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Identification of documented constructive stages of the San Ignacio Bridge (Aguascalientes, Mexico) using electrical resistivity tomography (ERT)

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Abstract: The non-destructive technique known as Electrical Resistivity Tomography (ERT) has been used in the analysis of historical buildings in recent years. It provides insights into the internal structure of the structural elements, such as layer thicknesses, and potential irregularities. In this investigation the ERT technique was applied to the ancient San Ignacio Bridge, located in the state of Aguascalientes, Mexico. The resulting resistivity profiles unveil the primary construction stages of the bridge, which corroborate and enhance the historical information regarding its construction phases. Additionally, the profiles indicate the presence of moisture concentrations in the pavement fillings, which could be attributed to rainwater infiltration. The usefulness of the ERT technique applied to edified patrimony is demonstrated in this study.

Keywords: Electrical Resistivity Tomography, San Ignacio Bridge, constructive stages, historical information

Identificación de etapas constructivas documentadas del Puente de San Ignacio (Aguascalientes, México) mediante tomografía de resistividad eléctrica (TRE)

Resumen: La técnica no destructiva conocida como Tomografía de Resistividad Eléctrica (TRE) se ha utilizado en el análisis de edificios históricos en los últimos años. Proporciona información sobre la estructura interna de los elementos estructurales, como el grosor de las capas y posibles irregularidades. En esta investigación, se aplicó la técnica TRE al antiguo Puente San Ignacio, ubicado en el estado de Aguascalientes, México. Los perfiles de resistividad resultantes desvelan las etapas primarias de construcción del puente, lo que corrobora y enriquece la información histórica sobre sus fases de construcción. Además, los perfiles indican la presencia de concentraciones de humedad en los rellenos del pavimento, que podrían atribuirse a la infiltración de agua de lluvia. La utilidad de la técnica de ERT aplicada al patrimonio edificado se demuestra en este estudio.

Palabras clave: Tomografía de Resistividad Eléctrica, Puente de San Ignacio, etapas constructivas, información histórica

Revelação das etapas de construção documentadas nos registos históricos da Ponte San Ignacio, Aguascalientes, México, mediante medições de Tomografia de Resistividade Elétrica (ERT)

Resumo: A técnica não destrutiva conhecida como Tomografia de Resistividade Elétrica (TRE) tem sido utilizada na análise de edifícios históricos nos últimos anos. Fornece informações sobre a estrutura interna dos elementos estruturais, como espessura das camadas e possíveis irregularidades. Nesta pesquisa, a técnica TRE foi aplicada à antiga Ponte San Ignacio, localizada no estado de Aguascalientes, México. Os perfis de resistividade resultantes revelam as etapas primárias de construção da ponte, corroborando e enriquecendo a informação histórica sobre as suas fases de construção. Além disso, os perfis indicam a presença de concentrações de humidade nos preenchimentos do pavimento, o que pode ser atribuído à infiltração de águas pluviais. A utilidade da técnica ERT aplicada ao património edificado é demonstrada neste estudo.

Palavras-chave: Tomografia de Resistividade Elétrica, Ponte San Ignacio, etapas de construção, informações históricas

Introduction

One of the activities involved in the diagnosis of the conservation status of built heritage is historical research into the construction process used, the documented alterations and modifications, as well as the interventions that the building has undergone throughout its history. Although the data revealed by historical research is often anecdotal and imprecise, it provides information to understand many of the pathologies that currently affect the building. Furthermore, once the construction has been reviewed in more detail, it is possible to find discontinuities in the construction system or in the materials that demonstrate and corroborate the data obtained from the historical research. This paper presents the application of the electrical resistivity tomography (ERT) method as an auxiliary tool for verifying the history of the construction stages of an 18th century bridge in the city of Aguascalientes, Mexico.

The bridge locally named San Ignacio is located northeast of the city of Aguascalientes and represents a monumental building from the 18th Century that spans the San Pedro River [Figure 1 and 2]. Originally, the bridge was an integral part of a secondary road called the "Camino Real de Tierra Adentro" which was designated as an UNESCO World Heritage Site in 2010 (World Heritage Committee 2010). However, the bridge itself was not included in this declaration but it is included in the Mexican catalog of historical monuments of the National Institute of Anthropology and Hystory (INAH).

Other studies have shed light on the main constructive stages of the building (Boils-Morales, 2009; Soto-Zamora, 2017), although these studies only present limited data and partial physical evidence in their analysis. Despite the incomplete information, the stages of construction can be classified as follows:

- The first stage began in 1743 and concluded in 1759, leaving only the parapets and road pavement unfinished. Unfortunately, the completion of the bridge was abruptly halted due to the flooding of the San Pedro River, which caused a partial collapse of the structure (Boils-Morales 2009).

- The second stage marked the initial reconstruction phase after the partial collapse, spanning from 1760 to 1797 (Boils-Morales 2009).

- Moving into the early 20th century, the third intervention involved replacing the original boulder paving of the bridge road with a layer of tiling made of blocks of foundry slag. Additionally, damaged sections of the parapets were substituted with the same type of blocks (Soto-Zamora, 2017).

- The activities of the most recent phase occurred in the early 1980s and entailed the realignment of the avenue. This included replacing the pavement on the north and south approaches of the bridge, as well as reconstructing the southern approach to align it with the new avenue. Moreover, reinforced concrete parapets were constructed during this phase (Soto-Zamora 2017).

