with acquisition designed to maximize subsurface coverage despite spatial constraints. Apparent resistivity values were processed through a non-linear least-squares inversion algorithm based on a finite element model (Loke & Barker, 1996), producing both 2D and 3D resistivity models. The choice of a mixed dipole-dipole/multiple gradient configuration provided enhanced depth penetration and lateral resolution, particularly effective in urban environments where surface access is fragmented. The 2D and 3D ERT imaging allow for differentiation of lithological units based on resistivity contrasts, which are particularly useful in identifying high-resistivity anomalies potentially associated with voids or dry calcarenite blocks.

The SRT acquisition employed a MAE X610-S seismograph with vertical and horizontal geophones co-located with the ERT electrodes. The seismic acquisition employed stacking and signal filtering techniques to maximize signal-to-noise ratio, crucial in noisy urban settings. First-arrival times were processed using WET (Wet Tomography Eikonal Traveltime) inversion, which utilizes wavefront modelling (Zhou & Greenhalgh, 2000) to enhance depth accuracy and resolve complex refractor geometries. The seismic data were particularly sensitive to changes in elastic moduli, with low P-wave velocities indicating possible weakness zones or cavities within the subsurface. The theoretical framework for the inversion process follows the classical formulation of Tarantola (2005), emphasizing model optimization based on travel-time fitting.

Independently inverted ERT and SRT datasets were integrated through a non-hierarchical cluster analysis (k-means), following and extending the methodology introduced by Carollo et al. (2020). The method was previously validated on synthetic models simulating both anomalous and non-anomalous structures and field-tested on a limestone quarry with known subsurface cavities. While the original approach was applied to single 2D profiles, in this study the clustering technique is applied to a 3D tomographic framework aggregated into a coherent voxel-based volume. The joint analysis was carried out within a voxel-based domain, using a binary classification scheme based on threshold combinations of physical parameters—specifically, high resistivity and low seismic velocity—to identify zones potentially associated with cavities or altered foundation materials. In this application, ERT and SRT data were acquired with co-located sensor arrays to maximize spatial correlation and ensure consistent input for the clustering algorithm. Furthermore, the spatial coherence of the identified clusters across adjacent tomographic planes was evaluated to reduce false positives and enhance the robustness of the interpretation in highly heterogeneous urban settings.

Results

The 3D ERT model (Figure 2a) revealed heterogeneous resistivity structures with clear vertical and lateral discontinuities. Low-resistivity zones ($<300 \Omega \cdot m$), generally associated with marly sediments (Trubi formation), were found interbedded with high-resistivity anomalies ($>1000 \Omega \cdot m$) near the surface, which may correspond to calcarenite blocks or anthropogenic voids.

The 3D SRT model (Figure 2b) showed similar stratification. High-velocity zones ($>1500 \text{ m/s}$) indicated compacted calcarenite layers, while shallow low-velocity zones ($<1500 \text{ m/s}$) were interpreted as potential cavities or fracture zones. These seismic anomalies correlated spatially with resistive anomalies, enhancing confidence in void detection.

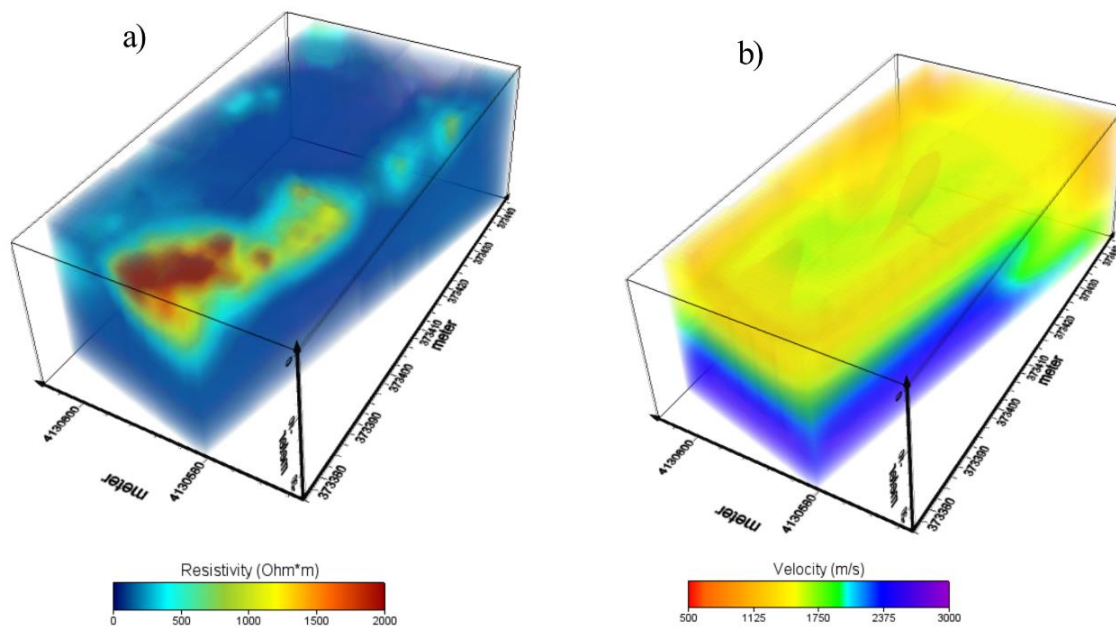


Figure 2: a) 3D resistivity model showing high-resistivity anomalies near the surface, indicative of calcarenite zones and potential cavities; b) 3D seismic velocity model displaying near-surface low-velocity layers, likely associated with altered or unconsolidated foundation soils, or possibly cavities, overlying deeper, higher-velocity layers interpreted as seismic bedrock.

