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Contribution of geophysical methods for detecting underground cavities in the Abda-Doukkala region (Morocco)

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Abstract The present paper examines the contribution of geophysical methods to the detection of underground cavities, with a particular focus on a case study in the Sahel region between El Jadida and Safi. This coastal area, marked by urban development and critical infrastructure, faces significant risks due to cavity formation and potential subsidence, which pose threats to local populations and essential transport networks. To address these challenges, the study employs an integrated geophysical approach, combining Electrical Resistivity Tomography (ERT), Ground-Penetrating Radar (GPR), and borehole drilling. Each method plays a distinct yet complementary role in cavity detection. ERT identifies resistivity anomalies associated with subsurface voids, offering insight into deeper structures. GPR provides high-resolution imaging of shallow subsurface features, allowing for the identification of cavities near the surface. Borehole drilling serves as a direct validation tool, confirming anomalies detected by ERT and GPR. The integration of these methods enhances the precision, reliability, and depth of cavity detection, enabling accurate mapping and characterization of underground anomalies. This methodological synergy facilitates risk assessment and early intervention, offering a robust framework for monitoring subsidence-prone areas and supporting decision-makers in the implementation of preventative measures. By safeguarding infrastructure and local communities from potential collapses, this study highlights the importance of geophysical techniques in mitigating geotechnical hazards. The results underscore the vital role of geophysics in enhancing safety, infrastructure resilience, and sustainable urban development in vulnerable coastal regions, demonstrating the effectiveness of multidisciplinary approaches to addressing complex subsurface challenges. This approach promotes proactive risk management, reducing potential socio-economic impacts and ensuring long-term infrastructure sustainability.

Keywords: underground cavity detection, electrical resistivity tomography (ERT), ground-penetrating radar (GPR), infrastructure resilience, karst collapse, infrastructure development

1. Introduction

With rapid urbanization, many areas once considered stable are becoming vulnerable, underscoring the importance of risk assessment and management to ensure public safety. Urban expansion often leads to increased construction of buildings, roads, and underground infrastructure, which places additional stress on the subsurface environment. The collapse of underground cavities, whether due to natural phenomena such as karst erosion or human activities such as mining and infrastructure development, poses a major risk to urban areas. These events, often unpredictable, lead to dramatic consequences, as demonstrated by the 2010 collapse in Guatemala City, where a 60-meter-deep sinkhole swallowed several buildings, exposing infrastructure and populations to severe dangers (Fu, 2022; Hermosilla, 2012). Similar incidents have been reported in various parts of the world, causing economic losses, displacing communities, and endangering human lives. Given the increasing frequency and severity of these events, there is a pressing need to develop effective methods for early detection and risk mitigation.

Detecting underground cavities before they lead to catastrophic collapses is crucial for ensuring public safety and protecting critical infrastructure. The inability to predict such collapses poses a significant challenge for urban planners, engineers, and policymakers. This article examines the impact of such collapses on infrastructure and populations, emphasizing the importance of detecting these cavities through geophysical methods. By employing techniques such as Electrical Resistivity Tomography (ERT) and Ground-Penetrating Radar (GPR), this study seeks to establish a reliable framework for identifying subsurface anomalies. The outcomes of this study aim to inform decision-making processes, support the development of

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preventative measures, and promote sustainable urban development in geotechnically vulnerable areas. This research is essential for advancing risk mitigation strategies and enhancing the resilience of urban environments in the face of growing geotechnical challenges.

