






# Application of the Electrical Resistivity Tomography Technique in the Assessment of Historical Buildings in the State of Aguascalientes, Mexico

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**Abstract.** Diagnosis of historic buildings is relevant because it contributes to their preservation in adequate and safe conditions; in the present work, the Electrical Resistivity Tomography (ERT) technique is applied on horizontal and vertical planes to study aspects of humidity, to recognize the internal geometry of elements, and to detect resistivity anomalies in two old buildings in the state of Aguascalientes, Mexico; these buildings are the Temple of the Inmaculada Concepción and Terán House. In the first, the electrical profiles obtained from the subsoil show a zone of low resistivity associated with a saturated layer that damages the wall due to rising dampness. On the second, the resistivity images obtained from measurements on two walls with humidity problems show the source and define some flow patterns. It could be concluded that using the obtained results ERT technique generates valuable information for the preservation of built heritage and, therefore, is viable for the diagnosis of historical buildings, mainly in the study of humidity and discontinuities in walls.

**Keywords:** Non-Destructive Testing · historical buildings · Electrical Resistivity Tomography · Temple of the Inmaculada Concepción · Terán House

## 1 Introduction

Historical buildings are exposed, through time to several factors such as rain, wind, and sun that, on one side, affect them aesthetically but also generate hygiene problems and damage their structural health [1].

Nowadays, research on methodologies that allow obtaining information about historical buildings without involving their aesthetic-structural integrity is one line of research for many professions due to this information is helpful at the moment in an intervention [2].

In most cases, water is the main and the most complex issue in the architectonic heritage [3]; for this reason, the study of humidity in walls is pertinent to preserve and conserving these. Humidity could be present in buildings by capillarity, condensate drains in pipes, and filtration by rain and floods [4]. Some effects can be generated as acceleration of material degradation processes due to freezing and thawing problems [5] salt crystallization phenomenon [6], chemic and biologic attack [7–9], metallic corrosion and eolic erosion [10–12].

The buildings downtown the city of Aguascalientes, Mexico, present a high deterioration due to ascendant and filtration humidity. According to [13], there is humidity in subsoil due to the existence of gardens and canals that existed until the latest XIX century covered by buildings settled; in some cases, these buildings were built with no foundation and with materials susceptible to humidity as mud. Other causes of problems are the deterioration of pipes with antique installations that generate drains in buildings.

## 1.1 Study Case

The studied buildings are in the city of Aguascalientes; both are of interest to the population and authorities in charge as the National Anthropology and History Institute (INAH) and the Cultural Institute of Aguascalientes (ICA).

**Case 1. Temple “Inmaculada Concepción”.** The Temple (Fig. 1) is in the municipality of Tepezalá, called Puerto de la Concepción; it is located in the north of the state, 40 km from the capital (Aguascalientes, Mexico). It is one of the few monasteries from the latest XVII century or the beginning of the XVIII century; it was built by the Franciscan friar [14] with masonry walls with limestone of poor carve, using lime mortar and raw land to join, with a *cantaritos* vault. This technique is from the XVII century; in this mud, empty *cantaritos* were located to light the roof [14].



**Fig. 1.** a) Lateral View of the Temple Inmaculada Concepción. b) *Cantaritos* vault.

**Case 2. Terán House.** It is located downtown in the city of Aguascalientes, Mexico. Nowadays is used as Cultural Animation Center; it is considered one of the most important historical buildings in the state due to its history and architectonic richness (Fig. 2). It was built from 1775 to 1986, using mud walls and ceilings. It has an architectonic style called “Neo-style”; it is a transition period from baroque to classic. The architectonic scheme is on yards surrounded by rooms [15]. Nowadays, this building presents humidity problems on walls and vaults that gradually deteriorate it.



**Fig. 2.** a) Terán House façade. b) Terán House indoor

## 1.2 Electrical Resistivity Tomography as Non-destructive Test for Evaluating Historic Buildings

It is a complex task to value historical buildings to know the deterioration status and structural damages that could put them at risk; for this reason, it is important to use non-invasive and invasive techniques to obtain a diagnosis; in most cases, authorities in charge of protecting and conserving heritage buildings and current regulations recommend the use of methods that do not involve the integrity of the building; nowadays, non-destructive methods obtain information without damaging it [16].

The study of humidity in buildings includes propagation patterns, distribution through time, and type of humidity is essential to know the level of damage to materials and the general conditions of the building [17]; one of the forms to evaluate them is without involving their integrity, using Non-Destructive Tests (NDT); however, the intrinsic homogeneity and interventions through time difficult this task; for this reason, it is necessary to use two or more methods to increase the certainty of results [18, 19].