The latter two events are evidenced by a photograph from the early 20th century [Figure 2a], which depicts one edge of the bridge showcasing the original paving and an approach that followed a different direction than the current one. Below is a summary of the events [Table 1] described above:

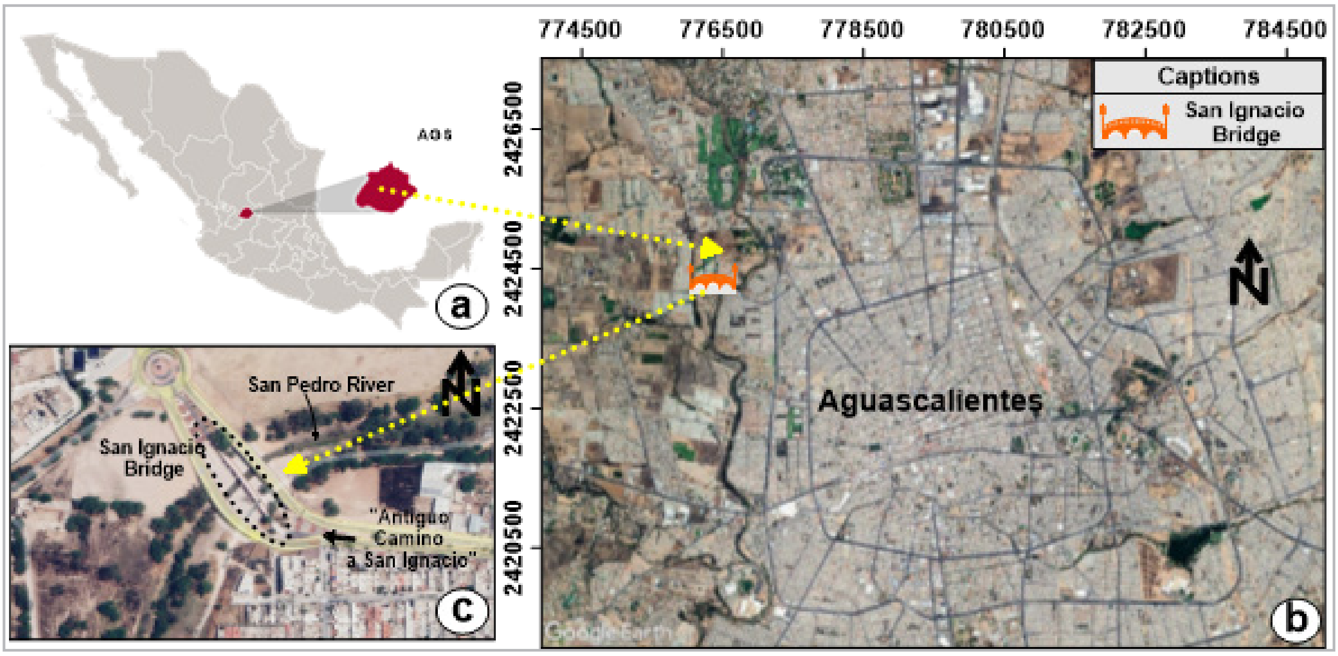

Figure 1.- Location and images of the bridge of San Ignacio. a) Map with the political division of the Mexican Republic where the state of Aguascalientes (AGS) is highlighted, b) and c) Depicts the large-scale and small-scale positioning map in the city of Aguascalientes.

Period	Events or activities
1743 to 1759	Construction beginning
1760 to 1797	Construction of the structure after a partial collapse
Beginning of the XX Century	Construction of a layer of tiling with blocks of found-ry slag.
Beginning of the eighties	Rectification of the layout of the avenue

Table 1.- Events and periods according to the historical sources

The last two events mentioned above are corroborated in the photograph at the beginning of the 20th century, depicting one edge of the bridge. In the photograph, the original stonework and an approach that follows a different direction to the current one can be observed [Figure 2a].

On the other hand, several authors have shown interest in the study of heritage building constructions (Sass and Viles 2006; Tsokas *et al.* 2008; Quesnel *et al.* 2011; Fauchard *et al.* 2013; Ghilardi *et al.* 2015; Evangelista *et al.* 2017; Martínez-Garrido *et al.* 2018; Hegyi *et al.* 2019; Cozzolino *et al.* 2020; Ortega-Ramírez *et al.* 2020, López-Gonzalez *et al.* 2022) in order to understand their characteristics and particularly their weaknesses, expanding knowledge of intangible aspects such as reconstructing history, and disseminating it through historical documentation, as well as in the use of non-invasive techniques such as the seismic method, ground penetrating radar (GPR), and electrical resistivity tomography (ERT).

Figure 2.- Old and recent images of the San Ignacio Bridge. a) Photo from the beginning of the XX century. Original boulder paving and the approach with a different direction than the current one. b) Arcs from axis A to H are shown. c) Arcs from axis G to J are shown [Figure 4].

ERT and GPR are recognized as the most used non-destructive methods in archaeology and the preservation of heritage buildings, due to their flexibility, adaptability, and ability to produce high-resolution results and images (Quesnel *et al.* 2011; Fauchard *et al.* 2013; Angelis *et al.* 2018; Hegyi *et al.* 2019; Cozzolino *et al.* 2020; Deiana and Previato 2023).

Some authors (Tsokas *et al.* 2007, 2008; Compare *et al.* 2009; Quesnel *et al.* 2011; Evangelista *et al.* 2017; Hegyi *et al.* 2019; Cozzolino *et al.* 2020) have focused on investigating buried structures belonging to ancient constructions. These studies aim to preserve remnants and verify information from documentary sources or records using various techniques, including ERT. In Mexico, notable studies have been conducted in the Cathedral of Puebla city (Ortega-Ramírez *et al.* 2020), the pyramid of Chichen Itza (Tejero-Andrade *et al.* 2018) and in the archaeological site of El Pahñú, in central Mexico (Argote-Espino *et al.* 2013), to define the internal structures built prior to the existing buildings and analyze moisture conditions in the subsurface and structures exposed to the elements.

