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Technical Note

A Geophysical Investigation in Which 3D Electrical Resistivity Tomography and Ground-Penetrating Radar Are Used to Determine Singularities in the Foundations of the Protected Historic Tower of Murcia Cathedral (Spain)

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Abstract: This study presents a procedure in which 3D electrical resistivity tomography (ERT) and ground-penetrating radar (GPR) were used to determine singularities in the foundations of protected historic towers, where space is limited due to their characteristics and location in highly populated areas. This study was carried out on the Tower of the Cathedral "Santa Iglesia Catedral de Santa María" in Murcia, Spain. The novel distribution of a continuous nonlinear profile along the outer and inner perimeters of the Tower allowed us to obtain a 3D ERT model of the subsoil, even under its load-bearing walls. This nonlinear configuration of the electrodes allowed us to reach adequate investigation depths in buildings with limited interior and exterior space for data collection without disturbing the historic structure. The ERT results were compared with GPR measurements and with information from archaeological excavations conducted in 1999 and 2009. The geometry and distribution of the cavities in the entire foundation slab of the Tower were determined, verifying the proposed procedure. This methodology allows the acquisition of a detailed understanding of the singularities of the foundations of protected historic towers in urban areas with limited space, reducing time and costs and avoiding the use of destructive techniques, with the aim of implementing a more efficient and effective strategy for the protection of other tower foundations.

Keywords: three-dimensional electrical resistivity tomography; ground-penetrating radar; tower foundation; cavity detection; historic building protection; non-destructive testing; built heritage

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1. Introduction

Currently, in the "European Framework for Action in the field of Cultural Heritage", the preservation and protection of cultural heritage are the responsibility of both individual countries and the European Union [1], which recommends that the invasiveness of tests should be restricted as much as possible [2]. Historic towers are part of cultural heritage due to their unique structural and architectural characteristics. They are slender protected buildings made of masonry constructed using traditional techniques; they have reduced interior space, and many of them are located in urban centres. Their cultural value has been threatened by various factors, such as poor foundations, tilting and cracking [3], and earthquakes [4], in addition to the passage of time.

The criteria for intervention in historical heritage are complex and must begin with a rigorous investigation of a building before any work is carried out. The aim is to acquire sound knowledge of a building that allows an accurate diagnosis to establish appropriate proposals of intervention. In this context, it is important to ensure the monitoring and

control of the foundations of historic towers because of the problems they can present. The foundation is the part of a building that connects the ground and the structure, and its condition can influence a building's health. Therefore, one of the main challenges regarding this type of protected historic building is developing non-invasive methodologies for diagnosing its foundation using high-resolution 2D or 3D images. The lack of space and the high degree of protection are the main onsite problems that need to be solved.

Along these lines, non-destructive techniques are increasingly being used to assess historic buildings and their surroundings [5–10]. The general procedure used to understand buried structures involves the use of various non-destructive geophysical techniques. Specifically, electrical resistivity tomography (ERT) surveys combined with other techniques such as ground-penetrating radar (GPR) are widely used in archaeological prospection [11–16]. They have also been applied inside historic buildings. Authors such as Ortega-Ramírez et al. [17] used ERT and GPR to locate and identify the remains of an ancient cathedral in the subsoil, and Evangelista et al. [18] used these methods to detect the geometry of the foundations of a bell tower.

In the specific case of protected historic towers for which the characteristics of their foundations are unknown, the application of the ERT method allows the electrical resistivity values of the subsoil materials to be determined with 3D models. These 3D models can be obtained in two ways: by means of the parallel distribution of 2D linear profiles, which are subsequently joined through software to form a 3D model [19], or by means of a continuous profile with a nonlinear distribution with which a 3D model is obtained [20]. The application using 2D parallel linear profiles in historic towers has several drawbacks and limitations, given the limited interior space available for placing linear profiles inside with a length sufficient for reaching adequate depths of investigation. Therefore, 2D ERT linear profiles could be deployed in the vicinity of a tower to reach sufficient depths of investigation. In this case, the subsoil around the tower would be characterised, but not its foundations [21]. In addition, the equipment used only measures between the electrodes of each 2D profile, obtaining a 3D model through interpolations between profiles, not with real measurements made between them [22]. Additionally, if a 2D profile is placed on the outside of a tower wall and another is placed parallel to it inside of the tower wall, the interpolation between profiles does not consider the bottom of the wall, so it is not possible to obtain reliable data on the area under the load-bearing walls.

Another limitation of the layout of 2D linear profiles is that it is necessary to create a number of longitudinal profiles according to the dimensions of the tower in order to obtain a 3D model, implying the need to go through the walls of the tower due to the reduced space, something unfeasible in this type of protected building. It is also necessary to have sufficient interior space to accommodate the minimum length of the surface profile, something impossible in historic towers due to their characteristics (reduced interior space) and the fact that they are often in urban centres or on protected sites.

Several authors have proposed different configurations depending on the characteristics of the analysed building and its environment to obtain 3D models. Jiang et al. [23] presented a design involving arbitrarily distributed electrodes in an urban environment, where each unit is independent and can be used as a current or potential electrode. Argote et al. [24] reported the application of linear L-shaped ERT profiles in each of the outer corners of the Pyramid of the Moon in Teotihuacán (Mexico), with the aim of providing information on the existence of cavities in the subsoil. Chavez et al. [25] investigated the subsurface of the El Castillo pyramid in Chichen Itza (Mexico) by combining different unconventional arrays (L arrays, corner arrays, equatorial arrays, and minimum-coupling arrays), although they obtained a shallow resolution in the central part of the 3D model due to a lack of data. Tejero-Andrade et al. [26] carried out a study on the same pyramid of El Castillo by means of the distribution of 10 profiles located by level around the pyramid with L arrays and corner arrays, presenting low vertical resolution. Almeida et al. [27] proposed the use of an odd–even pole–pole array to study the subsoil beneath historic buildings using different nonlinear configurations.

This study, focused on the Tower of the Cathedral of Murcia, highlights a procedure for investigating the possible singularities of the foundations of this type of historic structure to provide information for appropriate interventions. Using the 3D ERT method, with a continuous nonlinear profile along the external and internal perimeter of the Tower, a non-invasive 3D study of the entire foundation was carried out. A 3D ERT model of the subsoil of the building, including that under its load-bearing walls, was then obtained. At the same time, GPR measurements were taken to verify the data obtained in the interior area together with the existing archaeological documentation of the building. The geometry and distribution of the cavities were verified for the entire foundation slab, validating the proposed methodology.

Hence, the objectives of this study were to (i) determine the singularities in the foundation slab of a protected historic tower via 3D electrical resistivity tomography; (ii) use ground-penetrating radar to analyse the accessible inner surface of the Tower; and (iii) verify the data obtained via the methodology proposed with respect to previous archaeological studies of the site.

2. Materials and Methods

2.1. The Test Site

Murcia, situated in the southeast of Spain, is home to an important historic tower, the Tower of Murcia Cathedral. This building is part of the cathedral complex of the "Santa Iglesia Catedral de Santa María", a building with an area of almost 5000 m^2 that includes a church, a cloister, and a bell tower. This cathedral complex has been assigned the highest degree of protection, and it is located in the urban centre of the city (Figure 1).



Figure 1. Location map of the Tower of Murcia Cathedral: projection of the Tower in Murcia, showing the east façade and its main parts.

The Tower is a square masonry construction built at the left end of the temple between 1519 and 1793, with two thick parallel load-bearing walls between which access ramps leading to the Conjuratorios body were built. From this point onwards, the double wall was eliminated, leaving only the interior wall as an extension of the upper bodies, and the horizontal structure of the upper enclosure of each body was resolved by means of various vaults. The Tower is joined to the cathedral complex on two of its four façades (Figure 1). During its construction, the Tower experienced major structural complications, which forced the discontinuance of work for 201 years to correct problems consisting of differential settlement and the collapse of the east façade [28]. Greater or lesser loads were placed depending on the tilt that appeared on one side or the other, increasing the thickness of the walls in certain areas and reducing it in others, as well as making adjustments. The

loads were balanced by means of a "trial-and-error" procedure [29] in which workers attempted to prevent the increase in collapses on the east side by balancing them with greater weights on the west side.

It is a building that has undergone numerous maintenance and repair interventions throughout its history due to multiple deteriorations, such as the loss of mass of the exterior ornamental stone elements with the risk of detachment; fissures and cracks in ashlars occurring mostly due to oxidation phenomena of the internal anchors; oxidation with a loss of mass of metal supporting elements (ramps and the spiral staircase); the deterioration of pavements; and humidity problems due to capillary rise [30].