2. Review of the Literature

2.1. Impact of Underground Cavities (Karstic Areas) Collapsing on Infrastructure and Public Safety

In light of the growing risks posed by underground collapses, it is crucial to increase awareness and understanding of the true impact that these events in karst regions or areas with underground cavities have on daily life, especially concerning infrastructure and public safety. In Italy, especially in some regions, such as Emilia Romagna or Apulia, safety concerns are greater than they are in the rest of the world because karst areas constitute a significant portion of our national territory. In all the approximately 3000 km² affected by underground cavities and abandoned mines, particularly in the central and southern areas of the nation, there is a rich network of roads, railway lines, towns, industrial plants, and all kinds of socioeconomic settings (Andriani and Loiotine, 2020). The energy that karst areas can transmit into the ground above, from underground groundwater flows to convection lifts, can induce or accelerate original surface/subsurface instability phenomena, such as landslides, collapses, and crack openings. In particular, the bottom selection or fragmentation of a void at a given depth can transform underground environmental matter into a heavily dimensioned inclined conduit capable of injecting very high hydraulic, mechanical, and chemical energy into the underground environment, causing significant collapse at the ground above (Reina and Loi, 2020). According to (Vennari and Parise, 2022), the cavities that may collapse can have different shapes, geometries, and morphologies: the literature reports simple caves, meander caves, dug tunnels, or crypts, and mining works. To paraphrase, the cavities that may collapse can be classified into two main categories, depending on their conservation state and filling material: full cavities, with complete or very diluted filling, and empty chambers, not showing any filling or with limited deposits. Some state-of-the-art information on collapses in cavities, such as (Esposito et al., 2021; Margiotta et al., 2021; Stevanović and Stevanović, 2021), suggests that despite the evolution of survey and monitoring techniques, recognizing the presence of cavities underground until collapses or even disasters occur is difficult. The best solution is a preventive one, putting together, in the area affected by a given collapse, a deeper geological survey and a geophysical survey in a strategic sector. A trapped void can also be avoided by setting a source and a detector that considers the primary underground hydrodynamic convective system in the touristic zone.

2.2. Cavities collapse literature examples

This section presents several case studies from the literature to illustrate the impact of sinkholes and underground cavity collapses on urban areas.

An illustrative example of the dangers posed by sinkholes in urban areas can be seen in Winter Park, Florida, where in 1981, a massive sinkhole opened in a karst-prone area (Beck, 1984). Measuring approximately 100 m in diameter and 30 m deep, this sudden event caused significant structural and financial damage as roads were destroyed, and several vehicles, homes, and swimming pools were engulfed. This incident highlighted the pressing need for thorough risk assessments in urban planning, particularly in regions susceptible to karst activity.

(Toulkeridis et al., 2016) expose the Guatemala city example, Guatemala (2010). A sinkhole approximately 60 m deep and 20 m wide formed suddenly after heavy rainfall from Tropical Storm Agatha. The collapse affected a densely populated area, causing buildings to fall into the cavity and displace families. This case highlights the severe risks of rapid urbanization in geologically sensitive zones.

In Saint-André-d'Apchon, France, in 2014, an abandoned coal mine triggered a cavity collapse that damaged a national road and nearby homes, leading to emergency evacuations (Namjesnik et al., 2022). The incident emphasized the dangers posed by old mines near residential areas and the importance of stabilizing such sites.

Finally, in Fukuoka, Japan (2016), a road collapse occurred near a subway construction site, creating a 30-meter-wide and 15-meter-deep cavity that disrupted traffic and damaged local utilities. A swift government response revealed that the road was repaired in just one week, highlighting the value of efficient crisis management in dense urban areas (Tabassum et al., 2022; Tan and Long, 2021).

Each of these cases highlights unique challenges associated with cavity collapses in various urban settings, underscoring the importance of geological surveys, infrastructure planning, and rapid response to safeguard public infrastructure and safety.

2.3. Detection and Monitoring Techniques

Several detection techniques and methods are currently used for identifying caves, sinkholes, voids, and cavities, as well as monitoring their potential collapses. As outlined by Hussain et al. (2020), advanced noninvasive technologies, such as ground-penetrating radar, are used to gather useful data on the presence of underground cavities. Additionally, remote sensing derives important information about the characteristics of karst depressions included in detailed engineering geological maps and plans. Furthermore, geophysical methods often use versions of seismic hypocenter determination as tools to study earthquakes. Some of these methods can detect cavities and, at the same time, estimate depth, size, and shape to assess the internal and external morphologies of caves (Funk et al., 2024; Hajna et al., 2024; Ocakoğlu et al., 2024). To assess the conditions of the subsoil, thus guaranteeing the safety and stability of any existing infrastructure, it is necessary to carry out extensive geophysical surveys since investigations of karst environments are continuously progressing. The spontaneous potential values are affected by the presence of turbulent waters circulating in subsuperficial structures, which, according to the geologic-tectonic context, are normally complex and not easily interpretable karst systems. Several monitoring systems are used to detect the initial stages of sinkhole collapse and analyze its eventual evolution over time, thus increasing public safety (Fu, 2022; Liu et al., 2024). Damage produced by the collapse of the sinkhole can be considerably reduced if it is predicted in advance, during the insignificant stage, by the continuous monitoring system. Geographic information system-based methods were applied to evaluate the favorable areas where caves and sinkholes could eventually collapse. Referring to (Anbazhagan and Panjami, 2024; Putiška et al., 2021; Vyzhva et al., 2020), the identification of collapse-related criteria in the selected areas allows the cadaster of possible sinkhole areas to be prepared, and criteria decision analysis may be used to build a priority classification. Nevertheless, owing to the complexity of the karst environment, recognizing sinkholes is highly difficult. This is because the bodies responsible for detecting new cavities and verifying the risk are unaware of one another. There is a need for good performance on the part of technology, necessitating more reliable and competitive technological solutions (Farfour et al., 2020; Toulkeridis et al., 2016).