It has been an increase in interest in implementing NDT in the analysis of buildings in the last years due to the continuous improvement of equipment, software, and images obtained; also, its use is less invasive [20]. ERT and GPR are two methods applied in the last years with a higher rate of estimation of contents of humidity and porosity [18, 21, 22].

Works that apply these methods research the distribution of humidity on masonry walls and also; the ones that research monitoring the filtration of water through antique walls, creating measurements in 2D and 3D [23, 24]. One of the main reasons the ERT method was accepted, in the last years is because of its easy management of equipment and the adaptation of electrodes, causing few affectations on the surface of walls [25]. For example, the use of a group of medical electrodes, clay, and gel has provided very reliable results without damaging the building. However, one of the difficulties of the ERT technique is attaching electrodes to the surface in question. Also, the use of reduced electrodes that difficult the reduction of contact resistance (RC) [26].

### 1.3 Research Objectives

The objective of this work is to determine the origin, the areas with the highest concentration and the forms of propagation of humidity in walls and subsoil of historic buildings by means of 2D and 3D electrical resistivity profiles.

## 2 Materials Y Methods

The methodology used the ERT technique to explore the subsoil of Temple Inmaculada Concepción and the walls of Terán House; in both cases, it knows the current conditions of the buildings.

The wall of Temple Inmaculada Concepción is in the Northwest, and it has a 0.5 m thickness and is 6 m height, with limestone joined with lime-soil mortar and gravel. Nowadays, it has a high level of deterioration in joins to 2 m height (Fig. 3a). The causes of humidity are the land topography due to water going to it in the rainy season, which stalls and filtrates to the subsoil where the building is.

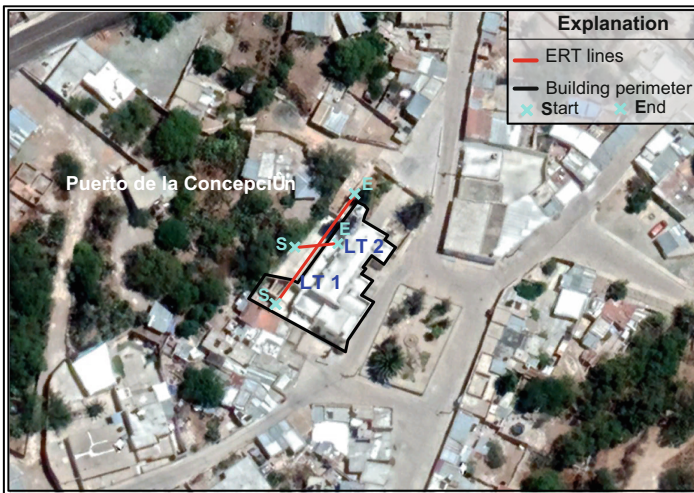
The wall of Terán House (Fig. 3b) is on the perimeter of the building in the zone of one yard. It is a divider wall because it is the only element that divides into the surrounding buildings. It was built with mud and joined with raw land and gravel with 0.70 m thickness and 5.5 m height. At the moment of these measurements, damages by humidity were in an area of 1 m above the soil to 3.5 m high.



**Fig. 3.** View of the interested walls a) Northwest wall of Temple of Inmaculada Concepción b) Surrounding wall of Terán House



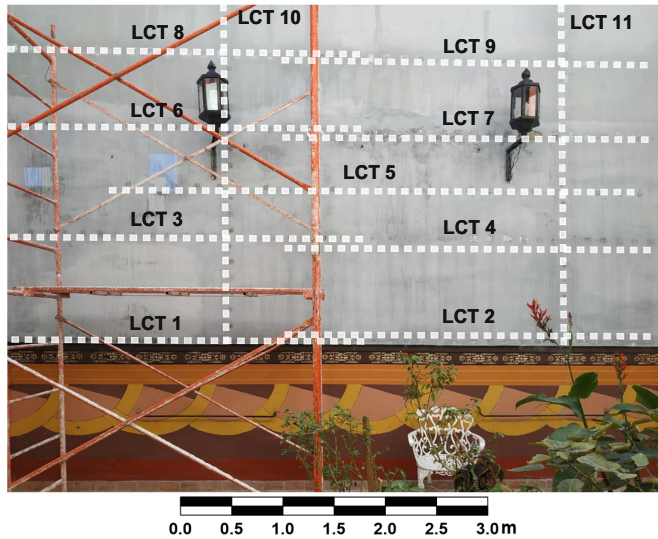
A resistivity meter Syscal Junior R1 Plus of 24 electrodes was applied using dipole-dipole settles to develop the measurements ERT. In the case of the Inmaculada Concepción building (Case 1), this technique was conducted in a traditional way of geophysics, with electrodes of 1/2" rod in the soil, on the north part of the building and one side of the interested wall. The first measurement was made parallelly on it, with a length of 29.9 m and a separation between electrodes of 1.3 m. The second measurement was conducted transversally to the first, with a 9.2 m length and 0.4 m separation between electrodes, starting in the exterior and ending in the interior of the building (Fig. 4). It was not viable to make more measurements because of the space.