The Tower, like the rest of the Cathedral complex, has suffered significant humidity problems due to capillarity in its load-bearing walls. This issue was especially important from the 1960s onwards, when the Cathedral was resurfaced, closing almost all of the existing vents and, as a consequence, cutting off the capillary water evaporation circuit. The vaulted spaces remained, with stagnant air with a relative humidity of 100%, which condensed on the floors and, thus, increased the phenomenon of capillary rise, increasing dampness in the load-bearing walls [29]. Subsequently, for these reasons, intervention projects were requested, with the aim of creating an aeration chamber in the subsoil of the interior of the Tower. In addition, the construction of an external aeration chamber on the perimeter of the building, which would be connected to other existing ones, was also planned. This would complete the treatment of the subsoil, improving the elimination of the capillary rise that had been increasing dampness and deteriorating the stone ashlars.

When work began in 2009, archaeological remains were discovered both inside the tower and outside its perimeter. Specifically, in the interior, the existence of four empty chambers was discovered, one in each corner of the sacristy. For this reason, project modifications were made, and the new ventilation chamber was only built in an area where a wooden drawer was located. The perimeter was excavated to install the sanitary slab, with a lost formwork, and ventilation was established through a trench made in the attached wardrobe room, towards the exterior catch basin. Regarding the outer perimeter of the Tower, when the excavation was carried out, a series of archaeological remains (such as the remains of a brick wall and several mortar factories) were discovered on the east, north, and west sides [30]. Once the corresponding archaeological documentation was completed, work began on the creation of a ventilation system, with the objective of improving the air circulation in the base of the walls, starting from the foundations. It was therefore decided that a very simple ventilation chamber should be constructed on the outer perimeter of the Tower, as this chamber would help evaporate the water contained in the walls. The archaeological remains were respected and protected while this task was carried out through the construction of a trench filled with draining material, with subsequent paving and the installation of a perimeter ventilation grille.

Therefore, knowing of the existence of the previously indicated interventions in the subsoil of the Tower of the Cathedral of Murcia, we propose to validate this procedure by using 3D electrical resistivity tomography through the distribution of a continuous nonlinear profile and measurements with GPR.

2.2. Three-Dimensional Electrical Resistivity Tomography

Electrical resistivity tomography is an approach in which electricity is used to assess a subsurface by means of a set of connected electrodes that inject a current, simultaneously measuring the potential difference. Geo-electric profiles are calculated based on the electrical contrast resulting from the interaction of the currents with the subsurface materials [31]. These materials are characterised by the physical parameter of electrical resistivity (ρ) in Ohm·m because each material behaves differently with respect to the flow of injected current due to said material's own characteristics. In each measurement, the resistivity meter uses what is essentially a four-electrode array, comprising two current electrodes (named A and B) that send an electrical current with a known intensity (I) in milliamperes (mA) and two potential electrodes (named M and N) that measure the

potential difference (ΔV) in millivolts (mV). This set of four electrodes can have different geometries characterised by the geometric factor (K) in metres. Ohm's law relates to the following parameters: ρa = K ΔV/I, which is the apparent electrical resistivity (ρa), the parameter that is calculated due to the heterogeneity of the subsoil, and the characteristics of the measuring device [32].

There are different types of array configurations for measurements, such as the Wenner–Schlumberger array [18], the dipole–dipole array, and the pole–dipole array [33]. A pole is a single transmitting electrode, and a dipole is a pair of oppositely charged electrodes that are so close together that the electric field seems to be a single electrode field instead of fields from two different electric poles. The pole–dipole array is similar to the dipole–dipole array, but the pole–dipole array is used when a surveyor needs to see deep within a cross section of the earth. The achievable depth is based entirely on the distance between the two electrodes (the dipole and the pole). On the other hand, the dipole–dipole array is used to provide a very detailed image of a cross section of the earth, but it will lose a signal if the dipoles are placed too far apart.

When conducting a survey using the pole–dipole array, the position of the transmitting remote electrode is moved to infinity. In other words, the transmitter remote electrode should be so far away from the receiver dipole that the instrument does not sense the effect of the remote (pole) electrode, which is often 3.5 times the distance of the survey area in 3D models. The reason for this is that the distance between the two electrodes determines the depth of electrical penetration and explains why the pole–dipole array is popular when one needs to look deep into the earth [34].

Due to its status as a protected historic building and its construction characteristics, the Cathedral Tower of Murcia has posed a challenge to conventional ERT measurements. This investigation was carried out using the SuperStingTM Wi-Fi R8 Resistivity/IP/SP DC multi-electrode resistivity system produced by AGI Advanced Geosciences, Inc. (SuperSting Wi-Fi | AGI, Austin, TX, USA) [35]. This system consists of a high-precision resistivity meter, a central unit for electrode control, eight multi-conductor cables containing 7 passive electrodes each (56 electrodes in total), cable connectors, a control tablet, and an electric power generator (Figure 2a–c). To carry out the measurements in this protected historic building, aluminium plates measuring 100 × 100 × 10 mm with a steel spring were used to attach the electrode to the plate (Figure 3). To improve the conductivity of the electric current, a conductive gel based on a carbomer that does not leave a stain and can easily be removed (Figure 3) [36] was placed in the area between the plate and the electrode, and between the floor of the building and the plate, in each of the 56 electrodes. A profile was also deployed along the outer and inner perimeters of the Tower, following a continuous layout to cover the entire area under study, due to the lack of space and the impossibility of making 2D linear profiles of sufficient length because of the need to pass through the walls in a protected building. The electrode spacing was 2 m, giving a total area of 484 m^2 (22 × 22 m square) on the outside of the Tower and 9 m^2 (3 m × 3 m square) on the inside with a 1 m electrode spacing due to the limited space. It should be noted that this multi-electrode resistivity system requires the connection of the cable terminations next to electrode numbers 28 and 29 to the equipment (Figure 4a).

The instrument was used in the resistivity model for 1.2 s of current injection with a range of 0.1 to 450.52 mA between every two points and a voltage measurement with a range of 0.01 to 945.35 mV between every two points. A total of 56 electrodes were used in a 3D design with the pole–dipole configuration. The instrument calculated and stored a total of 578 apparent resistivity values with a range of 1 to 9800 Ohm·m. Then, the entire 3D layout of an electrode control unit was connected to the resistivity meter. This computer-controlled central unit provided electrical measurements of the subsurface, allowing a 3D model to be generated based on the electrical resistivity of the Tower subsurface.

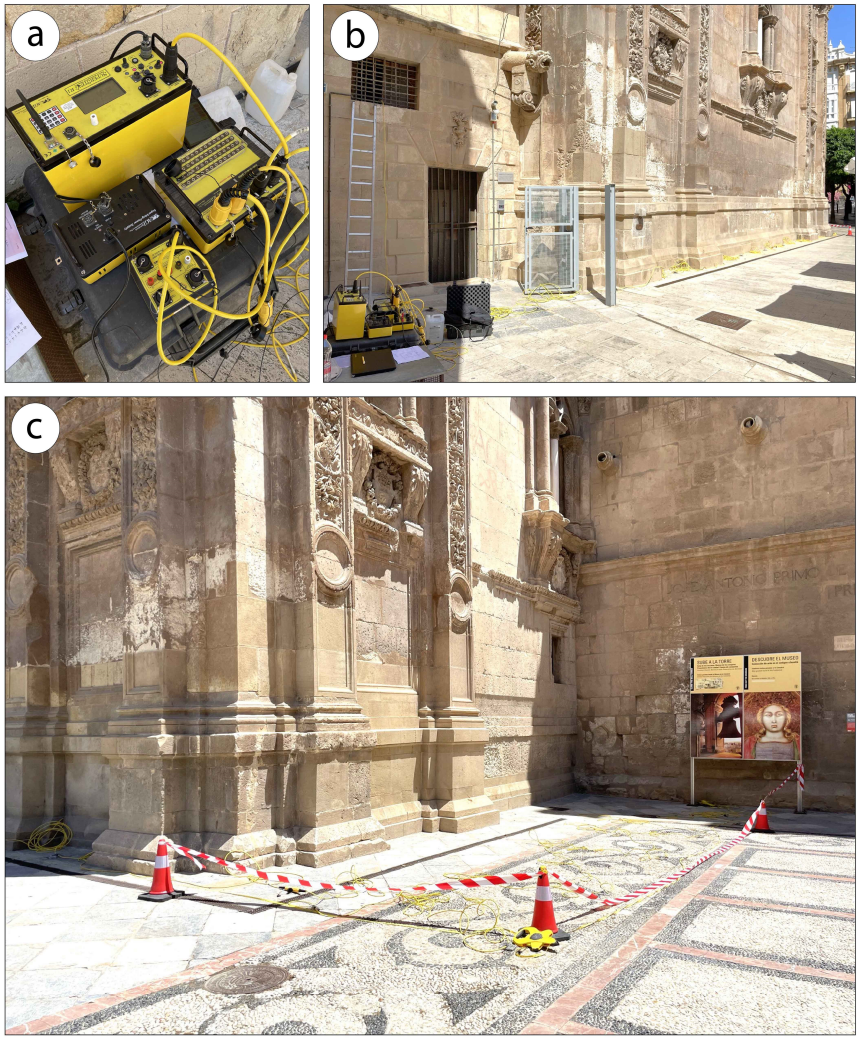


Figure 2. Continuous ERT profile. (**a**) Measuring equipment; (**b**) ERT profile in the east façade of the Tower; (**c**) electrodes placed in the northwest corner of the Tower.