2.4. Abda doukkala case study

The Doukkala–Abda region in Morocco is one of the areas highly exposed to the risk of underground cavity collapse. The region's geology is characterized by the presence of karst and gypsum. When dissolved by water run-off, these materials create natural underground cavities. The region also contains a number of artificial cavities (former quarries, underground grain storage shelters, underground water reservoirs, etc.).

These underground cavities present potential risks of collapse, which can cause significant damage to infrastructure foundations and buildings (Soussi et al. 2020).

This article presents the contribution of geophysical methods to the detection of underground cavities in the Sahelian subsoil.

The following are illustrations of cavities available in the Sahel region (Figures 1, 2 and 3). A distinction is made between artificial cavities (man-made) and natural cavities:

2.4.1. Artificial cavities:

These cavities are often shallow and limited in volume. They generally have a gallery entrance or a small-diameter well in a talweg.

2.4.2. Natural cavities

The natural cavities found at the site are classified into three types:

- Decametric to hectometric sinkholes: large surface depressions caused by the collapse of underground cavities;
- Karstic dissolution conduits;
- Underground cavities created by the dissolution of gypsum by water runoff.

Natural cavities originate from:

- Karstic (dissolution of limestone),
- Related to erosion,
- Or a combination of the two.

Figure 1 Limestone erosion near the town of Oualidia.

Figure 2 Gypsum dissolution between Oualidia and Safi.

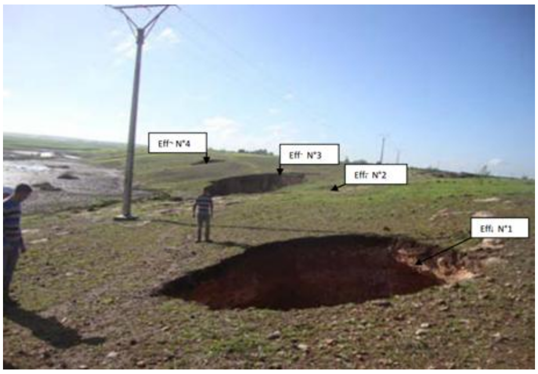

Figure 3 Underground collapse in the rural municipality of Moul El Bergui near Safi following heavy rainfall in November 2014 (presence of gypsum in the area).

3. Materials and methods

The method used in this work for the detection of underground cavities is geophysics coupled with anomaly control drilling.

It consists of carrying out an electrical tomography scan coupled with destructive drilling, with parameter recordings (Soussi et al., 2018, Ait Elfakih et al., 2018, 2020; Boualla et al., 2021).

These boreholes are used to check the anomalies revealed by electrical tomography profiles (Ouadif et al. 2012, 2014, 2015).

Another prospecting method could be Georadar (MASSAAD et al., 2014, Grégoire et al., 2018).

As a result, several areas are likely to develop cavities that can rise to the surface.

3.1. Electrical tomography investigation

3.1.1. Principle and limitations

The aim of electrical resistivity tomography (ERT) is to provide multidimensional recognition of the intrinsic electrical properties of the object under study (soil or material sample). In this method, an electric current is injected into the object under study via a pair of electrodes. The resulting electric field is a function of the electrical resistivity distribution in the body and is measured via another pair of electrodes. The measurements are then repeated by positioning the electrodes at different points on the object. By an interpretation procedure, called inversion, we then seek to define the presence of heterogeneities, more or less resistant, in the object that influence the distribution of the electric field for the different measurements (Figure 4).