Similar studies can also be found in the literature, such as the research conducted by Ghilardi *et al*. (2015), which determined the construction and disappearance dates of the Avignon Bridge in southern France using sedimentological and stratigraphic evidence with the ERT technique. Similarly, Fauchard *et al.* (2013) employed both ERT and GPR to investigate the internal structure and characterize the foundations of a small masonry arch bridge in Normandy, France.

In addition to the aforementioned approaches, these techniques have also been used to assess deteriorated areas, detect voids, measure sulfate content, and characterize construction materials that could potentially cause fractures or other damage to structures (Tsokas *et al.* 2007; Cardarelli and Di Filippo 2009; Tsourlos and Tsokas 2011; Di Maio *et al.* 2012; Argote-Espino *et al.* 2013; Cardarelli *et al.* 2016; Ercoli *et al*. 2016; Angelis *et al.* 2018; Hauquin and Mourey 2019).

This paper presents an application of Electrical Resistivity Tomography (ERT) to find out evidence of the main constructive stages and verify the documented interventions in the history of a heritage bridge, while providing evidence of the reconstructions throughout history. Additionally, electrical resistivity profiles are used to evaluate the condition of the fillings, taking into account the materials' heterogeneity and moisture content.

Materials and Methods

For the development of the ERT measurements, a 24-electrode Syscal Junior R1 Plus resistivimeter with dipole-dipole arrangements was used [Figure 3a].

The electric measurements were applied on the pavement of the bridge in longitudinal arrangement, 23 in total. An ERT measurement of 105 m long was made, covering the entire length of the bridge [Figure 4], in order to obtain general information about the bridge. In addition, 22 ERT measurement profiles were made on the road pavement, distributed as shown in Figures 3b and 4, with a length of 11.5 m and electrode separation at every 0.5 m, to obtain a better definition of the bridge fills up to approximately the level of the impost (2m deep). These profiles were measured at a distance of 0.5 to 1 m from the bridge parapets, with an

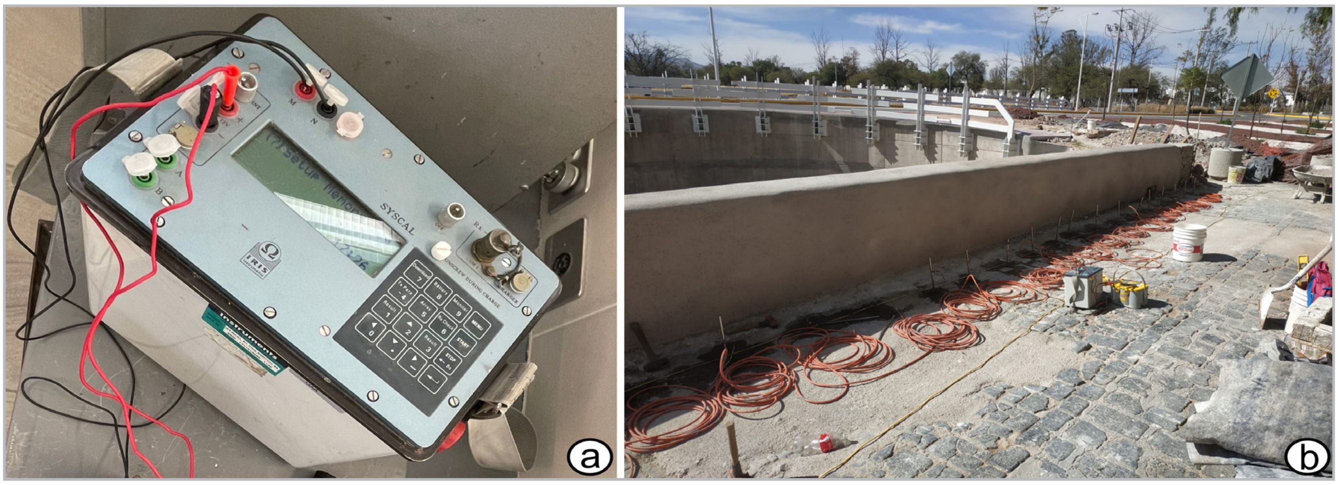

Figure 3.- a) Syscal Junior R1 Plus resistivity meter used in the measurements on the bridge b) ERT measurement with electrodes every 0.5 m at the north end of the bridge.

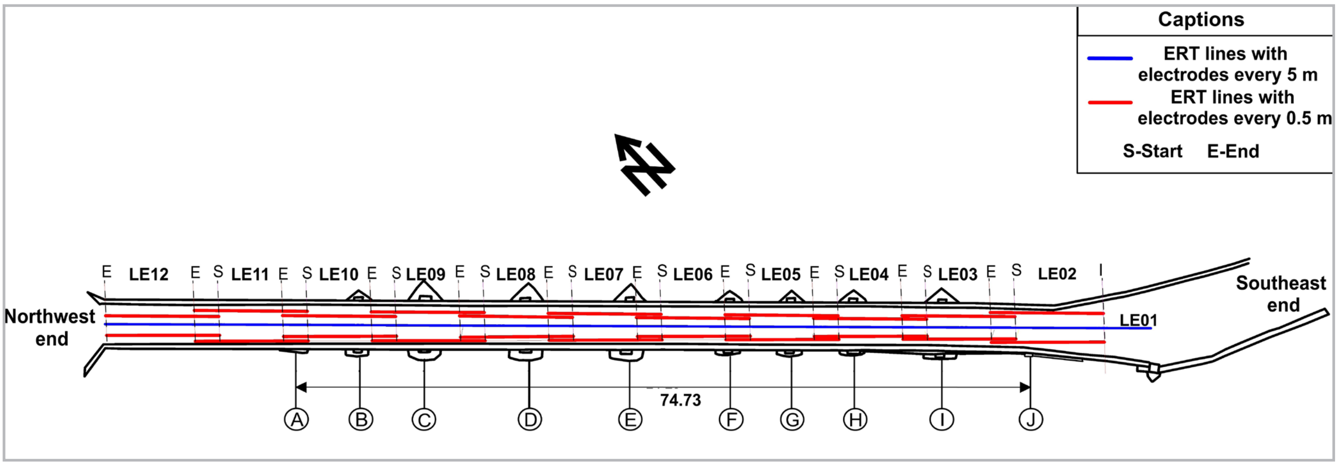

Figure 4.- Main characteristics of the San Ignacio bridge. a) Location of the ERT lines in plan view. The edges of the lines are indicated.

overlap of 6 electrodes between lines to have continuity in the profiles.