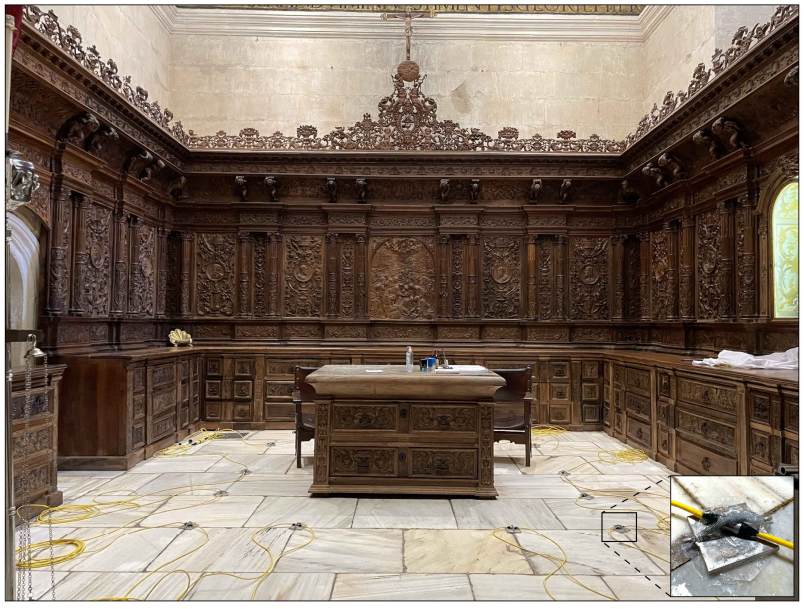


Figure 3. The electrodes placed inside the Tower (sacristy) and a detailed view of the arrangement, consisting of an electrode with an aluminium plate, a steel spring, and a carbomer-based gel.

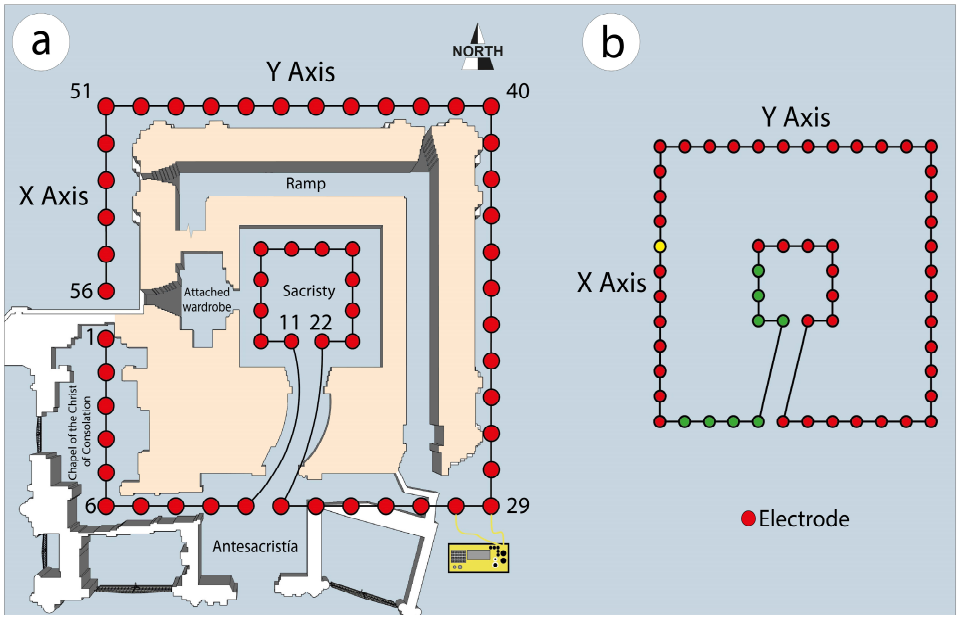


Figure 4. Continuous ERT profile: (**a**) location of the electrodes inside and outside the Tower and measuring equipment between electrodes 28 and 29; (**b**) an example of a measurement sequence of the electrodes used in a 3D array.

In this case, given the nonlinear configuration of electrodes, the measurements do not always follow a linear configuration; i.e., the current electrodes A and B and the potential electrodes M and N are not always placed in a straight line as in the 2D profiles. Figure 4b shows an example of a measurement sequence performed in the 3D model, where the electrodes that are measuring are represented in yellow and green. Therefore, information was obtained from the entire foundation slab, including the subsoil under its load-bearing walls, reaching depths adequate for the study of the buried structures. Ensuring that the quality of the resistivity data of the 3D model is high is crucial to infer the subsoil structure of the building. As noted earlier in this study, the solution adopted to carry out the ERT measurements was the use of the pole–dipole configuration to reach greater depths of investigation (Figure 5).

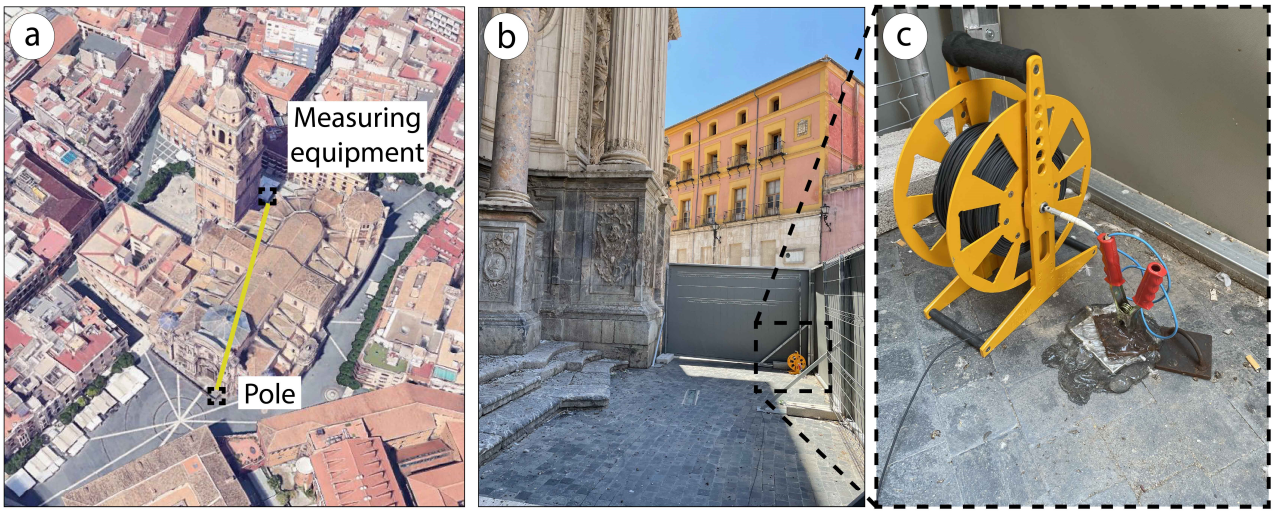


Figure 5. Position of the pole: (**a**) distance from the pole to the measuring equipment (80 m); (**b**) location of the pole outside the west façade of the Cathedral; (**c**) detail of the pole.

Once the measurements were recorded, they were stored and filtered to eliminate outliers. Continuous profile data processing was performed using the least-squares inversion method [37] using EarthImagerTM 2D/3D version 2.4.2 software. For the inversion, the L2 norm was used; it is defined as the sum of the squared weighted data errors of the data. The L2 norm depends on the estimation of the data weights (errors). In this case, the percentage (noise) considered is 3%. Convergence is achieved when the normalised L2 norm is equal to or less than 1. The data weights play a key role in the estimation of the L2 norm by varying the number of measurements from one dataset to another. To avoid confusion, a normalised L2-norm measure is defined as L2-norm = L2-norm/(number of data). The absolute errors obtained are L2 = 1.1 after the eighth iteration of adjustment and considered acceptable.