The electrical resistivity tomography method consists of passing an electric current through the soil between two current electrodes, A and B, and measuring the potential difference between two other electrodes, M and N, called potential electrodes, in the vicinity of the current electrodes. Since the current intensity I is known and the potential difference ΔV is measured, it is possible to determine the apparent resistivity of the soil under study. This apparent electrical resistivity depends on the configuration of the current and potential electrodes. The apparent electrical resistivity ρa can be expressed as a function of the potential difference and current intensity (Ward, 1990) (Equation 1):

$$\rho_a = K\frac{\Delta V}{I} \qquad (1)$$

where K is the geometric factor, which depends on the electrode configuration (Equation 2).

$$K = 2\pi \left(\frac{1}{AM} - \frac{1}{BM} - \frac{1}{AN} + \frac{1}{BN}\right)^{-1} \qquad (2)$$

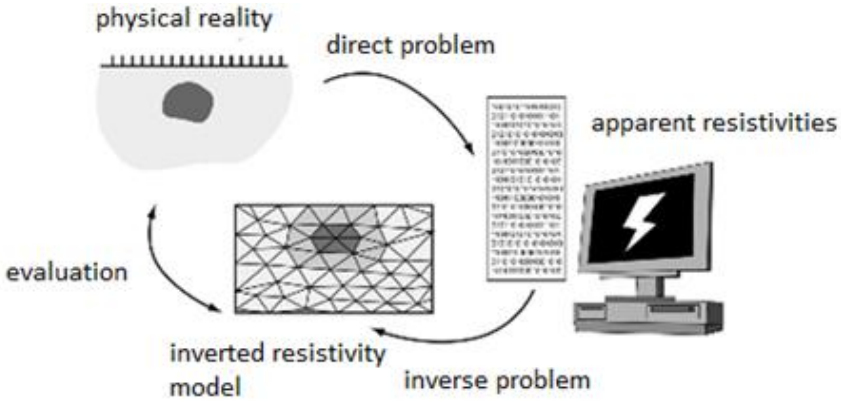

Figure 4 Principle of electrical imagery and definitions of direct and inverse problems.

3.1.2. Data processing and modeling

3.1.2.1. Data acquisition

Tomography measurements were acquired along 4 electrical profiles of 64 electrodes distributed across each studied soil. The device configuration chosen for the study was the Schlumberger device, which is recommended for the study of lateral facies variations. The distance between the electrodes was set equal to 3 m to ensure good resolution in the first few meters of the subsoil (10 to 15 m below the surface).

The data are presented in the form of apparent resistivity panels whose horizontal and vertical axes correspond to the distance along the profile and the separation between the two mobile electrodes, respectively. On the panels, measurements are plotted in the middle of the acquisition device at a height corresponding to the current separation between the mobile electrodes. Subsurface models showing the cross-sectional distribution of resistivity are calculated from the panels via the data inversion method.

Example of an electrical panel with a dipole–dipole device (Figure 5):

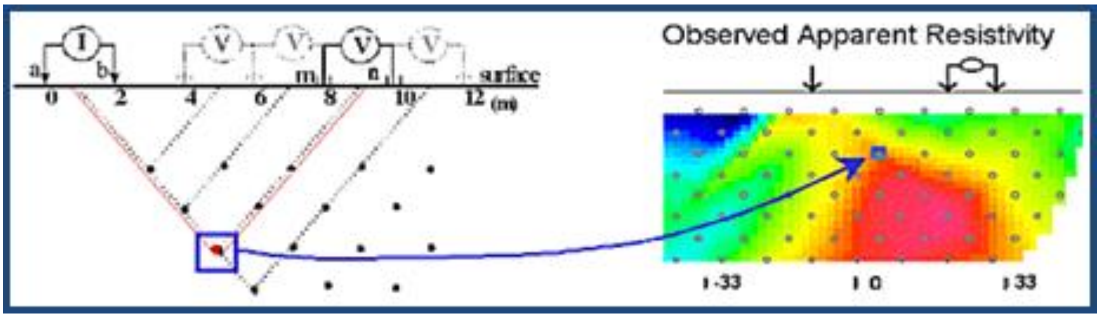

Figure 5 Pseudosection construction.

This makes it possible to obtain models of the subsurface in the form of sections of the true resistivity of the terrain explored.

3.1.2.2. Analysis and interpretation

A detailed analysis of these models reveals the significant variations in intrinsic resistivity, defining several buried resistive and conductive sources in relation to a host rock whose mean background level varies to a greater or lesser extent depending on the location of the tomography profiles.