**Fig. 4.** Location map of the electrical lateral lines in Temple, in the community of Puerto de la Concepción, in the municipality of Tepezalá.

A reticle was drawn on the zone of interest in Terán House (case 2) as a reference to make the longitudinal measurement. After that, the Electrical Resistivity Tomography technique was adapted to walls (micro geophysics) using square pads (electro stimulators) used in the area to measure. Most of the ten measurements were on the superficial zone with higher deterioration, which presented changes of color due to humidity measurements of 3.45 m length and separation between electrodes of 0.2 m.; just one of the measurements was located upper the deteriorated zone, apparently with no presence of humidity.

Longitudinal measurements on the wall were conducted from left to right from a height of 1.42, 2.4, 2.85, 3.4, and 4.12 m from the floor. Vertical measurements start on 1.42 m in height and end at 4.87 m from the floor. In four different heights, two continuous and longitudinal, with an overlap between lines of eight electrodes, were continuous models that covered the length of the wall (Fig. 5). The vertical lines were on the interested zones with low resistivities that resulted from the horizontal models.



**Fig. 5.** Location of the electrical lines on the wall of Terán House

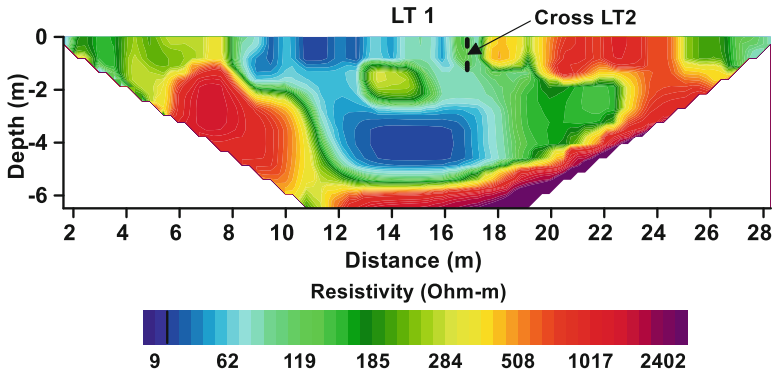
In case 1, the transversal profile shows where the wall is to know the soil-wall interaction (Fig. 7). In case 2, an image is elaborated with a group of all profiles, adding wall photography where it is possible to observe the superficial aspects to link them (Fig. 10).

In case 2, a 3D model defined precisely resistivities anomalies, the origin of humidity, the distribution flow, and the zones with a higher concentration of humidity; the image of the wall overlaps the 3D model to compare the damaged zone and the resistivity values associated.

### 3 Results and Discussions

#### 3.1 Case 1. Temple “Inmaculada Concepción”

The longitudinal profile is located on the side of the wall (Fig. 4) and shows resistivity values in the range of 1 to 2600  $\Omega$ -m. In the central part of the model, there are concentrated low resistivity values from 1 a 100  $\Omega$ -m. In extremes of the profile, resistivity values increase from 200 to 2600  $\Omega$ -m, between 16 and 17 m of distance crossing a short transversal profile (Fig. 6). The model defines the superficial resistive stratum in the extremes; the central zone is a hollow that probably is presented by alluvial deposits poorly consolidated. On the surface of the measured soil, a compacted limestone outcrop could link resistivities higher than 500  $\Omega$ -m in yellow and tones.