2.3. Ground-Penetrating Radar (GPR) Profiles

Ground-penetrating radar is a non-invasive, fast, reliable, and easily transportable technique that generates high-resolution images (radargrams), especially of the first few metres of the subsurface [38]. This is a technique that generates short electromagnetic pulses of high-frequency waves (commonly from 10 MHz to 1000 MHz) through a transmitting antenna [39]. These electromagnetic waves propagate through the different layers of the subsoil, producing different reflections when changes in the electromagnetic properties of the materials occur. The reflections are recorded by the receiving antenna. The recording is transmitted to the control unit, which amplifies and records the signal. This is a technique that provides real-time recording of subsurface waves, ideal for identifying resistive soils (voids, gravel, loose sand, etc.), although it has enormous difficulties when applied to soils with high conductivity (clay soils, groundwater, etc.). Additionally, most of the equipment can work at different frequencies. Most antennas used in geotechnical studies operate in the frequency range between 100 MHz and 500 MHz [40].

Given the geometry of the Tower and considering the objective of this study (the foundation slab of the Tower), the GPR measurements were only taken in the accessible area inside the building (the sacristy). Measurements could not be taken inside the wardrobe attached to the interior of the sacristy due to the limited space available, nor in the access ramps for the upper bodies of the Tower due to the objective of this research. The equipment used was produced by Malá technology, employing 250 and 500 MHz antennas to achieve different resolutions and depths of investigation. A total of 15 profiles were made with the 250 MHz antenna, and 10 profiles were made with the 500 MHz antenna (Figure 6), covering the surface of the room.

To georeference the position and length of each profile, a polygonal survey was carried out with a total station. The GPR data were processed with the ReflexW version 10.5 package. A standard processing flow was applied to the data, consisting of the use of the following filters: zero-time correction, time-based gain addition, dewow, background removal, and migration.

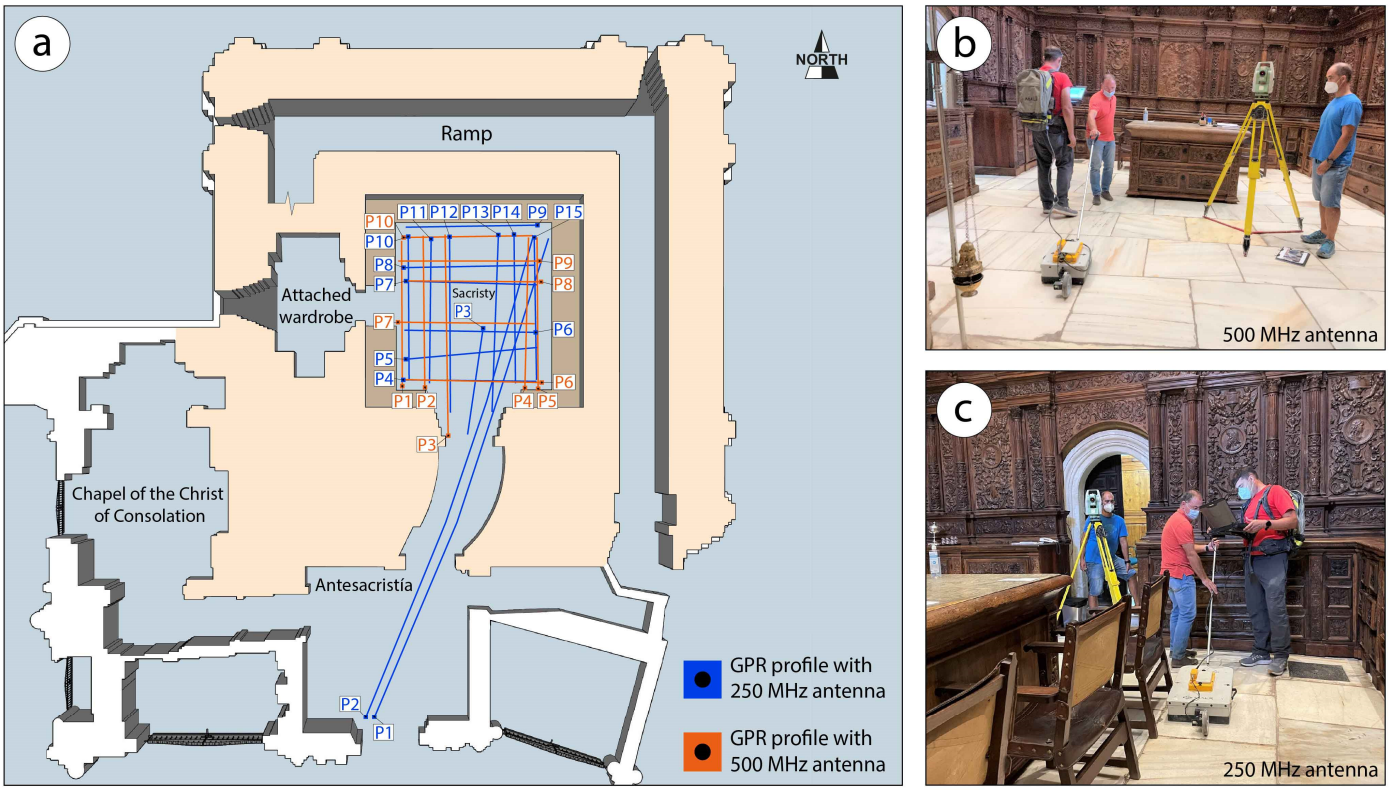


Figure 6. (**a**) Location plan for the profiles made with the 250 and 500 MHz antennas; (**b**) measurements made with the 500 MHz antenna; (**c**) measurements made with the 250 MHz antenna.

3. Results and Discussion

After the inversion of the ERT data, a 3D electrical resistivity model with a surface measuring 22 × 22 m^2 with a depth of investigation of 16.2 m was obtained. For a better interpretation of the results regarding the foundation slab, with the aim of visualising its singularities, resistivities between 100 and 5000 Ohm·m were selected. We found that the foundation slab had a variable depth and some highly resistive zones (in red) with values between 4000 and 5000 Ohm·m (Figure 7). Some studies have demonstrated that the existence of high values of resistivity, depending on the subsoil composition, can be associated with hollow cavities [41–43]. Therefore, the anomalies with high resistivity values could be associated with the presence of cavities in the foundation slab of the Tower.

After processing the GPR data, the migrated profiles were obtained. Figure 8 shows the results for profiles P5 and P6 recorded with the 250 MHz antenna inside the sacristy (Figure 6). Significant reflections compatible with hollows can be seen at the ends of each profile, indicated by red rectangles.

With the 500 MHz antenna, profiles P1-P10 were obtained inside the sacristy from north to south and from south to north parallel to each other (Figure 6). These profiles also show significant reflections compatible with hollows at their ends (Figure 9). With the 500 MHz antenna, the depth of investigation allowed is less than that with the 250 MHz antenna, but the resolution increases. Therefore, Figure 9 shows more detail in the resolution of the migrated profile, and the heights of these anomalies, found to be at around 1 m, can be visualised more precisely. Thanks to the application of the two antennas, it was possible to confirm the existence of hyperbolas compatible with hollows in most of the profiles made.