We are particularly interested in resistant sources likely to correspond to underground cavities (excessively high anomalies of up to 30000 Ω.m) and conductive sources likely to correspond to gypsiferous layers or cavities or sinkholes (low resistivities of less than 200 Ω.m). Thus, for each subsoil model obtained via inversion, these resistive sources were delineated on the basis of the sources' intrinsic resistivity values, their shapes and the density of the contours that delineate them. The resulting bodies have a variety of shapes and sizes. A geophysical anomaly linked to a karst conduit can be measured only if the depth of the karst conduit is too great in relation to its dimensions. In this case, structures linked to the development of the karst network can be detected, such as zones of intense fracturing in the epikarst zone.

3.2. Geo radar investigations

Geo-radar (GPR ground penetrating radar) works on the principle of studying the propagation of an electromagnetic wave in the object under study.

It provides real-time images of the subsurface for precise determination of its characteristics (Grégoire et al., 2018).

The results are presented in the form of a radargram similar to an ultrasound or seismic image.

Geo-radar provides 6 main types of signatures:

- Type A: open cavity, presence of unfilled voids
- Type B: cavity with probable filling
- Type C: interface with varying degrees of fracture index
- Type D: Diffraction hyperbola, very punctual anomaly
- Type E: presence of heterogeneities with the possibility of voids (macroporosity)
- Type F: significant local geological variation (contact, rift, etc.).

4. Results

The tomography results presented below are interpreted and correlated with those of the boreholes. They relate to areas located between Sidi Smail and Safi:

The location of the tomographic profile is shown below (Figure 6):

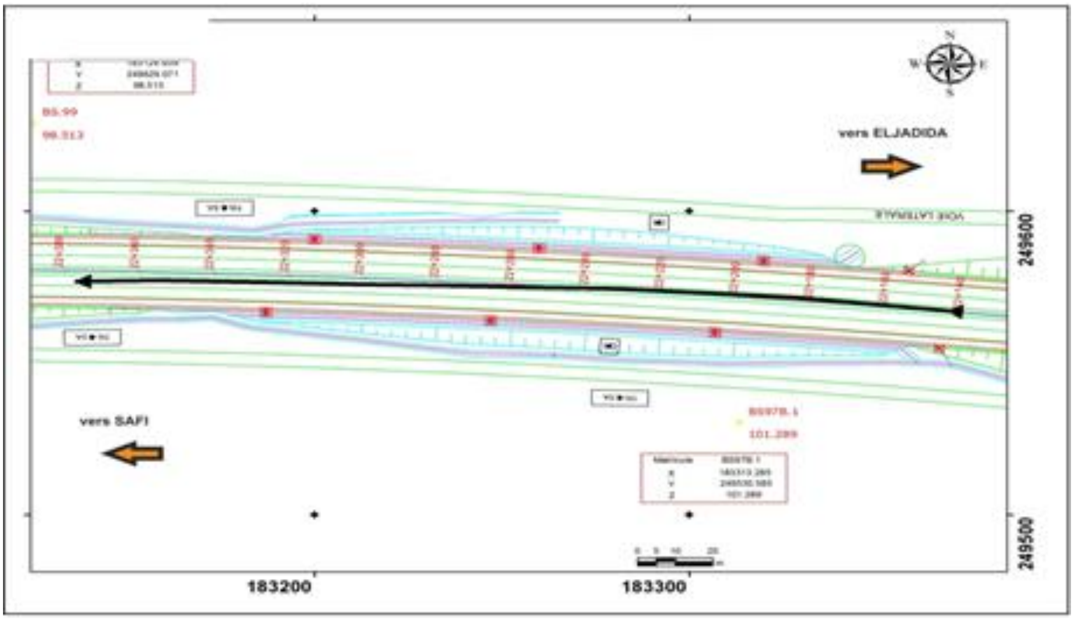

Figure 6 Tomographic profile location.