The measured field data is known as the apparent resistivity because it has the contribution of all the construction elements and their materials, but in the case of the measurements made, there is also an effect of the empty space around the bridge that we will call the effect of the geometry.

The field data were processed using the RES2DINV software to develop the resistivity model shown in Figure 5a, which shows the resistive anomalies due to the construction elements and their materials, and a distortion of the anomalies due to the effect of the geometry.

The axes labeled A-J on the plan [Figure 4] were established during the preparation of the architectural plans and serve as key reference points in this study. These axes are positioned within the buttresses at the center of each pilaster. The sequence of axes starts from the northwest and extends to the southeast.

Profiles LE02 through LE12, SW, and NE were located on the longitudinal elevation profile and areas of greatest interest were highlighted. On the area of the arches, the models were cut at a depth of 1.7 m at the lower level of the keystone due to the high resistivity values (greater than 10,000 Ohm-m) that corresponded to the empty space below the arches [Figure 6 and 7].

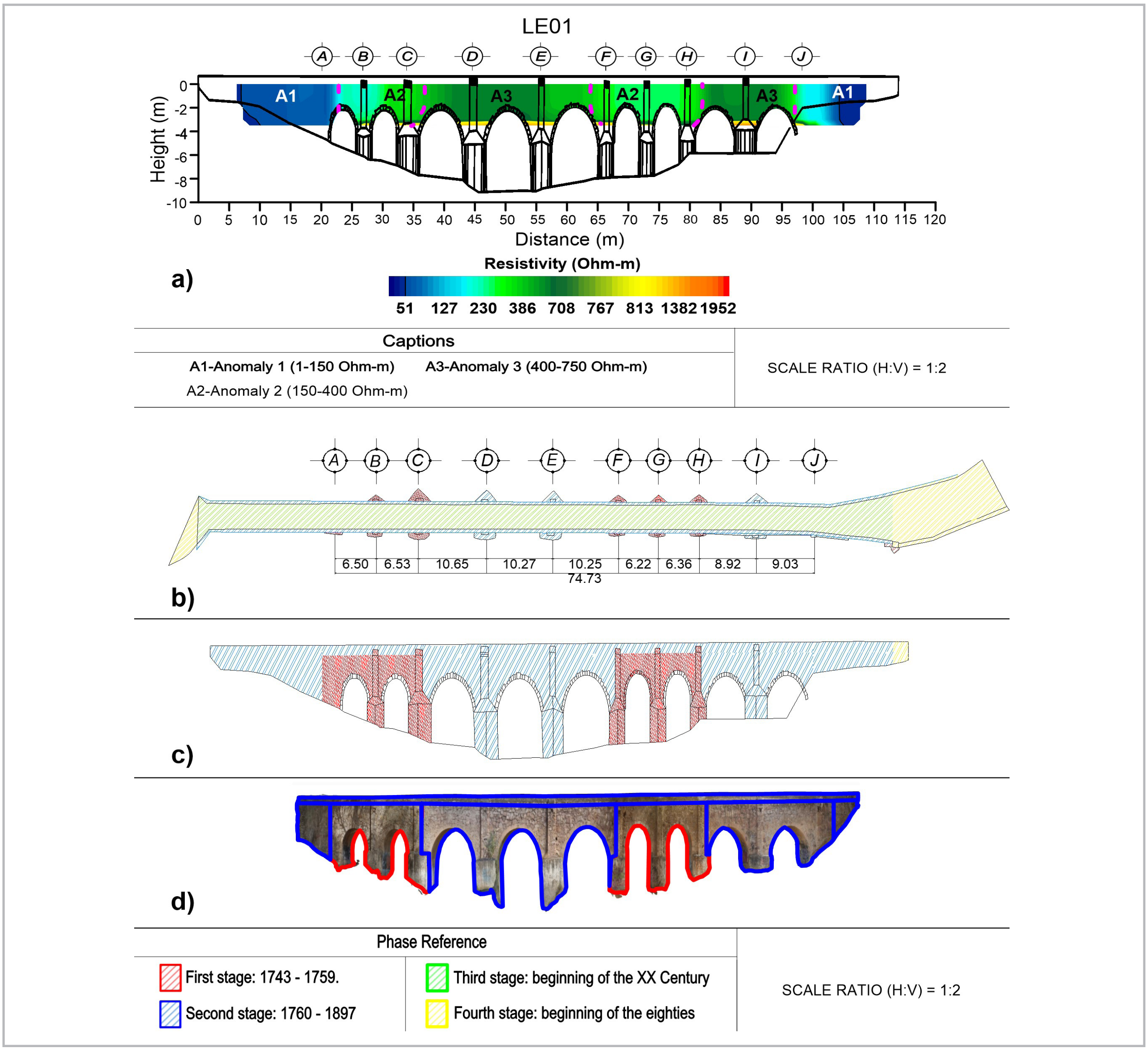

Figure 5.- Identification of the construction stages in the floor plan and elevation, based on the anomalies interpreted from the LE01 model and the historical information. The reference axes of the bridge located in each of the pillars or support structures are shown. a) Profile LE01 superimposed on the longitudinal section of the bridge. Resistive anomalies A1, A2 and A3 are identified. b) Plan view of the bridge with identification of the construction stages mentioned in historical records. c) Longitudinal section of the bridge with the construction stages defined from the resistive anomalies in figure 4a. d) Image of the southwest side of the bridge obtained from a photogrammetric model. Two of the construction stages are identified.