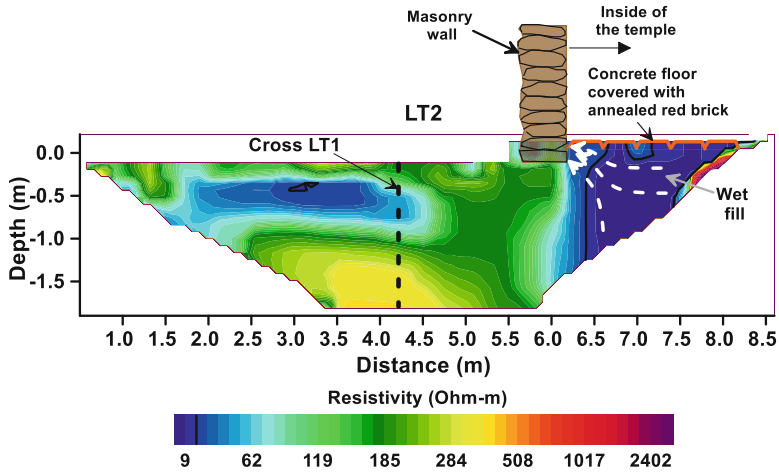
**Fig. 6.** Longitudinal electrical profile LT1. The crossing of LT2 is indicated.

A transversal form of the building is in Profile LT2 (Fig. 7). It is a division of resistive anomalies between 6 and 7 m distance; to the left side of the profile, the resistivity values are under  $500 \Omega\text{-m}$ , and to the right side, the resistive anomaly is in the range of 1 a  $50 \Omega\text{-m}$ . The resistive anomalies contrast 5 and 6 m under the wall, which divides the interior and exterior. After a 6 m distance to the interior of the building is defined as a stratum of approximately 1 m depth with values lower than  $20 \Omega\text{-m}$ ; this suggests the existence of a material with a high amount of humidity. The following are some factors that could be causing the concentration of moisture in this area: a) the use of incompetent filling materials with poor compaction during the construction of the temple's side spaces, and b) the low rate of moisture evaporation because these spaces are not exposed to the sun.

The lack of foundations or any element could inhibit the increases of humidity vulnerable the constructive system of the wall; consists of limestone stone joined with lime mortar and raw land. The proximities of the stratum to the wall could generate a higher rate of humidity filtration and a humid front with higher elevation in the wall. The last factor is possible to corroborate because superficial humidity in the wall is visible in the darker joins until 3 m height. According to [12, 27], the elevation of the humid front is because of three main factors: the rate of infiltration soil to the wall, high content of pores in the materials and the thickness of the wall.

### 3.2 Case 2. Terán House

The obtained profiles on different heights from the wall show a rate of resistivity from 1 to  $20,000 \Omega\text{-m}$ . Figure 8 shows the profiles where two resistive anomalies highlight due to they are in one or two zones. The anomaly in color dark blue (A1) with values under  $20 \Omega\text{-m}$  is in the profiles LCT 3, 4, 5, and 7. The resistive anomaly in the color purple (A2) with values higher than  $10,000 \Omega\text{-m}$  with prevalence in profiles LCT 6, 7, and 8.



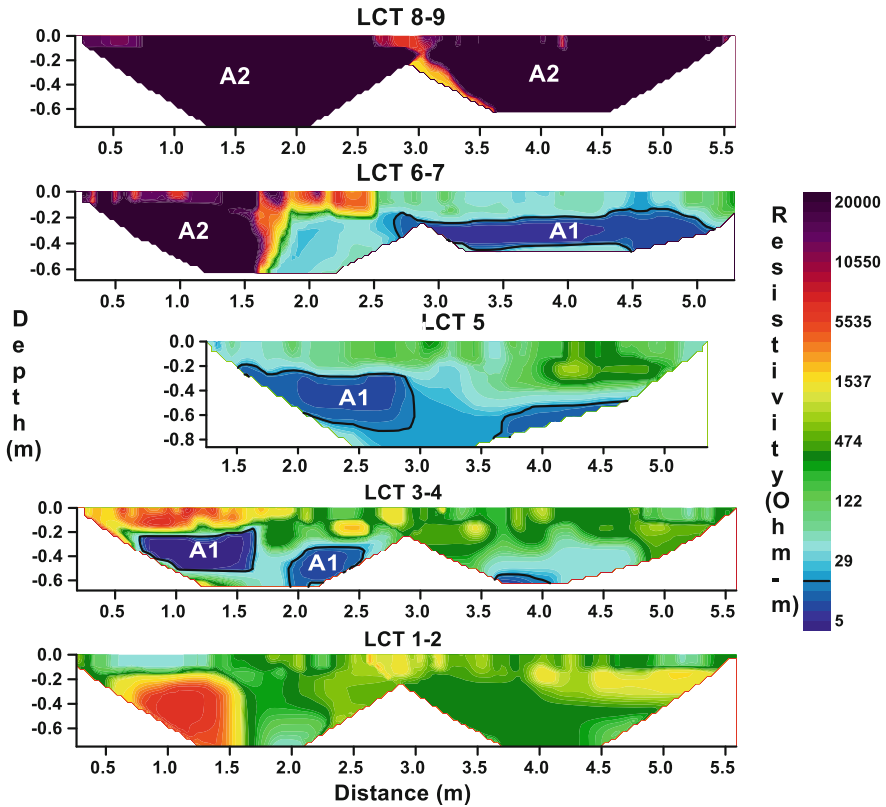
**Fig. 7.** Electrical profile LT2 transversal to the building is by the cross of the profile LT1, present in the wall of interest. Moisture flow lines are marked, indicating the possible upward flow of moisture from the subsoil to the wall.