Analysis of the resistivity profile at two depths of 12 m/TN (distance between electrodes 3 m) revealed the following (Figure 7):

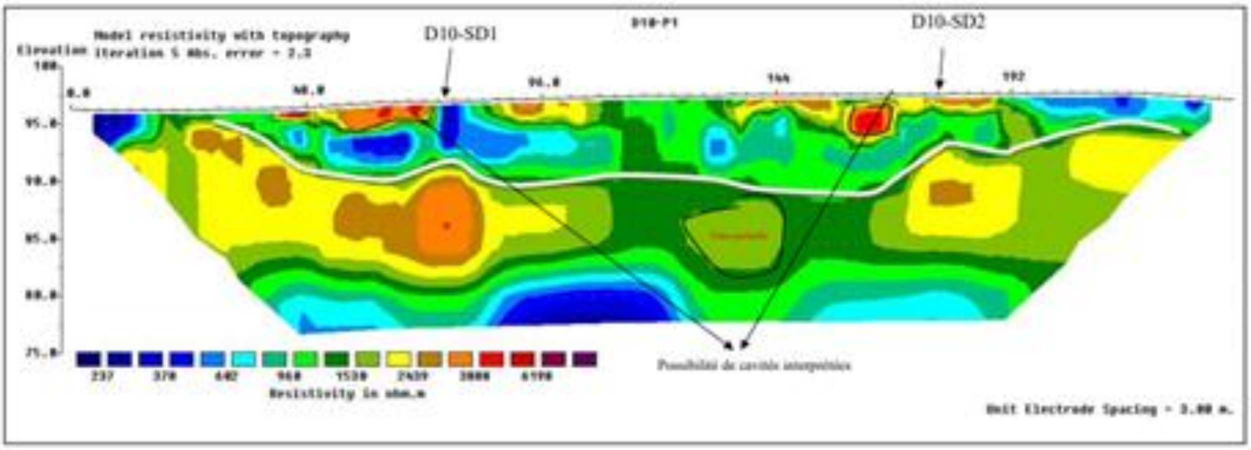

Figure 7 Electrical resistivity model.

- Conductive blue horizons with resistivity values between 240 Ω.m. and 600 Ω.m. from a depth of 5 m may correspond to shell sandstones.
- Resistant horizons (green and red zones) with resistivity values between 800 Ω.m and 6200 Ω.m correspond to lumachelic limestone sandstones that may also be sites of extensive fracturing and possibly cavities.
- Some suspect areas of high resistivity (red and green) are visible in the resistivity profiles above (Figure 7). These zones can be interpreted as voids in view of their geometry.

In light of the results of this profile, two test holes, each 15 m deep, were drilled in this zone (D10-SD1 and D10-SD2). Only borehole D10-SD1 below (Figure 8) confirmed the presence of a cavity at a depth of approximately 7 m, measuring 0.70 m.

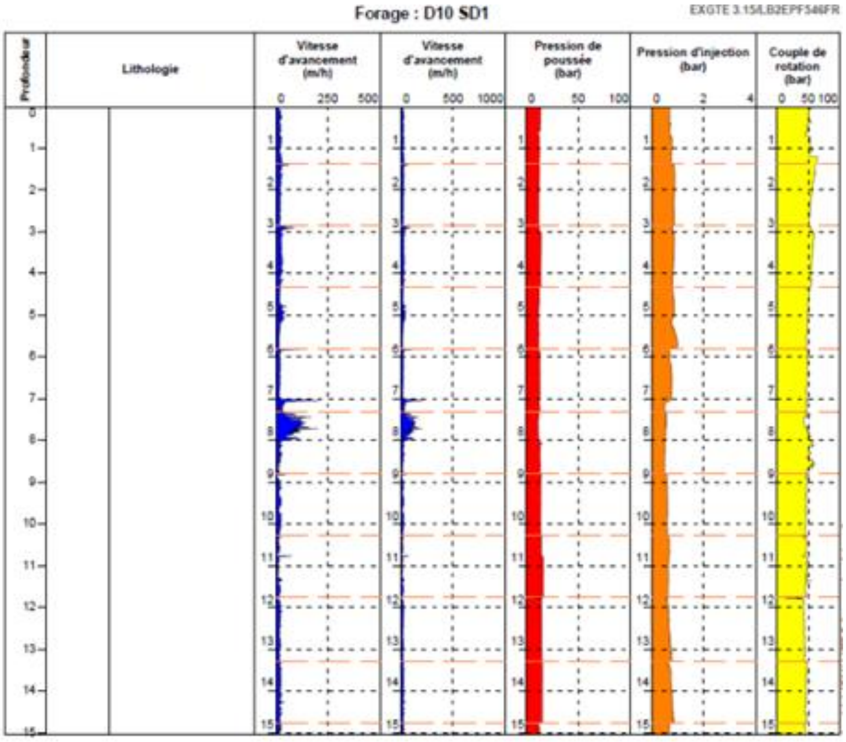

Figure 8 Cavity confirmed at a depth of 7 m at SD1.