In addition, a correlation process was carried out between the anomalies identified in resistivity models and the data reported and summarized in Table 1 (Boils-Morales 2009; Soto-Zamora 2017).

Results

At both ends of profile LE01 [Figure 5a], between 7 and 23 m and 98 to 108 m, resistivity values were below 150 Ohm-m are represented in blue and cyan colors. Two light green zones are defined in the portions between 23 and 36 m and 64 to 83 m, with resistivity values in the range of 150 to 400 Ohm-m. Between 36 to 64 and 83 to 98 m, two dark green zones are defined with resistivity values in the range of 400 to 750 Ohm-m. The model reveals significant variations in resistivity between the different zones, establishing clear boundaries.

The profiles LE02 through LE12 NE and the SW profiles show resistivity values of up to 2300 Ohm-m, with blue tones predominating with resistivities in the range of 1 to 150 Ohm-m and green color with values in the range of 150 to 900 Ohm-m [Figures 6 and 7].

In most of the models (LE03-LE09 and LE11), particularly in the measurements near the northeast parapet (NE), resistive anomalies appear in green in the first 50 cm of depth, with values up to 1000 Ohm-m [Figure 6]. In the case of the profiles to the Southwest (SW), the resistive anomaly in green color is intermittent along the profiles from 0 to 50 cm depth [Figure 7].

Below the first resistive layer there is a second layer that deepens up to 1.7 m in the central profiles (LE03-LE10) and up to 2m in the case of the end profiles (LE02, LE11 and LE12) on both sides of the bridge [Figures 6 and 7] with low resistivity values lower than 150 Ohm-m. For the profiles located on the arches, from 1.5 to 2 m deep, a resistive anomaly with values of 150 to 2000 Ohm-m is observed. The low resistivity values (lower than 25 Ohm-m) in the LE05, LE10 and LE11 models stand out, coinciding on both sides (NE and SW). Finally, red resistivity values greater than 1300 Ohm-m are defined in superficial areas in a punctual manner in the LE04 NE, LE05 NE, LE05 NW, LE11 NE and LE12 SW models [Figures 8 and 9].

Discussion

As the anomalies fit the boundaries of the documented constructive stages, it is considered that although there is an effect of the space alongside and beneath the bridge on the resistivity values of the model shown in Figure 5a, in this case, it was not significant and it does not mask the anomalies related to the constructive stages. More research is needed to define and characterize the effects of the geometry in the measurements of resistivity in a building as the studied bridge.

Based on the aforementioned considerations, it can be inferred that the short ERT data, acquired with a 0.5 m spacing [Figure 6 and 7], may also be influenced by their close proximity to the void alongside the bridge. However, due to their short length, this influence is expected to exhibit uniformity or near-uniformity across the dataset. As a result, the anomalies are not distorted; they should have only increased by a constant value. Therefore, these anomalies reflect the structure of the fills and variations in moisture content.

Between axes C- F and H-J in figure 5a, the A3 resistive anomaly is identified with values between 400 and 750 Ohm-m in dark green color, which may correspond to the partial collapse of 1759 occurred mainly in this area and described in the narration of Boils-Morales (2009). These findings are supported by the field investigation conducted on the bridge, during which a change in the geometry of the arches and a slight rotation of the pillars located on the E and D axes were observed. Furthermore, physical modifications in the materials, such as changes in color and texture, were observed in areas without coating on the intrados of the arches.

On the other hand, the low resistivity anomalies A1 located at both edges of the bridge [Figure 5a] are spatially related to the construction stage 4 [Table 1] which corresponds to the modification of the approach slabs to align with the new layout of the “Antiguo Camino a San Ignacio” in the early 1980´s. The fill material used in the construction of the approaches has a higher moisture content [Figure 5a], since it lacks lateral confinement that blocks the flow coming from the avenues that connect with the bridge and from its sides. Furthermore, it only has a wearing course, without the presence of the second layer of tiling with blocks of foundry slag found on the Bridge roadway, which could reduce water infiltration.

Anomaly 2 is therefore linked to the area that corresponds to the initial construction phase, identified as stage 1, which spans from 1743 to 1759 [Table 1].

To assess the effect of the space beneath and alongside the bridge, i.e., the bridge geometry, an inversion was performed solely on the data from the first and second survey levels, corresponding to data acquired with a dipole spacing of 5 m and 10 m. These data contain information only about the top 3.5 m depth, where the bridge fills and masonry are primarily located, resulting in anomalies mainly caused by the electrical properties of these bridge elements.

However, the roadway has a width of 5 m, and the thickness of the fills above the arches is 2 m on average. Therefore, the resulting model still includes an unquantified effect caused by the space alongside and beneath the bridge, which could not be eliminated. This is due to the requirement of having data from at least two survey levels for constructing a 2D resistivity model of the bridge roadway. Additionally, given the dipole size, the second survey level is located 1.5 m below the arches. By placing the LE02-LE12 NE and SW models [Figures 6 and 7] in a continuous arrangement in the elevation profile upstream of the bridge, is possible to associate some low resistivity zones with humid fills, as is the case of zones 1, 2 and 3, which present values lower than 25 Ohm-m. Zone 1 and 2 [Figure 6 and 7] show values below 25 Ohm-m in blue in profiles LE10 and 11 on both sides, between 0.5 and 1.5 m deep. These areas with high moisture concentrations coincide with the cement-sand mortar fillings on the road surface, as well as with pothole areas with stagnant water.

The presence of fillings with high moisture content, as observed in the highlighted areas [Figures 6 and 7], likely contributes to the deterioration of the immediate arch intrados.