The vertical profiles LCT 10 and 11 are on 1.95–4.92 in the longitudinal sense of the wall (Fig. 5) matches with the distributions of the resistive defined anomalies in the horizontal profiles (Fig. 8, profiles LCT 3 and 7). Anomaly A1 highlights in both profiles between 2.6 and 3.6 m height from the floor level under 0.15 m dept. Anomaly A2 in purple is in the top part of profile LCT 11 (Fig. 9).

The contact resistances obtained in the 11 measurements were in the range of 2 to 6.5 kOhm-m, with a variation of 3 units in each measurement. The RMSE obtained in the inversion process for both models was 10.3 and 7.1%.

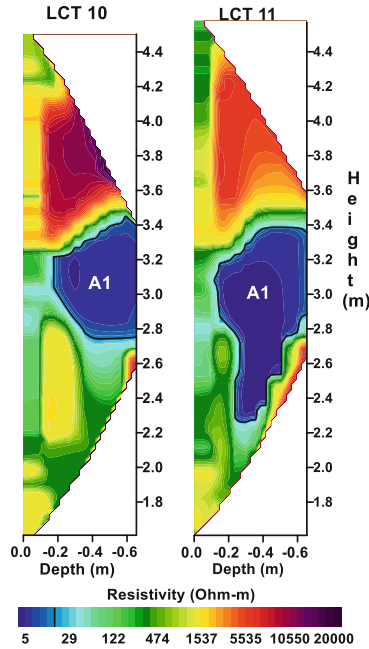
Figure 10 shows the models of the horizontal measures (LCT 6–7) and vertical (LCT 10 and 11) of higher interest and the image of the wall as a reference element. It is possible to observe that the anomaly with low resistivity in dark blue matches the superficial deteriorated zones due to the presence of humidity in dark tones marked with a divided line in blue when comparing the image with the resistivity models; this means that anomaly A1 is related to a humid mean; this is by the distribution of Anomaly A1 that the source of humidity comes from the adjacent construction; it is in the wall at an elevation of 3.4.

The tridimensional model (Fig. 11) configures the mean with a high amount of humidity and defines the origin of the water. The 3D model has configurated more precisely the zones where humidity propagates. Also, the zone with none is up to 4.2 m in height (Fig. 11b).

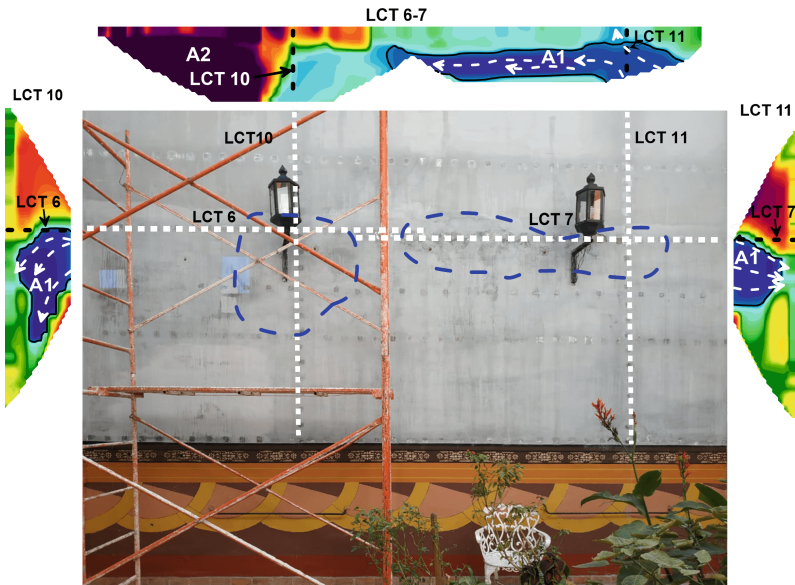


**Fig. 8.** Horizontal electrical profiles LCT 1-LCT 9 on the wall of Terán House. The most relevant resistive anomalies, A1 and A2, are indicated.