For the georadars, some results illustrate the presence of cavities (Figures 9 and 10):

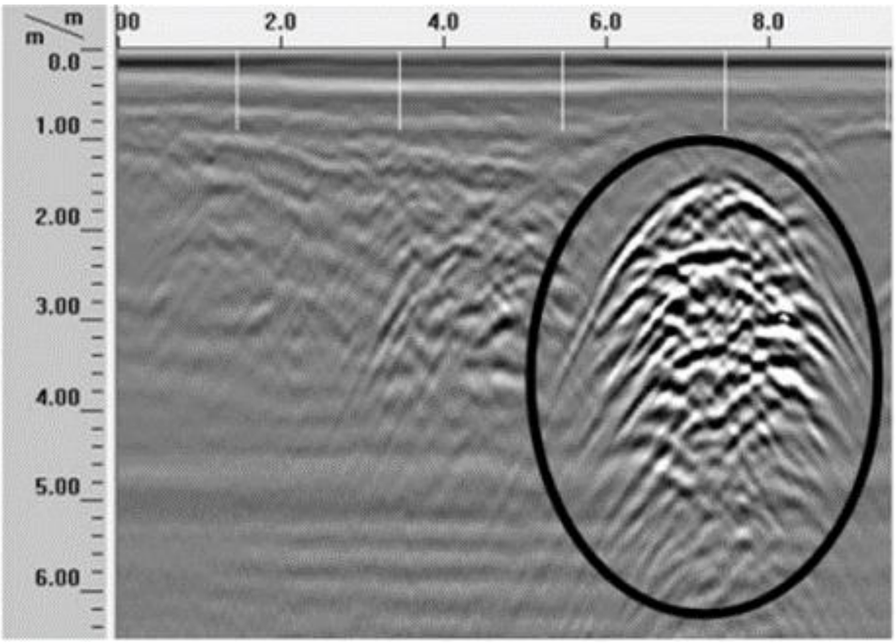

Figure 9 Cavity radargram-lear cavity radar signature.

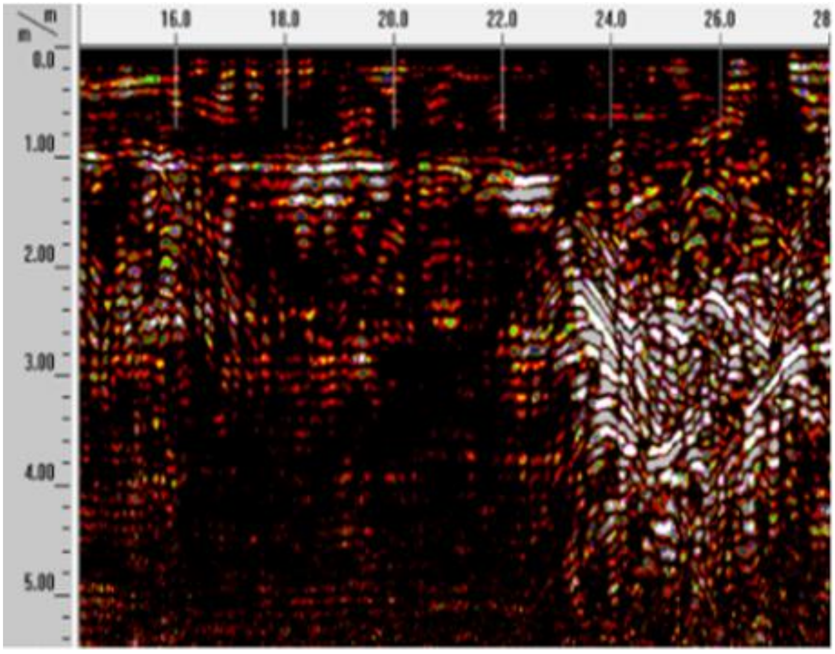

Figure 10 Cavity radargram - Decompression-type radar signature near a sinkhole.

The georadar method is refined by creating several profiles in places where the dielectric constant of the terrain allows electromagnetic waves to penetrate. This method is justified by its simplicity and short lead time.