In addition to the aforementioned findings, the NE and SW continuous models [Figures 6 and 7] reveal the presence of a 0.5 m thick layer with resistivity values ranging from 150 to 2300 Ohm-m in the upper part. This layer spans the entire bridge profile and is marked with a dashed pink line. In most cases, areas exhibiting high resistivity values are located above low resistivity anomalies situated at greater depths. Consistently,

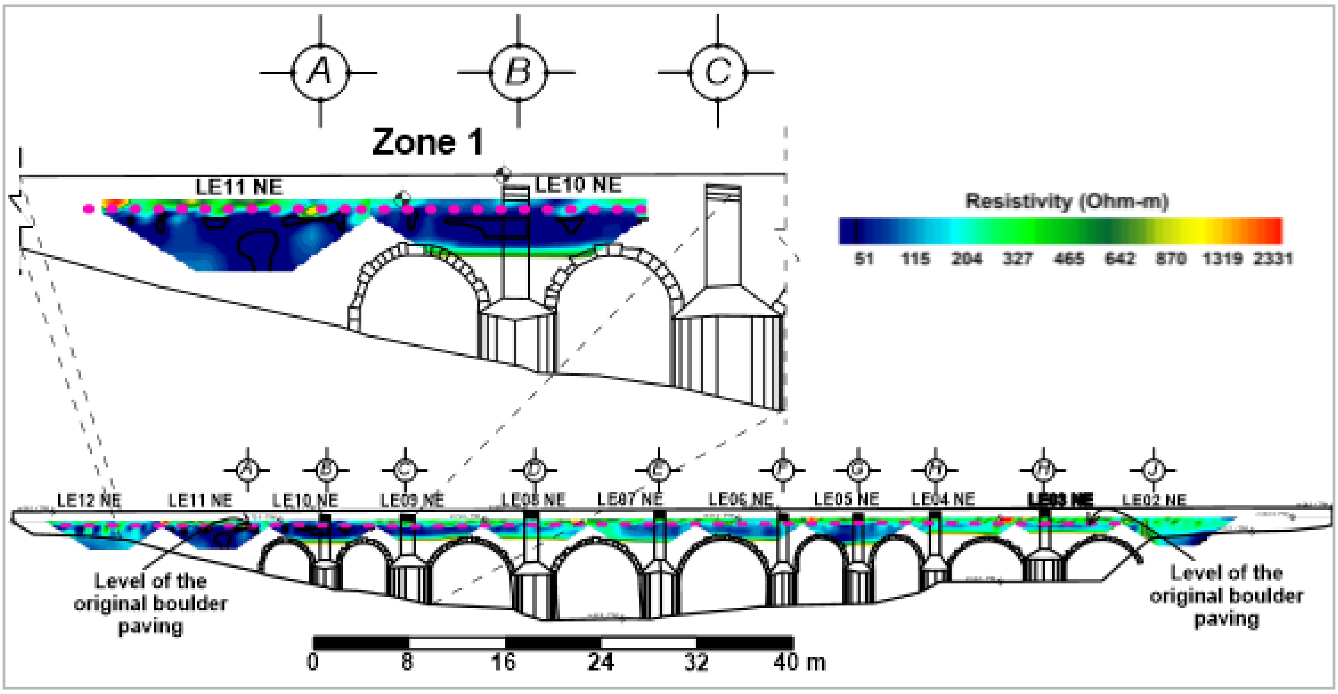

Figure 6.- LE02-LE12 NE models placed in continuous arrangement in the elevation profile. Areas of low resistivity are identified in blue and the surface layer with a dashed pink line.

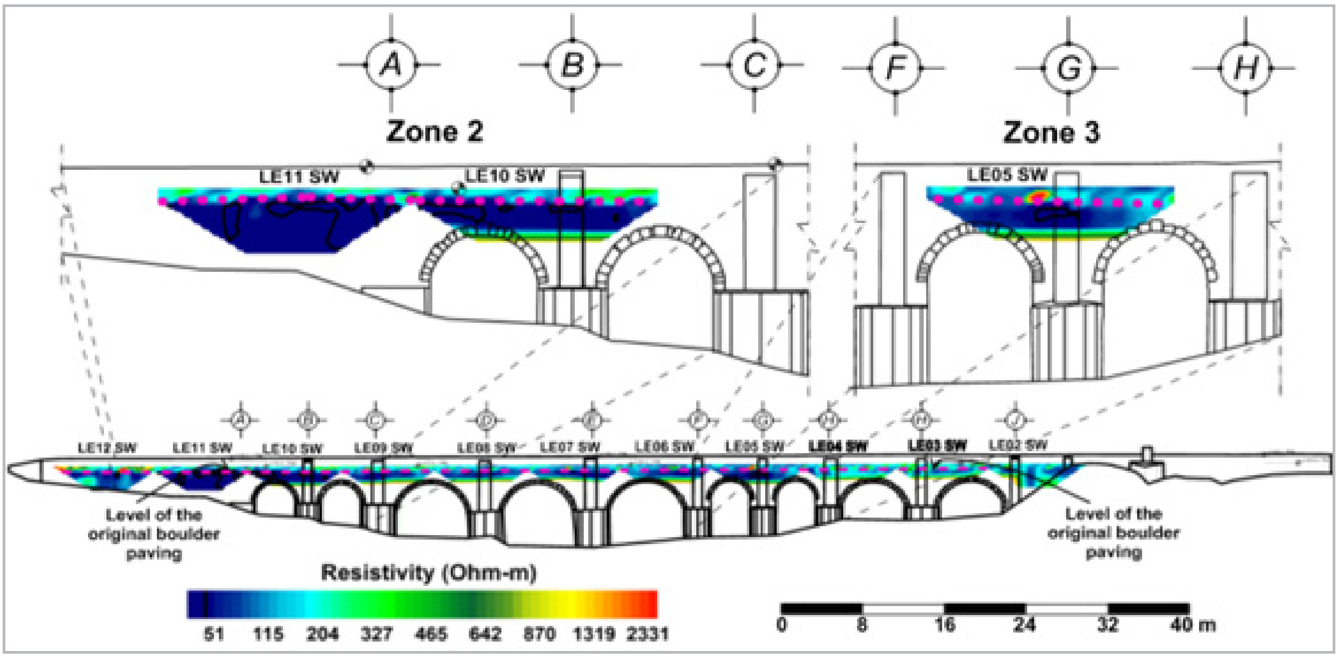

Figure 7.- LE02-LE12 NE models placed in continuous arrangement in the elevation profile. Areas of low resistivity are identified in blue and the surface layer with a dashed pink line.