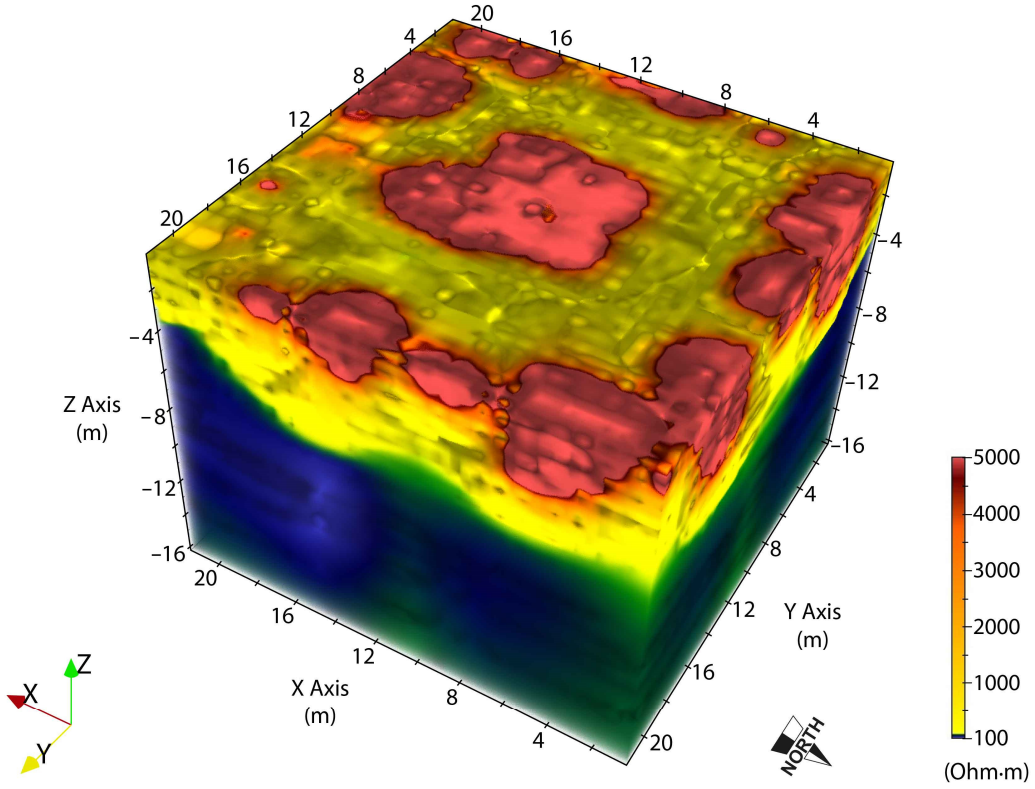


Figure 7. A 3D ERT model characterising the area underneath the Tower in terms of subsurface electrical resistivity values.

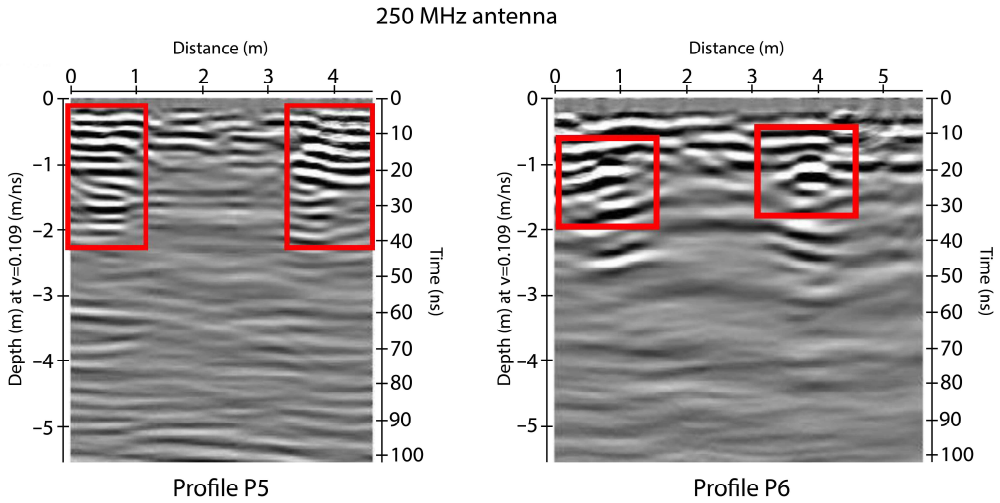


Figure 8. Radargrams obtained inside the Tower with the 250 MHz antenna. The significant reflections found are highlighted by red rectangles.

Figure 10 shows the radargrams obtained in the east-west direction from five profiles with the 500 MHz antenna. It can be seen that there are hyperbolas compatible with hollows at the ends of the profiles.

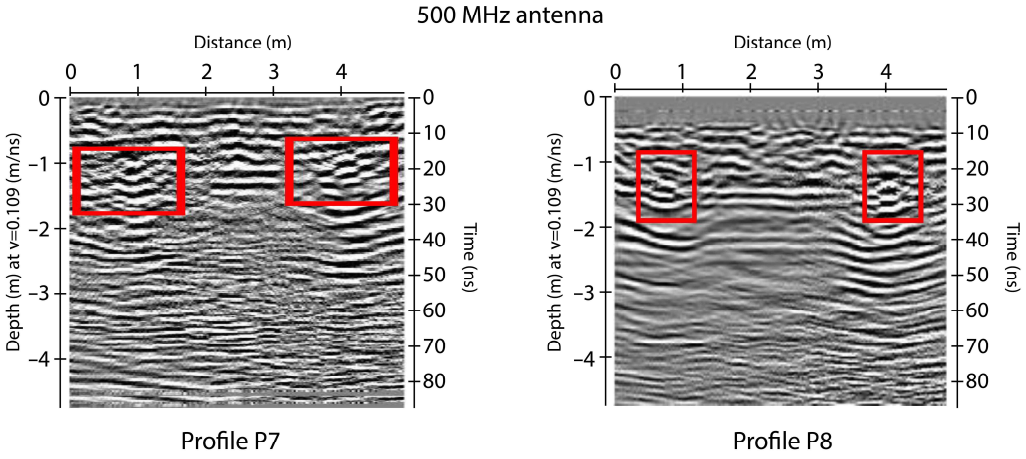


Figure 9. Radargrams obtained inside the Tower with the 500 MHz antenna. The significant reflections found are highlighted by red rectangles.

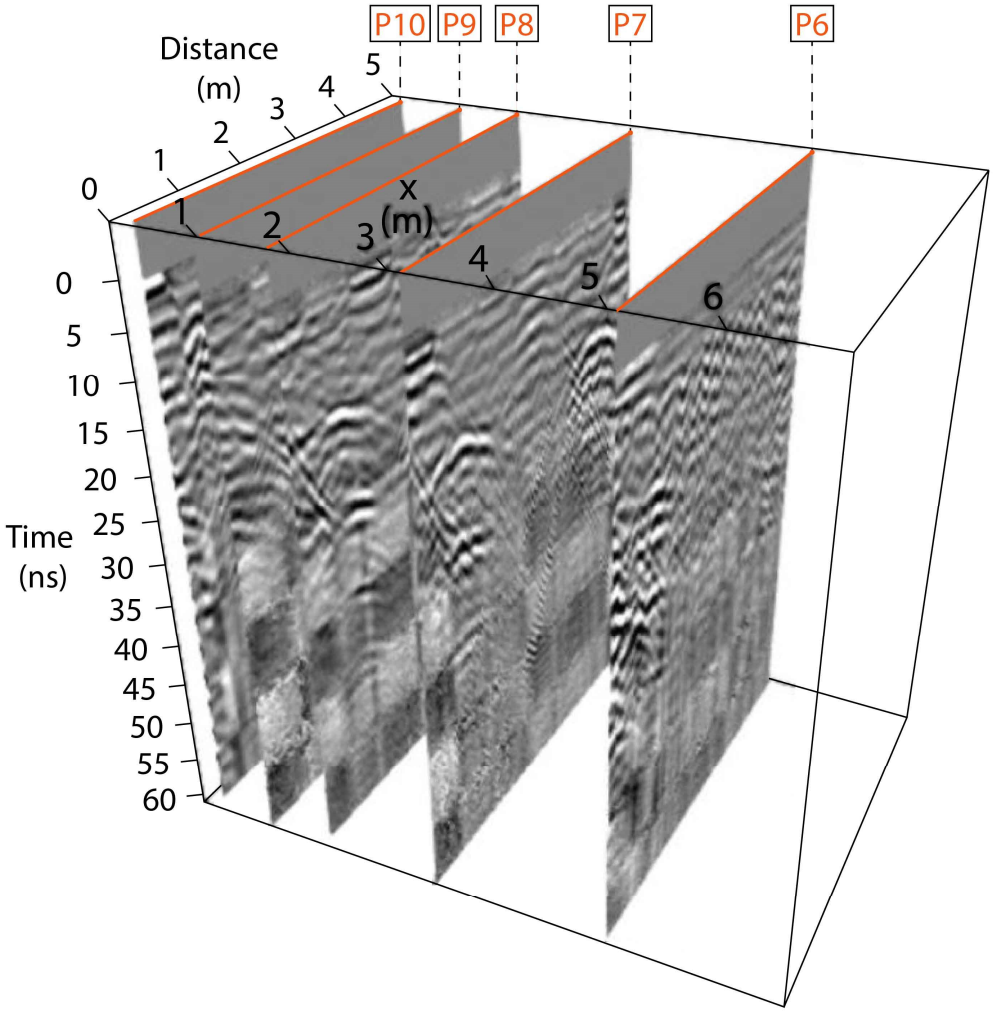


Figure 10. A 3D model of the radargrams obtained in the east-west direction inside the Tower with the 500 MHz antenna.

To facilitate the interpretation of the results provided by the 3D electrical resistivity tomography model, this model was placed under the Tower (Figure 11a), and the plan view of the model was combined with the plan view of the Tower (Figure 11b).