It reinforces the idea of water filtration due to a resilient source for the image obtained from the yard next to the wall, where is observed a possible tank on the second level (Fig. 12). The tank may present damages as cracks or fractures that could be generating filtrations to the wall of interest; due to the wall being of mud, the water of the tank filtrates with no resistance and flows to the lower levels of the wall, as the tridimensional model shows (Fig. 11b).

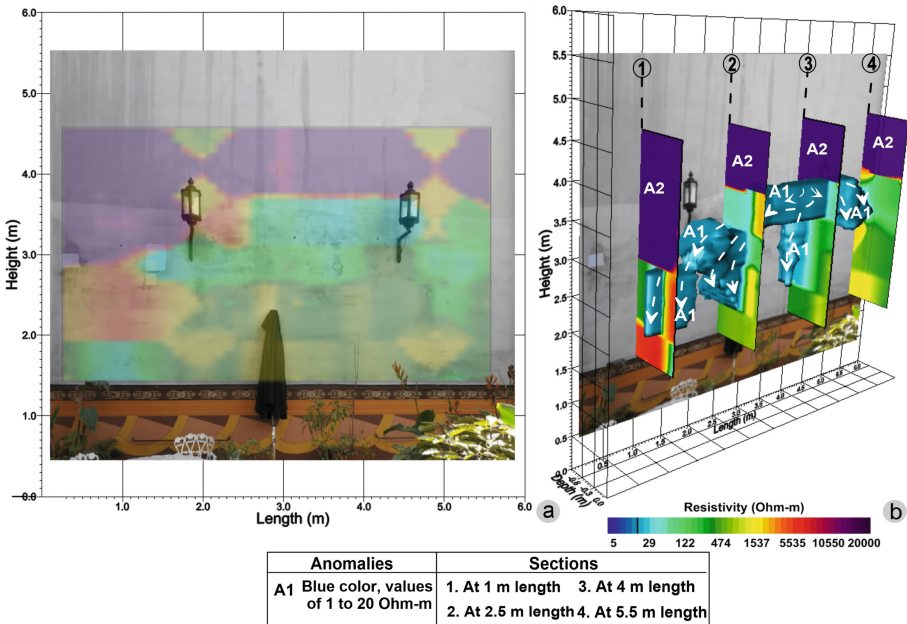


**Fig. 9.** Vertical profiles LCT 10 and 11 located at 1.95 and 4.92 along the wall. The resistive anomaly A1 is indicated.



**Fig. 10.** Image of the perimeter wall with the most important tomograms. Horizontal lines LCT 6 and 7 and vertical lines LCT 10 and 11 with their perspective models located in the exterior of the wall image. Also, the pointed line in blue marks the zones of dark tone due to humidity. Each model presents the electrical lines; at an orthogonally cross.





**Fig. 11.** The 3D model obtained from the horizontal and vertical 2D sections is a) a 3D model with an image of the wall overlap. b) a Tridimensional model with vertical sections located on 1, 2.5, 4, and 5.5 m. It is possible to see the volume with a high content of humidity and some arrows representing the flow of it in the interior of the wall.



**Fig. 12.** Location of the possible water cistern on the adjacent house a) Photography from the rooftop of Terán House. b) Photography from the roof of the adjacent parking lot. In the pointed line, it is possible to see some blades that could be covering the water cistern located on the second floor of the adjacent building of Terán House.

## 4 Conclusions

The Electrical Resistivity Tomography technique applied traditionally in the field of Geophysics or through micro-geophysics is very useful for analyzing moisture in historical buildings.

Temple of Inmaculada Concepción presents humidity on the wall-type ascendant; it was possible to know the zone, and the form of propagation of the subsoil flow to the wall by images in 2D, even if measurements were minimum.

In Terán House was possible to define the zones with a high concentration of humidity using the 3D model; also to know the forms of dispersion in the interior of the wall. The resistive anomaly A1 linked with a mean with a high concentration of humidity matches with the superficial damages observed on the wall. Upon concluding the study, the results of the ERT technique were confirmed, which indicate that the moisture comes from an external source located on the second level of the adjacent construction.

These results are significant for making decisions in future interventions. It is possible to implement works that mitigate the ascendant humidity and reduce the importance of the deterioration of walls when determining the causes of it.

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