these superficial zones of high resistivity coincide with pothole that were repaired with concrete. These concrete volumes are associated with the high resistivity values observed.

This thin surface layer corresponds to the third stage of construction (Soto-Zamora 2017), wherein the original boulder paving was covered with a tiling layer composed of foundry slag blocks. It is worth noting that in profile LE02 on both sides, this surface layer is not clearly defined, which is consistent with its location in the approach slabs area.

Regarding the profiles depicted in Figures 6 and 7, no significant change along the C-E axes related to the collapse was detected. This can be attributed to the fact that only the fillings are measured, which consist of a material similar to that used in the initial stage, as indicated by the resistivity values displayed in profiles LE07, LE08, LE09 NE, and SW.

It stands out that in the NE profiles [Figure 6] the layer of the original boulder paving is better defined along the bridge, in contrast to the SW profiles [Figure 7] the resistive anomalies exhibit transitional changes from green to blue colors within the first 0.5 meters of depth. This suggests that the water filtered more towards the SW side so that the superficial stratum experienced a larger modification in its mechanical properties. The observed high moisture content can primarily be attributed to two factors: the slope inclination towards the southwest and the obstruction of lateral drains on the bridge, leading to water stagnation and seepage predominantly on the SW side.

Table 2 summarizes the main construction activities in each historic stages until 2020 and how they are evidenced in this work.

Stage	Description of the stage	Evidence
1	Initial Construction	ERT Model LE01, (Boils-Morales, 2009)
2	Reconstruction due to a partial collapse	ERT Model LE01, (Boils-Morales, 2009)
3	Covering original boulder paving with a layer of tiling with blocks of foundry slag	ERT Model LE02-LE12 SW and NE and picture of the beginning of XX century
4	Modification of approach slabs	Picture of the beginnings of the XX Century (Figure 1d)

Table 2.- Constructive stages and evidences

Conclusions

In base to the obtained results, we can conclude the following:

• Through the application of ERT it was possible to reveal three constructive stages of the San Ignacio bridge: a) the initial construction, b) the partial collapse between the C-F and H-J axes and c) the original boulder paving. In both extremes of the bridge, we could identify anomaly A1 which was assumed to be related with the modification of the approach slabs.

• The area reconstructed during stage 2 after the collapse due to the flooding of the river is verified. The study demonstrated the existence of the partial collapse of the building which coincides with the documentary sources and the previously identified physical changes (changes in the dimensions of the arches, in the color and texture of the materials and the rotation of the pilasters).

• Low-resistivity anomalies were identified in the fill area, and were related to the excess of moisture due to leaks from the road surface, which could represent a potential long-term risk if the areas of humidity increase, mainly in the area of the arches.

• The results show that these types of studies can provide evidences to verify or reconstruct the history of heritage buildings. Additionally, valuable information is obtained for decision-makers and the planning of interventions in historic structures. Understanding the deterioration condition of materials and structural pathologies is crucial to prevent further damage and ensure effective restoration instead.

References

ANGELIS, D. et al. (2018). "Combined application of GPR and ERT for the assessment of a wall structure at the Heptapyrgion fortress (Thessaloniki, Greece)", *Journal of Applied Geophysics*, 152: 208–220. https://doi.org/10.1016/j.jappgeo.2018.04.003.

ARGOTE-ESPINO, D. *et al.* (2013). "3D electrical prospection in the archaeological site of El Pahñú, Hidalgo State, Central Mexico", *Journal of Archaeological Science*, 40(2): 1213–1223. https://doi.org/10.1016/j.jas.2012.08.034.

BOILS MORALES, G. (2009). Los puentes de la Independencia. *Boletín De Monumentos Históricos*, (16), 155–167. Recuperado a partir de https://revistas.inah.gob.mx/index.php/boletinmonumentos/article/view/2114

CARDARELLI, E. *et al.* (2016). "Geophysical and geochemical techniques to assess the origin of rising damp of a Roman building (Ostia Antica archaeological site)", *Microchemical Journal*, 129: 49–57. https://doi.org/10.1016/j.microc.2016.06.006.

CARDARELLI, E. AND DI FILIPPO, G. (2009). "Integrated geophysical methods for the characterisation of an archaeological site (Massenzio Basilica — Roman forum, Rome, Italy)", *Journal of Applied Geophysics*, 68(4): 508–521. https://doi.org/10.1016/j.jappgeo.2009.02.009.

COMPARE, V. *et al.* (2009). "Resistivity probability tomography imaging at the castle of Zena, Italy", *Eurasip Journal on Image and Video Processing*, 2009(1): 693274. https://doi.org/10.1155/2009/693274.

COZZOLINO, M. *et al.* (2020). "Non-Destructive Techniques for Building Evaluation in Urban Areas: The Case Study of the Redesigning Project of Eleftheria Square (Nicosia, Cyprus)", *Applied Sciences*, 10(12): 4296. https://doi.org/10.3390/app10124296.