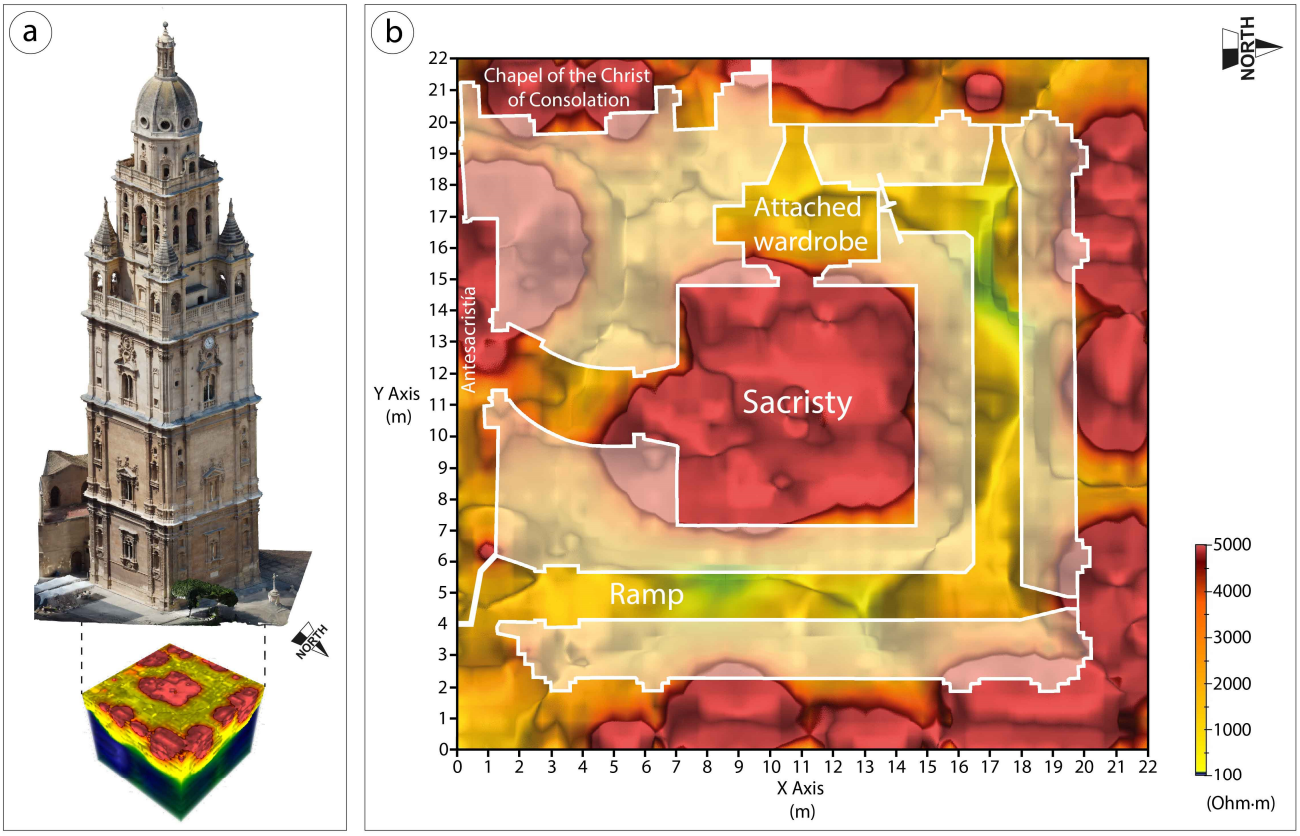


Figure 11. (**a**) A 3D ERT model positioned under the Tower; (**b**) a detailed view of the model with the location set according to the floor plan of the Tower of the highly resistive zones.

There are high electric resistivity values inside the Tower in a room denominated the sacristy (Figure 11b). According to the existing historical and archaeological documentation on this building, described in Section 2.1, these resistive zones correspond to four hollow chambers found in an intervention carried out in 2009 to solve the dampness problems affecting the Tower. In that year, four chambers were discovered, with each one situated in each corner inside the sacristy of the Tower (Figure 12a,b,d). These were, therefore, determined to be four empty spaces that had not been burial sites. It was in this location (the sacristy) where GPR measurements were made (Figure 6). The GPR results show important reflections compatible with empty spaces (Figures 8–10), especially with the 500 MHz antenna, which obtains data at a shallower depth and with higher resolution, helping to confirm the existence of hyperbolas compatible with cavities of around 1 m in depth. These results prove that, when it is possible, the joint use of GPR and ERT techniques is a valuable and essential tool for verifying singularities in the subsoil.

Next to the south face of the Tower, in a room before the sacristy called the Antesacristía and located inside the Cathedral (Figure 11b), there is another zone with high resistivity values. There is documentary evidence that a sub-floor ventilation system was installed in the Antesacristía in 1999 due to existing humidity problems. Among other works carried out (Figure 12c,d), a new well was built in this room (for liturgical reasons), with the existing one being closed because it could have caused humidity problems [30]. These documentary data suggest that the highly resistive zone found in the Antesacristía through the ERT measurements could correspond to the well referred to in the bibliographic documentation.

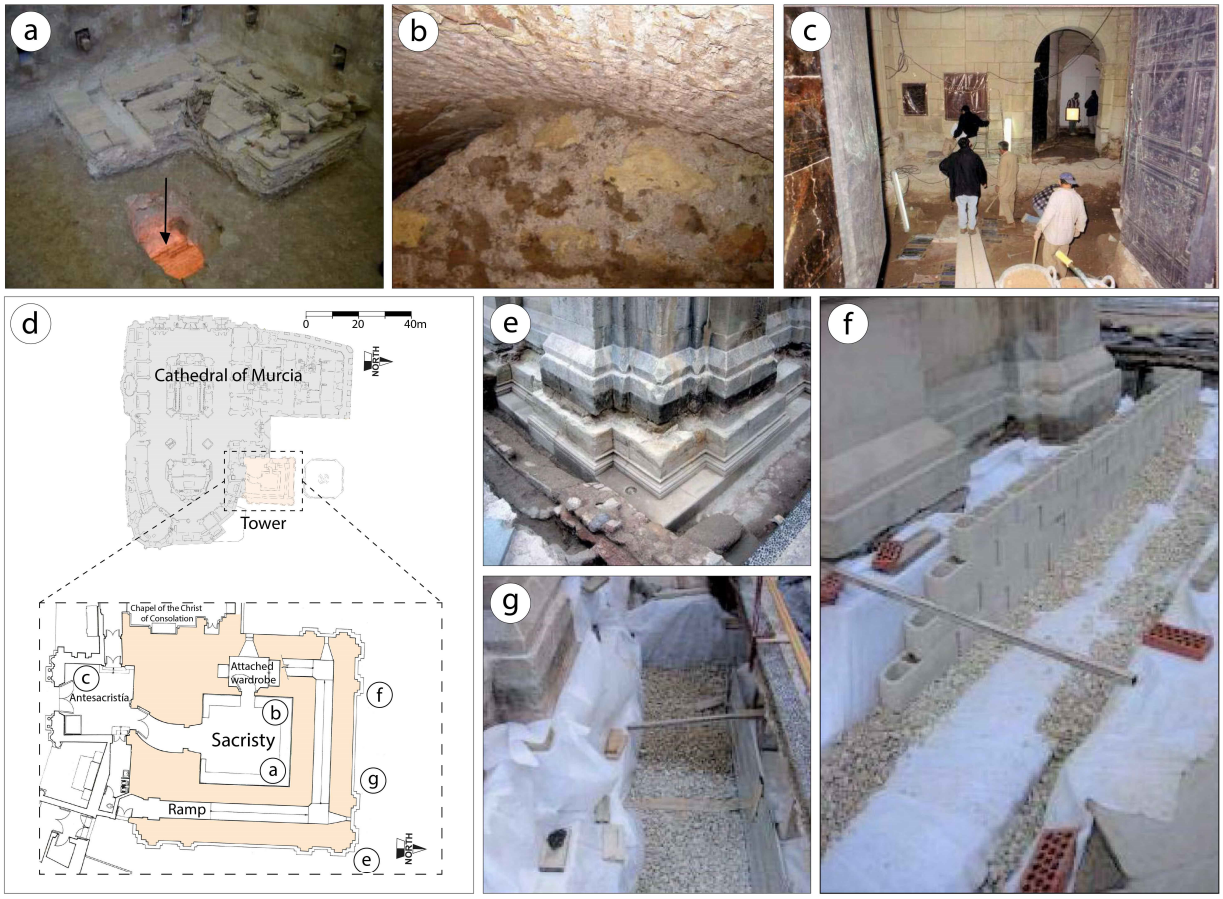


Figure 12. (**a**) Chamber located in the northeast corner (Geocisa, 2009 [30]); (**b**) interior of one of the chambers to which access was gained [30]; (**c**) actions carried out in 1999 in the interior of the Antesacristía (photograph taken by Juan Antonio Molina Serrano [30]); (**d**) location according to the floor plan of the Tower's cavities; (**e**) northeast corner in 2009, with the original plinth and archaeological remains of a rammed-earth wall [30]; (**f**,**g**) project carried out in 2009, involving the filling of the trenches with draining material and the creation of an aeration chamber. Photographs taken by José Antonio Sánchez Pravia. Images by Geocisa [30].