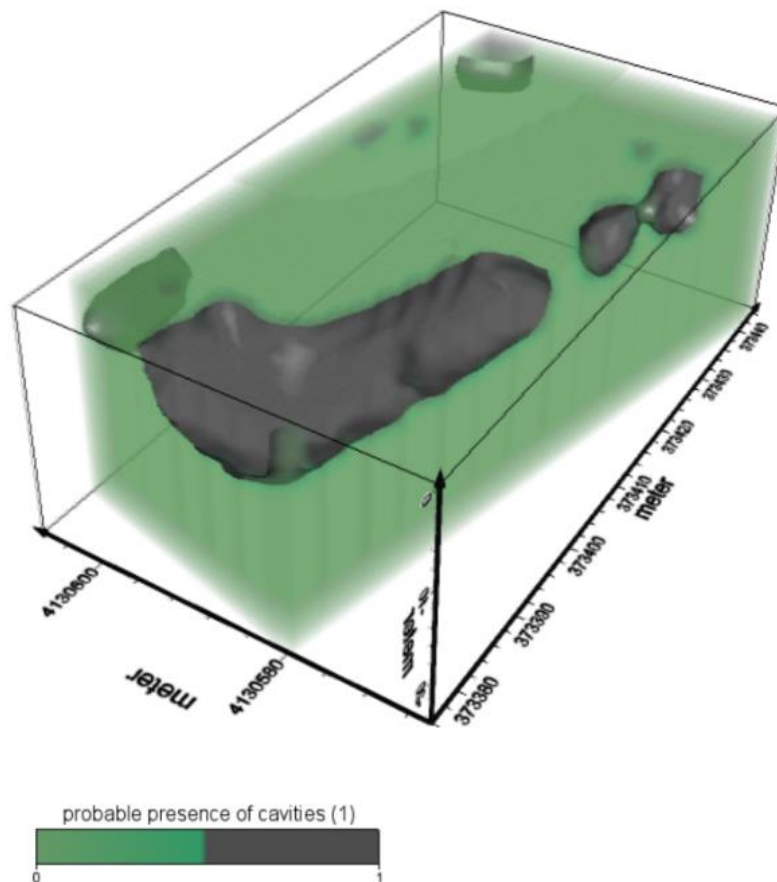


Figure 3: Results of the cluster analysis highlighting high-probability cavity zones (high resistivity and low seismic velocity) in grey.

The cluster analysis highlighted three main anomalies with a high probability of cavity presence (Figure 3). The most prominent is located near the Via Alletto and Vicolo Cobaitari intersection, starting at ~1 m depth. Two secondary anomalies were detected in Via Alletto and western Via Cobaitari at 1–3 m depth. These zones are characterized by the coincidence of high-resistivity and low-velocity features, indicative of possible underground voids. These high-probability zones of void presence are clearly visualized in the cluster analysis results, where affected volumes are shown in grey. The analysis was further supported by a consistency check of cluster continuity along the tomographic sections, helping distinguish likely voids from isolated inversion artifacts. The 3D rendering of cluster outputs facilitates spatial understanding of risk areas beneath the urban surface.

Conclusions

This study confirms the value of integrating 3D Electrical Resistivity Tomography and Seismic Refraction Tomography for the detection of underground cavities in complex urban environments. The adoption of a C-shaped electrode configuration, adapted to the spatial constraints of the investigation area, proved to be particularly effective for acquiring high-resolution data in settings where standard grid layouts are not feasible. The resulting resistivity and velocity models revealed coherent subsurface anomalies, and their joint interpretation through cluster analysis significantly improved the reliability of the cavity detection process. The observed spatial correspondence between high-resistivity and low-velocity zones supported the hypothesis of potential voids, thus providing a solid geophysical basis for evaluating structural risk in the context of urban redevelopment. This methodology demonstrates how flexible acquisition geometries, coupled with integrated data processing techniques, can overcome the challenges typically associated with restricted urban areas. Furthermore, the successful application of cluster-based voxel classification highlights the potential for more advanced interpretative approaches, including future integration of machine learning techniques. The extension of the 2D-based clustering method to a volumetric interpretation domain represents a key advancement, offering increased spatial context and interpretative stability across complex survey layouts. Overall, the investigation illustrates a replicable strategy for non-invasive geophysical diagnostics that can inform planning and safety measures in similar urban settings.

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