DEIANA, R. AND PREVIATO, C. (2023). "Geophysical Surveys for Archaeological Research in Urban Areas: The Case of the Roman Theatre in Padua", *Heritage*, 6(2): 946–956. https://doi.org/10.3390/heritage6020052.

DI MAIO, R. *et al.* (2012). "New Insights for Conservation of Villa Imperiale (Pompeii, Italy) Through Nondestructive Exploration", *International Journal of Architectural Heritage*, 6(5): 562–578. https://doi.org/10.1080/15583058.2011.593392.

ERCOLI, M. *et al.* (2016). "Inside the polygonal walls of Amelia (Central Italy): A multidisciplinary data integration, encompassing geodetic monitoring and geophysical prospections", *Journal of Applied Geophysics*, 127: 31–44. https://doi.org/10.1016/j.jappgeo.2016.02.003.

EVANGELISTA, L. *et al.* (2017). "Application of ERT and GPR geophysical testing to the subsoil characterization of cultural heritage sites in Napoli (Italy)", *Measurement*, 104: 326–335. https://doi.org/10.1016/j.measurement.2016.07.042.

FAUCHARD, C. *et al.* (2013). "Assessment of an ancient bridge combining geophysical and advanced photogrammetric methods: Application to the Pont De Coq, France", *Journal of Applied Geophysics*, 98: 100–112. https://doi.org/10.1016/j.jappgeo.2013.08.009.

GHILARDI, M., SANDERSON, D.C.W., *et al.* (2015). "Dating the bridge at Avignon (south France) and reconstructing the Rhone River fluvial palaeo-landscape in Provence from medieval to modern times", *Journal of Archaeological Science: Reports*, 4: 336–354. https://doi.org/10.1016/j.jasrep.2015.10.002.

HAUQUIN, T. AND MOUREY, Q. (2019). "The detection of old masonry tunnels as low electrical resistivity anomalies-application to one covered stream tunnel of the Cevennes Mountain region (France)", *Journal of Applied Geophysics*, 168: 12–23. https://doi.org/10.1016/j.jappgeo.2019.05.010.

HEGYI, A. *et al.* (2019.) "Mapping the subsurface structures of a lost medieval village in South-Western Romania by combining conventional geophysical methods", *Archaeological Prospection,* 26(1): 21–32. https://doi.org/10.1002/arp.1720.

LÓPEZ-GONZÁLEZ, L. et al. (2022). Coupling electrical resistivity methods and GIS to evaluate the effect of historic building features on wetting dynamics during wind-driven rain spells. *Journal of Cultural Heritage*, 58, 209-218. https://doi.org/10.1016/j.culher.2022.10.009

MARTÍNEZ-GARRIDO, M.I. *et al.* (2018). "A comprehensive study for moisture control in cultural heritage using non-destructive techniques", *Journal of Applied Geophysics*, 155: 36–52. https://doi.org/10.1016/j.jappgeo.2018.03.008.

ORTEGA-RAMÍREZ, J. *et al.* (2020). "Application of non-invasive geophysical methods (GPR and ERT) to locate the ancient foundations of the first cathedral of Puebla, Mexico. A case study", *Journal of Applied Geophysics*, 174: 103958. https://doi.org/10.1016/j.jappgeo.2020.103958.

QUESNEL, Y. *et al.* (2011). "Geophysical Signatures of a Roman and Early Medieval Necropolis", *Archaeological Prospection*, 18(2): 105–115. https://doi.org/10.1002/arp.411.

SASS, O. AND VILES, H.A. (2006). "How wet are these walls? Testing a novel technique for measuring moisture in ruined walls", *Journal of Cultural Heritage*, 7(4): 257–263. https://doi.org/10.1016/j.culher.2006.08.001.

SOTO-ZAMORA, M.Á. (2017) "El puente «San Ignacio»: testigo vivo del auge y caída de la Compañía de Jesús en la Nueva España", Actas del Décimo Congreso Nacional y Segundo Congreso Internacional de Historia de la Construcción : Donostia-San Sebastián, 3 a 7 de octubre 2017, III, pp. 1593–1602.

TEJERO-ANDRADE, A. *et al.* (2018). "Illuminating" the interior of Kukulkan's Pyramid, Chichén Itzá, Mexico, by means of a non-conventional ERT geophysical survey", *Journal of Archaeological Science*, 90: 1–11. https://doi.org/10.1016/j.jas.2017.12.006.

TSOKAS, G.N. *et al.* (2007). "Geophysical exploration in the Church of Protaton at Karyes of Mount Athos (Holy Mountain) in northern Greece", *Archaeological Prospection*, 14(2): 75–86. https://doi.org/10.1002/arp.305.

TSOKAS, G.N. *et al.* (2008). "Non-destructive electrical resistivity tomography for indoor investigation: the case of Kapnikarea Church in Athens", *Archaeological Prospection*, 15(1): 47–61. https://doi.org/10.1002/arp.321.

TSOURLOS, P. I. AND TSOKAS, G.N. (2011a). 'Non-destructive Electrical Resistivity Tomography Survey at the South Walls of the Acropolis of Athens', *Archaeological Prospection*, 18(3): 173–186. https://doi.org/10.1002/arp.416.

WORLD HERITAGE COMMITTEE (2010). Report of the Decisions Adopted By the world heritage committee At its *34th session of the World Heritage Committee*, Brasilia, Brazil, 2010.

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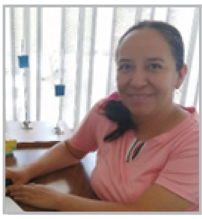

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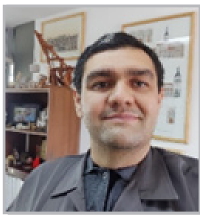

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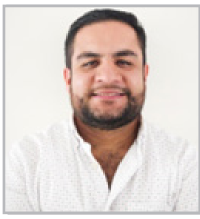

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