5. Discussion

The results obtained from Electrical Resistivity Tomography (ERT), borehole drilling, and Ground-Penetrating Radar (GPR) in the region between Sidi Smail and Safi provide valuable insights into the detection and characterization of underground cavities. The resistivity analysis revealed the presence of conductive blue horizons with resistivity values between 240 Ω.m and 600 Ω.m, likely corresponding to shell sandstones, while higher resistivity values (800 Ω.m to 6200 Ω.m) identified in green and red zones were attributed to lumachelic limestone sandstones. These results are consistent with those reported in previous studies. For instance, Xiao et al. (2019) found that conductive layers with resistivity values below 500 Ω.m corresponded to clay and sandy materials, while higher resistivity (above 800 Ω.m) often signaled fractured rocks or potential voids. Similarly, Yusuf et al. (2021) detected limestone cavities in karstic environments using resistivity thresholds of 1000 Ω.m to 5000 Ω.m, which aligns with the findings from this study.

The identification of cavities at approximately 7 m depth, confirmed by borehole D10-SD1, further reinforces the reliability of the ERT method. This result mirrors the findings of Zhou et al. (2016), who confirmed that ERT is effective for locating shallow voids when combined with borehole drilling, with a success rate of 85% for depths under 10 m. The confirmation of a 0.70 m cavity at this depth highlights the role of borehole validation in reducing false positives in resistivity surveys. Other studies, like that of Chen et al. (2020), emphasized the significance of borehole integration, noting that resistivity anomalies alone can be caused by lithological changes or moisture content, leading to misinterpretation if unverified.

The GPR results from this study also show remarkable consistency with existing research. The identification of cavity radar signatures (Figure 6) and decompression-type radar signatures (Figure 7) near a sinkhole bears similarities to the radargram interpretations presented in the study by Abdullah et al. (2022). Their research established that hyperbolic reflections in GPR radargrams are often indicative of air-filled voids or decompression zones within karst formations. The observed signatures in this study align with these known radar patterns, further supporting the claim that GPR is a useful non-invasive method for identifying subsurface voids. The refined profiling approach, creating multiple GPR profiles, enhances the precision of anomaly identification. Hermosilla et al. (2018) also employed this multi-profile approach and reported improved detection accuracy in karstic areas, noting that single-profile interpretations often fail to capture the full extent of subsurface anomalies.

The combined use of ERT, GPR, and borehole drilling in this study demonstrates the effectiveness of an integrated approach to subsurface investigation. This approach is in line with the findings of Nguyen et al. (2021), who emphasized that a multi-method strategy improves accuracy in subsurface anomaly detection by compensating for the limitations of each individual method. While ERT is effective for detecting deeper anomalies, it may misclassify zones with high moisture content as voids. GPR, on the other hand, offers high-resolution imaging but is limited in depth penetration in clayey or water-saturated soils. Borehole validation addresses these limitations by providing ground-truth verification of detected anomalies.

The results of this study are consistent with findings from similar investigations and demonstrate the critical role of multi-method geophysical approaches in identifying underground cavities. The correlation between resistivity anomalies, radargram signatures, and borehole validation highlights the effectiveness of this combined approach. These findings have significant implications for risk assessment and the management of geotechnical hazards in urban areas. Future studies could benefit from employing 3D ERT models and automated radargram classification algorithms, as proposed by Zhang et al. (2023), to improve the precision of cavity detection and reduce reliance on borehole drilling. This study reaffirms the value of integrated geophysical approaches for detecting and mitigating subsurface risks in geotechnically vulnerable areas.

6. Conclusions

This study was carried out to highlight anomalous zones that are related to the presence of underground cavities. The areas described in this article are all located between the towns of El Jadida and Safi.

The investigations consisted of the following:

- Surface mapping via electrical tomography or the georadar method,
- Control of anomalies via destructive drilling with parameter recording.

Geophysical methods for investigating karstic cavities make it possible to delimit their presence and, if present, to define the geometry and volume of the cavity to determine the appropriate treatment. Investigations are carried out via advanced techniques, enabling the disorder to be identified, located and delimited in space, hence the need to combine indirect (geophysical) and direct (borehole) investigation methods. Direct methods focus on verifying and confirming geophysical results by coring or destructive drilling with systematic parameter recording.

Ethical considerations

Not applicable.

Conflict of interest

The authors declare that there are no conflicts of interest.

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