There is a high-resistivity zone next to the west face of the Tower in a room called the Chapel of the Christ of Consolation inside the Cathedral (Figure 11b). This room is relatively recent, as its construction was completed in 1818 [44]. Nevertheless, there are no historical construction data with which to corroborate the existence of this highly resistive zone. In this case, the high values of electrical resistivity could correspond to hollow chambers, as have been found in other areas of the temple (such as the sacristy) or even crypts.

High electrical resistivity values were also found on the outer perimeter of the Tower in the east, north, and west façades (Figure 11b). According to the existing historical and archaeological documentation on the Cathedral described in Section 2.1, these resistive zones correspond to aeration chambers built in 2009 to solve the problems of rising dampness in the exterior walls of the Tower. For the construction of these chambers, several modifications of the project to be made due to the appearance of archaeological remains (Figure 12d,e), and they were made by constructing a trench filled with draining material, with subsequent paving and the installation of a perimeter ventilation grille (Figure 12d,f,g) [30].

4. Conclusions

The Tower of the Cathedral of Murcia is located in the urban and historical centre of the city of Murcia. There are other buildings close to it, and it poses limitations with respect to having enough space to make conventional 2D profiles, so the proposed methodology allows the placement of a continuous ERT profile. By distributing a nonlinear continuous ERT profile along the outer and inner perimeters of the Tower, a 3D ERT model of the electrical resistivity values of the foundation singularities was obtained. Thanks to the pole–dipole array, investigation depths of 16.2 m were achieved in the 3D model, identifying several highly resistive zones with values between 4000 and 5000 Ohm·m. These results were corroborated with GPR measurements carried out inside the Tower and with the available archaeological documentation resulting from previous interventions [30], allowing for the conclusion that these are various cavities located in the foundation slab of the Tower.

The results obtained verify the methodology proposed for this type of structure, allowing for the characterisation of singularities in the foundations of protected historic towers in a fast and versatile way, thus respecting the heritage. This represents a great advance in the characterisation of the foundations under protected buildings of this type using non-invasive techniques, reaching adequate depths of investigation in smaller spaces. Uncertainty about the characteristics of their foundations has therefore been minimised as reliable information was obtained about the state of the subsoil in the area under study, enabling the planning of future maintenance and conservation actions for this protected heritage site with scientific criteria, saving time and costs through the use of non-invasive techniques. We applied a methodology that has given positive results in the characterisation of the singularities of the foundation of the Tower of the Cathedral of Murcia. This methodology can be used for other historical towers for which a detailed knowledge of the characteristics of their foundations is required.

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References

1. European Union. *European Framework for Action on Cultural Heritage*; Publications Office of the European Union: Luxembourg, 2019; Available online: https://op.europa.eu/en/publication-detail/-/publication/5a9c3144-80f1-11e9-9f05-01aa75ed71a1/language-en (accessed on 1 October 2024).
2. ICOMOS. Place, memory, meaning: Preserving intangible values in monuments and sites. In Proceedings of the 14th General Assembly and Scientific Symposium, Victoria Falls, Zimbabwe, 27–31 October 2003.
3. Dabrowski, P.S.; Zienkiewicz, M.H.; Truong-Hong, L.; Lindenbergh, R. Assessing historical church tower asymmetry using point cloud spatial expansion. *J. Build. Eng.* **2023**, *75*, 107040. [CrossRef]
4. Porcu, M.C.; Montis, E.; Saba, M. Role of model identification and analysis method in the seismic assessment of historical masonry towers. *J. Build. Eng.* **2021**, *43*, 103114. [CrossRef]
5. Grassi, S.; Imposa, S.; Patti, G.; Boso, D.; Lombardo, G.; Panzera, F. Geophysical surveys for the dynamic characterization of a cultural heritage building and its subsoil: The S. Michele Arcangelo Church (Acireale, eastern Sicily). *J. Cult. Herit.* **2019**, *36*, 72–84. [CrossRef]
6. Grassi, S.; Patti, G.; Tiralongo, P.; Imposa, S.; Aprile, D. Applied geophysics to support the cultural heritage safeguard: A quick and non-invasive method to evaluate the dynamic response of a great historical interest building. *J. Appl. Geophys.* **2021**, *189*, 104321. [CrossRef]
7. Martínez-Segura, M.A.; García-Nieto, M.C.; Navarro, M.; Vásconez-Maza, M.D.; Oda, Y.; García-Jerez, A.; Enomoto, T. Seismic characterisation of the subsoil under a historic building: Cathedral Church of Saint Mary in Murcia case study. *Eng. Geol.* **2024**, *335*, 107529. [CrossRef]
8. Muradov, M.; Kot, P.; Markiewicz, J.; Łapiński, S.; Tobiasz, A.; Onisk, K.; Shaw, A.; Hashim, K.; Zawieska, D.; Mohi-Ud-Din, G. Non-destructive system for in-wall moisture assessment of cultural heritage buildings. *Measurement* **2022**, *203*, 111930. [CrossRef]
9. Rymarczyk, T.; Kłosowski, G.; Hoła, A.; Sikora, J.; Tchórzewski, P.; Skowron, Ł. Optimising the use of Machine learning algorithms in electrical tomography of building Walls: Pixel oriented ensemble approach. *Measurement* **2022**, *188*, 110581. [CrossRef]
10. Solla, M.; Ángel Maté-González, M.; Sáez Blázquez, C.; Lagüela-López, S.; Nieto, I.M. Analysis of structural integrity through the combination of non-destructive testing techniques in heritage inspections: The study case of San Segundo's hermitage (Ávila, Spain). *J. Build. Eng.* **2024**, *89*, 109295. [CrossRef]
11. Balkaya, Ç.; Levent Ekinci, Y.; Çakmak, O.; Blömer, M.; Arnkens, J.; Kaya, M.A. A challenging archaeo-geophysical exploration through GPR and ERT surveys on the Keber Tepe, City Hill of Doliche, Commagene (Gaziantep, SE Turkey). *J. Appl. Geophys.* **2021**, *186*, 104272. [CrossRef]
12. Fernández-Álvarez, J.-P.; Rubio-Melendi, D.; Quirós Castillo, J.A.; González-Quirós, A.; Cimadevilla-Fuente, D. Combined GPR and ERT exploratory geophysical survey of the Medieval Village of Pancorbo Castle (Burgos, Spain). *J. Appl. Geophys.* **2017**, *144*, 86–93. [CrossRef]
13. Imposa, S.; Grassi, S.; Morreale, G.; Pirrotta, C.; Cavalier, L.; Gilotti, A.; Giuliano, D.; Cayre, E.; Caliò, L.M. New discovery of an ancient building in Akragas (Valley of Temples, Agrigento, Italy) through the integration of geophysical surveys. *J. Archaeol. Sci. Rep.* **2024**, *53*, 104368. [CrossRef]
14. Leucci, G.; Miccoli, I.; Barbolla, D.F.; De Giorgi, L.; Ferrari, I.; Giuri, F.; Scardozzi, G. Integrated GPR and ERT Surveys for the Investigation of the External Sectors of the Castle of Melfi (Potenza, Italy). *Remote Sens.* **2023**, *15*, 1019. [CrossRef]
15. Russolillo, A.; Martin, F.F.; Merico, A.; Sapia, V.; Talamo, P.; Materni, V.; Pischiutta, M.; de Vita, S.; Furlani, S.; Targia, D.; et al. Unveiling a hidden fortification system at "Faraglioni" Middle Bronze Age Village of Ustica Island (Palermo, Italy) through ERT and GPR prospections. *J. Appl. Geophys.* **2024**, *220*, 105272. [CrossRef]
16. Yilmaz, S.; Balkaya, Ç.; Çakmak, O.; Oksum, E. GPR and ERT explorations at the archaeological site of Kılıç village (Isparta, SW Turkey). *J. Appl. Geophys.* **2019**, *170*, 103859. [CrossRef]
17. Ortega-Ramírez, J.; Bano, M.; Cordero-Arce, M.T.; Villa-Alvarado, L.A.; Chavez Fraga, C. Application of non-invasive geophysical methods (GPR and ERT) to locate the ancient foundations of the first cathedral of Puebla, Mexico. A case study. *J. Appl. Geophys.* **2020**, *174*, 103958. [CrossRef]
18. Evangelista, L.; de Silva, F.; d'Onofrio, A.; Di Fiore, V.; Silvestri, F.; Scotto di Santolo, A.; Cavuoto, G.; Punzo, M.; Tarallo, D. Application of ERT and GPR geophysical testing to the subsoil characterization of cultural heritage sites in Napoli (Italy). *Measurement* **2017**, *104*, 326–335. [CrossRef]
19. Bellanova, J.; Calamita, G.; Catapano, I.; Ciucci, A.; Cornacchia, C.; Gennarelli, G.; Giocoli, A.; Fisangher, F.; Ludeno, G.; Morelli, G.; et al. Remote sensing GPR and ERT Investigations in Urban Areas: The Case-Study of Matera (Southern Italy). *Remote Sens.* **2020**, *12*, 1879. [CrossRef]
20. Chávez, R.E.; Cifuentes-Nava, G.; Tejero, A.; Esteban Hernández-Quintero, J.; Vargas, D. Special 3D electric resistivity tomography (ERT) array applied to detect buried fractures on urban areas: San antonio tecómitl, Milpa alta, México. *Geofis. Int.* **2014**, *53*, 425–434. [CrossRef]
21. Rizzo, E.; Capozzoli, L.; De Martino, G.; Grimaldi, S. Urban geophysical approach to characterize the subsoil of the main square in San Benedetto del Tronto town (Italy). *Eng. Geol.* **2019**, *257*, 105133. [CrossRef]
22. Mohamed, A.M.E.; El-Hussain, I.; Deif, A.; Araffa, S.A.S.; Mansour, K.; Al-Rawas, G. Integrated ground penetrating radar, electrical resistivity tomography and multichannel analysis of surface waves for detecting near-surface caverns at Duqm area, Sultanate of Oman. *Near Surf. Geophys.* **2019**, *17*, 379–401. [CrossRef]

23. Jiang, L.; Tian, G.; Wang, B.; Guo, X.; He, X.; Zou, A.; Chen, H.; Yang, T.; EI-Raouf, A.A. Application of three-dimensional electrical resistivity tomography in urban zones by arbitrary electrode distribution survey design. *J. Appl. Geophys.* **2021**, *194*, 104460. [CrossRef]
24. Argote, D.L.; Tejero-Andrade, A.; Cárdenas-Soto, M.; Cifuentes-Nava, G.; Chávez, R.E.; Hernández-Quintero, E.; García-Serrano, A.; Ortega, V. Designing the underworld in Teotihuacan: Cave detection beneath the moon pyramid by ERT and ANT surveys. *J. Archaeol. Sci.* **2020**, *118*, 105141. [CrossRef]
25. Chavez, R.E.; Tejero, A.; Cifuentes, G.; Argote, D.L.; Hernandez, J.E. A special ERT-3D array carried out to investigate the subsoil of the Pyramid El Castillo, Chichen Itza, Mexico. In Proceedings of the Near Surface Geoscience 2015—21st European Meeting of Environmental and Engineering Geophysics, Turin, Italy, 6–10 September 2015; pp. 651–655. [CrossRef]
26. Tejero-Andrade, A.; Argote-Espino, D.L.; Cifuentes-Nava, G.; Hernández-Quintero, E.; Chávez, R.E.; García-Serrano, A. 'Illuminating' the interior of Kukulkan's Pyramid, Chichén Itzá, Mexico, by means of a non-conventional ERT geophysical survey. *J. Archaeol. Sci.* **2018**, *90*, 1–11. [CrossRef]
27. Almeida, F.; Barraca, N.; Moura, R.; Matias, M.J.S. Odd-even Pole-pole array and 3D resistivity surveys in urban and historical areas. In Proceedings of the 22nd European Meeting of Environmental and Engineering Geophysics, Near Surface Geoscience 2016, Barcelona, Spain, 4–8 September 2016. [CrossRef]
28. Vera Boti, A. *La Torre de la Catedral de Murcia: De la Teoría a los Resultados*; Real Academia Alfonso X El Sabio: Murcia, Spain, 1993.
29. Vera Boti, A.; Sánchez-Rojas Fenoll, M.C.; de la Peña Velasco, C.; Pascual Martínez, L.; Esbert Alemany, R.M. *La Catedral de Murcia y su Plan Director*; Colegio Oficial de Arquitectos de Murcia: Murcia, Spain, 1994.
30. Molina Gaitán, J.C. *Historia de la Restauración de la Catedral de Murcia: Intervenciones desde 1928 a 2010*; Universidad Politécnica de Cartagena: Murcia, Spain, 2014; Volume 1.
31. Everett, M.E. *Near-Surface Applied Geophysics*; Cambridge University Press: Cambridge, UK, 2013.
32. Loke, M.H. Tutorial: 2D and 3D Electrical Imaging Surveys. 2002. Available online: https://personales.upv.es/jpadin/coursenotes.pdf (accessed on 2 November 2024).
33. Simyrdanis, K.; Papadopoulos, N.; Kim, J.; Tsourlos, P.; Moffat, I. Archaeological investigations in the shallow seawater environment with electrical resistivity tomography. *Near Surf. Geophys.* **2015**, *13*, 601–611. [CrossRef]
34. Advanced Geosciences, Inc. Available online: https://www.agiusa.com (accessed on 27 April 2024).
35. SuperSting Wi-Fi | AGI. Available online: https://www.agiusa.com/supersting-wifi (accessed on 8 May 2024).
36. Vásconez-Maza, M.D.; Martínez-Pagán, P.; Aktarakçi, H.; García-Nieto, M.C.; Martínez-Segura, M.A. Enhancing electrical contact with a commercial polymer for electrical resistivity tomography on archaeological sites: A case study. *Materials* **2021**, *13*, 5012. [CrossRef]
37. Loke, M.H.; Barker, R.D. Rapid least-squares inversion of apparent resistivity pseudosections by a quasi-Newton method. *Geophys. Prospect.* **1996**, *44*, 131–152. [CrossRef]
38. Gilbert, R.; Douma, M.; Dyke, L.; Good, R.L.; Hunter, J.A.; Hyde, C.; Michaud, Y.; Pullan, S.E.; Robinson, S.D. *A Handbook of Geophysical Techniques for Geomorphic and Environmental Research*; Open File 3731; Geological Survey of Canada: Ottawa, ON, Canada, 1999; 125p.
39. Rodríguez-Santalla, I.; Gomez-Ortiz, D.; Martín-Crespo, T.; Sánchez-García, M.J.; Montoya-Montes, I.; Martín-Velázquez, S.; Barrio, F.; Serra, J.; Ramírez-Cuesta, J.M.; Gracia, F.J. Study and Evolution of the Dune Field of La Banya Spit in Ebro Delta (Spain) Using Lidar Data and GPR. *Remote Sens.* **2021**, *13*, 802. [CrossRef]
40. Greenhouse, J.P.; Gudjurgis, P.; Slaine, D. *An Introduction to Near-Surface and Environmental Geophysical Methods and Applications. Reference Notes*; SAGEEP Short Course; Versteeg, R., Ed.; Environmental and Engineering Geophysical Society: Denver, CO, USA, 1997; 131p.
41. Carollo, A.; Capizzi, P.; Martorana, R. Joint interpretation of seismic refraction tomography and electrical resistivity tomography by cluster analysis to detect buried cavities. *J. Appl. Geophys.* **2020**, *178*, 104069. [CrossRef]
42. Fischanger, F.; Catanzariti, G.; Comina, C.; Sambuelli, L.; Morelli, G.; Barsuglia, F.; Ellaithy, A.; Porcelli, F. Geophysical anomalies detected by electrical resistivity tomography in the area surrounding Tutankhamun's tomb. *J. Cult. Herit.* **2019**, *36*, 63–71. [CrossRef]
43. Zhao, W.; Tian, G.; Lin, Q.; Wang, X.; Wang, Y.; Bie, K. Integrated characterization of ancient burial mounds using ERT and limited drillings at the Hepu Han Tombs, in coastal area of Southern China. *J. Archaeol. Sci. Rep.* **2019**, *23*, 617–625. [CrossRef]
44. Del Baño Martínez, F. El oratorio del Obispo de la Catedral de Murcia, un espacio con diversas funciones a través del tiempo. In *Las Catedrales Españolas del Barroco a los Historicismos*; Universidad de Murcia: Murcia, Spain, 2003; pp. 357–372.

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